Advanced Workshop on Earthquake Fault Mechanics: Theory, Simulation and Observations
ICTP, Trieste, Sept 11 2019

Lecture 3:Beyond Rupture Imaging: Early Warning, GMPE, and off-shore seismicity detections

Lingsen Meng
UCLA Department of Earth, Planetary, and Space Sciences

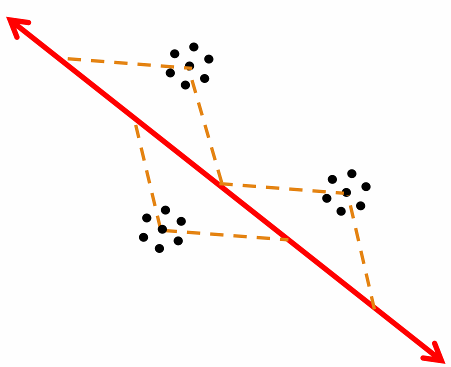
SCEC an NSF+USGS center

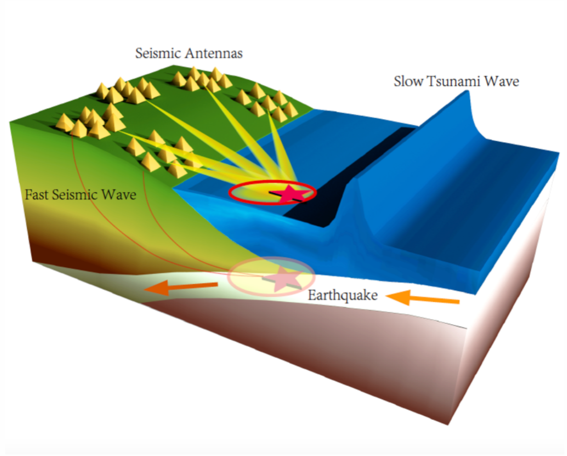
Knopoff Chair

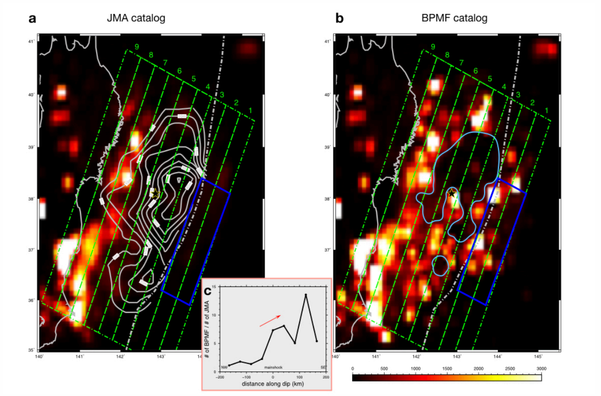
earthscope www.earthscope.org

Outlines

- Motivation: growing seismic hazard
- Array processing at regional and local scale
- Earthquake Early warning
- Tsunami Early warning
- Improving Ground motion prediction equation
- Detection of off-shore seismicity

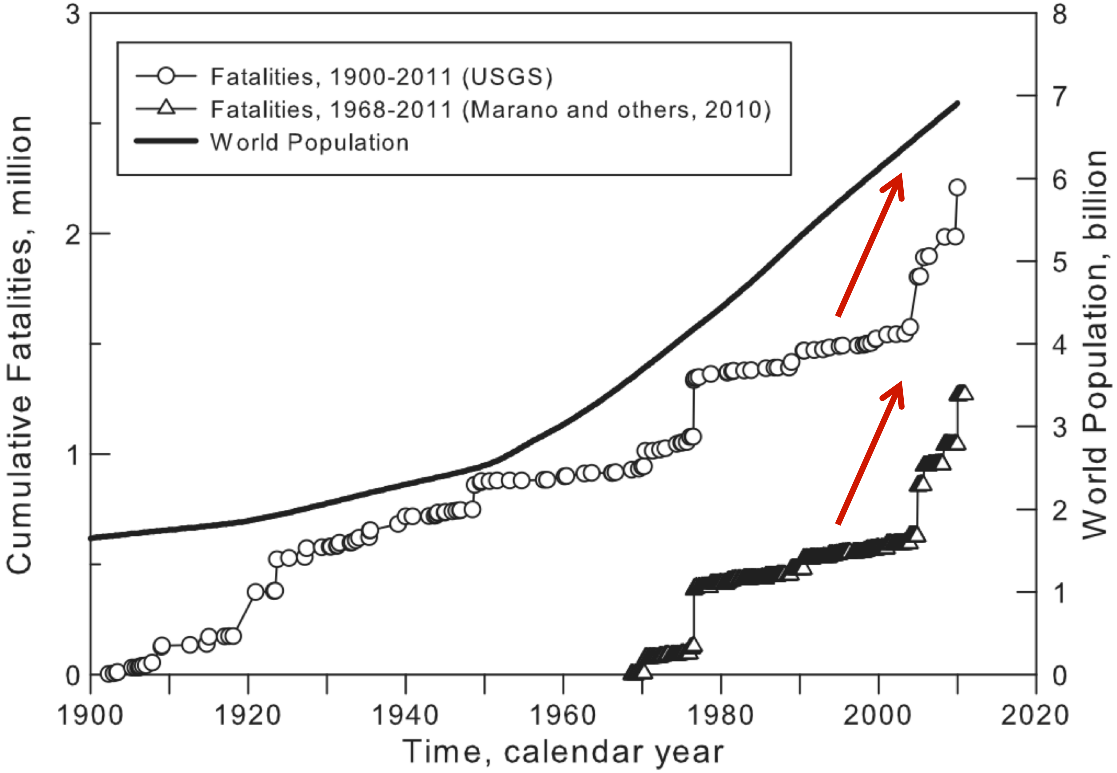






The Growing Earthquake Threat

21st century started with an increase in the rate of earthquake fatalities…



Holzer & Savage, 2013

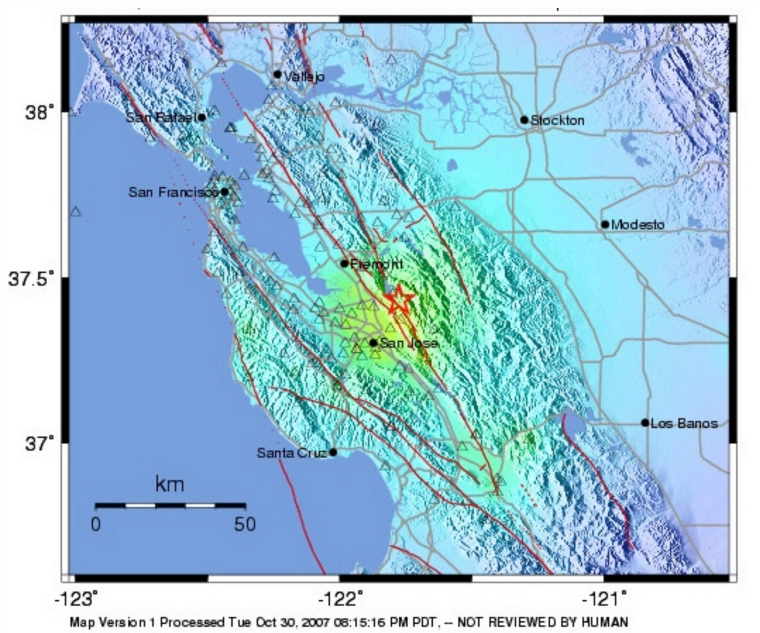
2004:
228,000
Sumatra-Andaman

2005:
86,000
Kashmir

2008:
88,000
Wenchuan

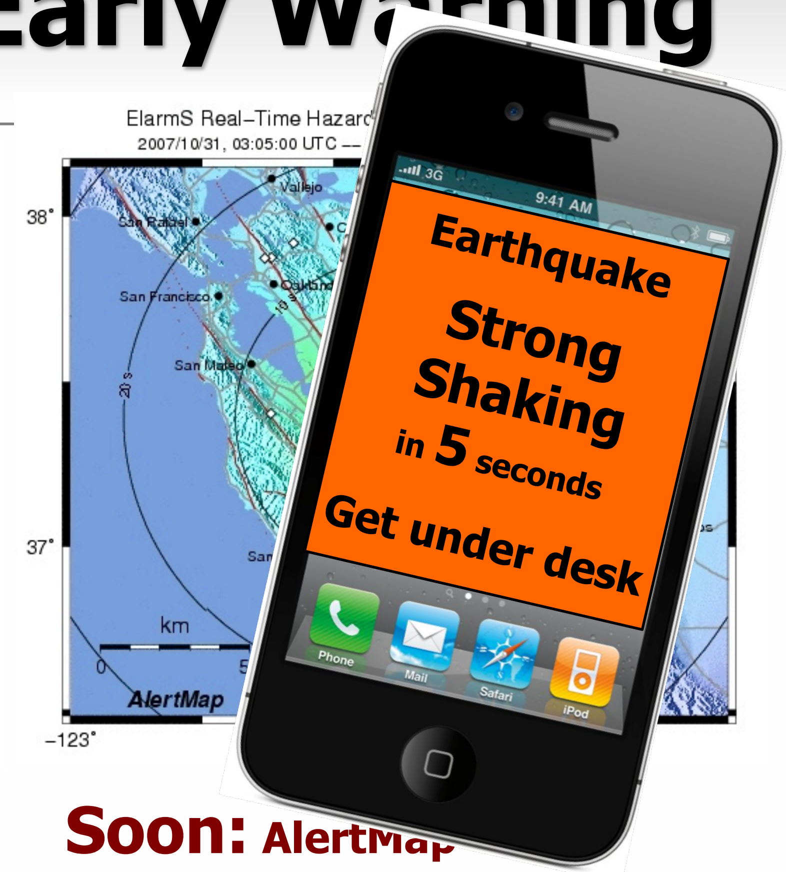
2010:
223,000
Haiti

Earthquake Early Warning



Today: ShakeMap

in 8-10 minutes



Soon: AlertMap

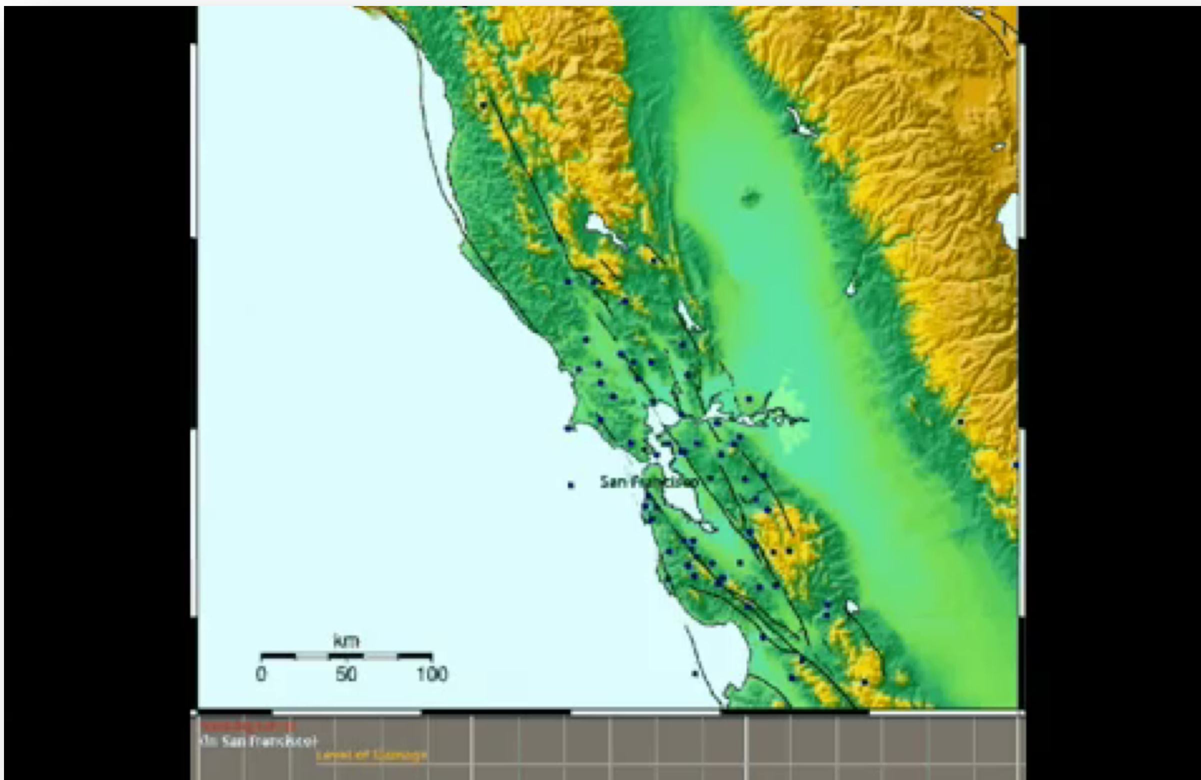
seconds to tens of seconds before shaking

Current realtime earthquake information

- location
- magnitude
- ground shaking distribution

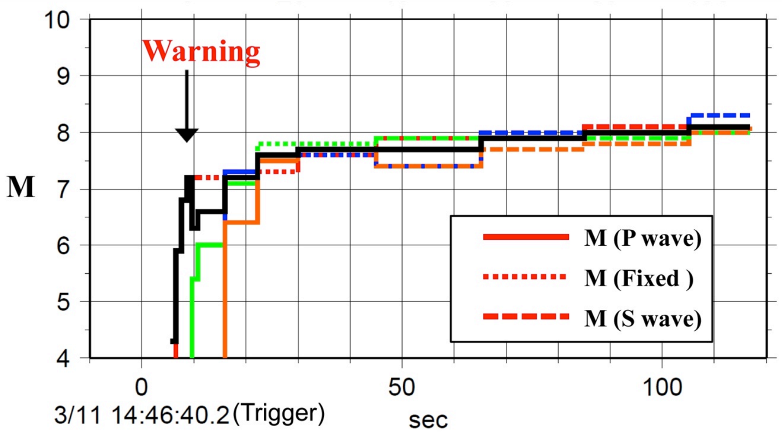
- people move to safe zone (under table)
- slow and stop trains (MRT)
- isolate hazards (equipment, chemicals)

Earthquake Early Warning



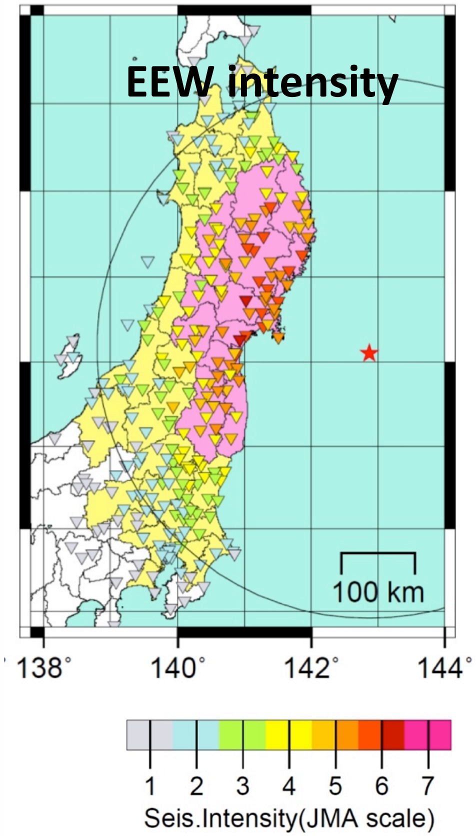
EEW Performance of the Tohoku Earthquake

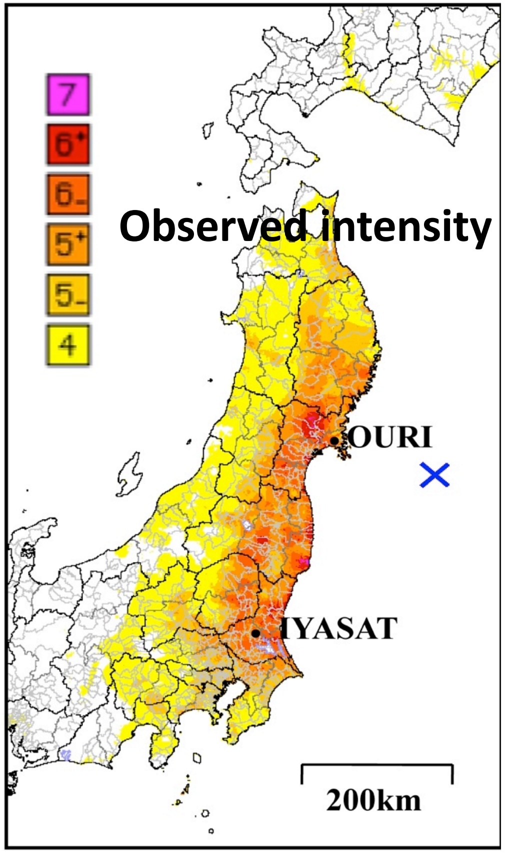
Predicted Magnitude as a function of warning time



All magnitude saturated at M8.1!

Hoshiba et al., 2011



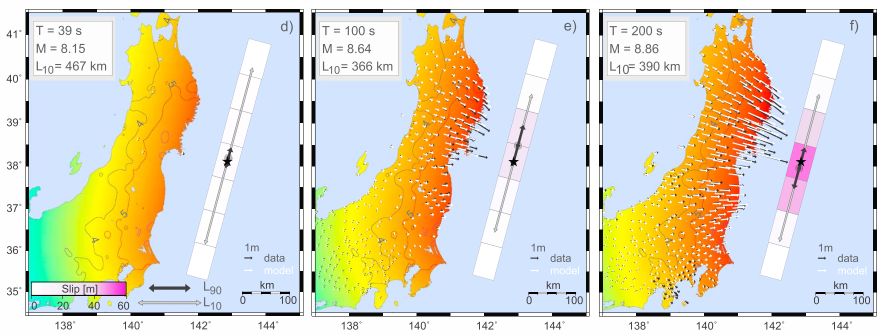


Much larger ground motion in Tokyo than predicted!

Need to know the **finite dimension** in real time !

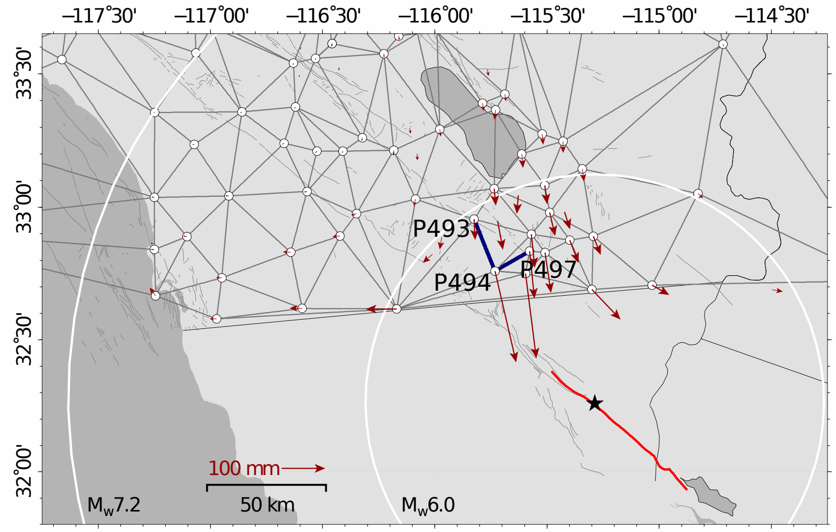
Real time finite fault models

M9 Tohoku-Oki Earthquake



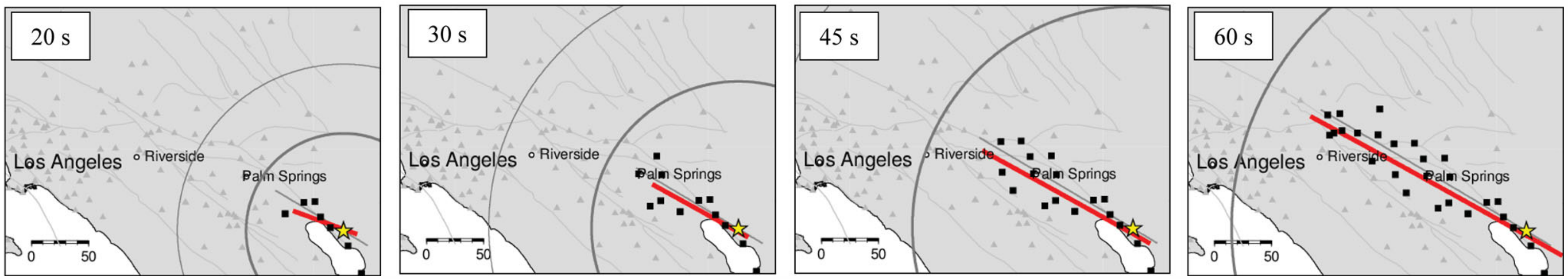
Colombelli et al., 2013

M7.2 El-Mayor Cucapah Earthquake



Grapenthin et al., 2014

M 7.8 ShakeOut Scenario



FinDer: Bose et al., 2012

Real-time Capability

Latest large earthquake

(BP using Hi–net, Japan data)

UT time: 2015–07–22 22:00:35

Mag: 4.7

Depth: 10.00 km

Lon: 94.89 Lat: 30.33

1. 6 min Data

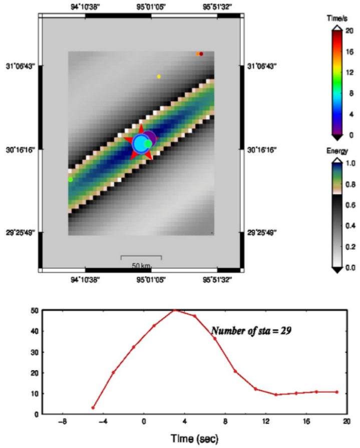


Figure 1-1 Top: Timings and amplitudes for the stack with the maximum correlation at each time step (2 s) and the cumulative stacked amplitudes (energy). Bottom: Normalized values of the maximum amplitudes in ech time window.

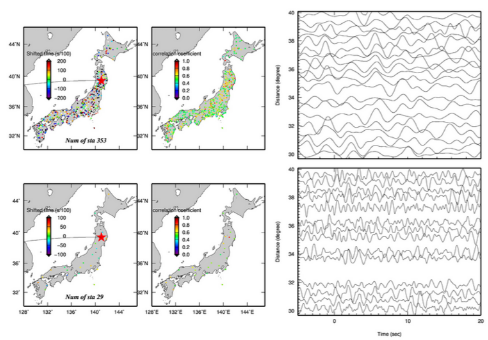


Figure 1-2 Station corrections for the data recorded at Hi-net. Left and middle: From top to bottom show shifted times (station corrections) and cross correlation coefficients of the low frequency waveforms (band-pass filtered between 0.05 and 0.5 Hz), shifted times and cross correlation coefficients of the high frequency waveforms (band-pass filtered between 0.5 and 2.0 Hz). Red star shows the location of the reference station. Right: Aligned waveforms filtered in the low (top) and high (bottom) frequency bands, sorted by epicenter distance.

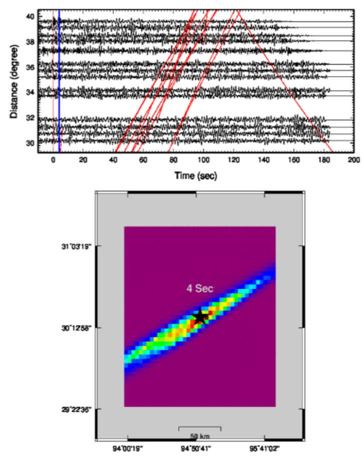
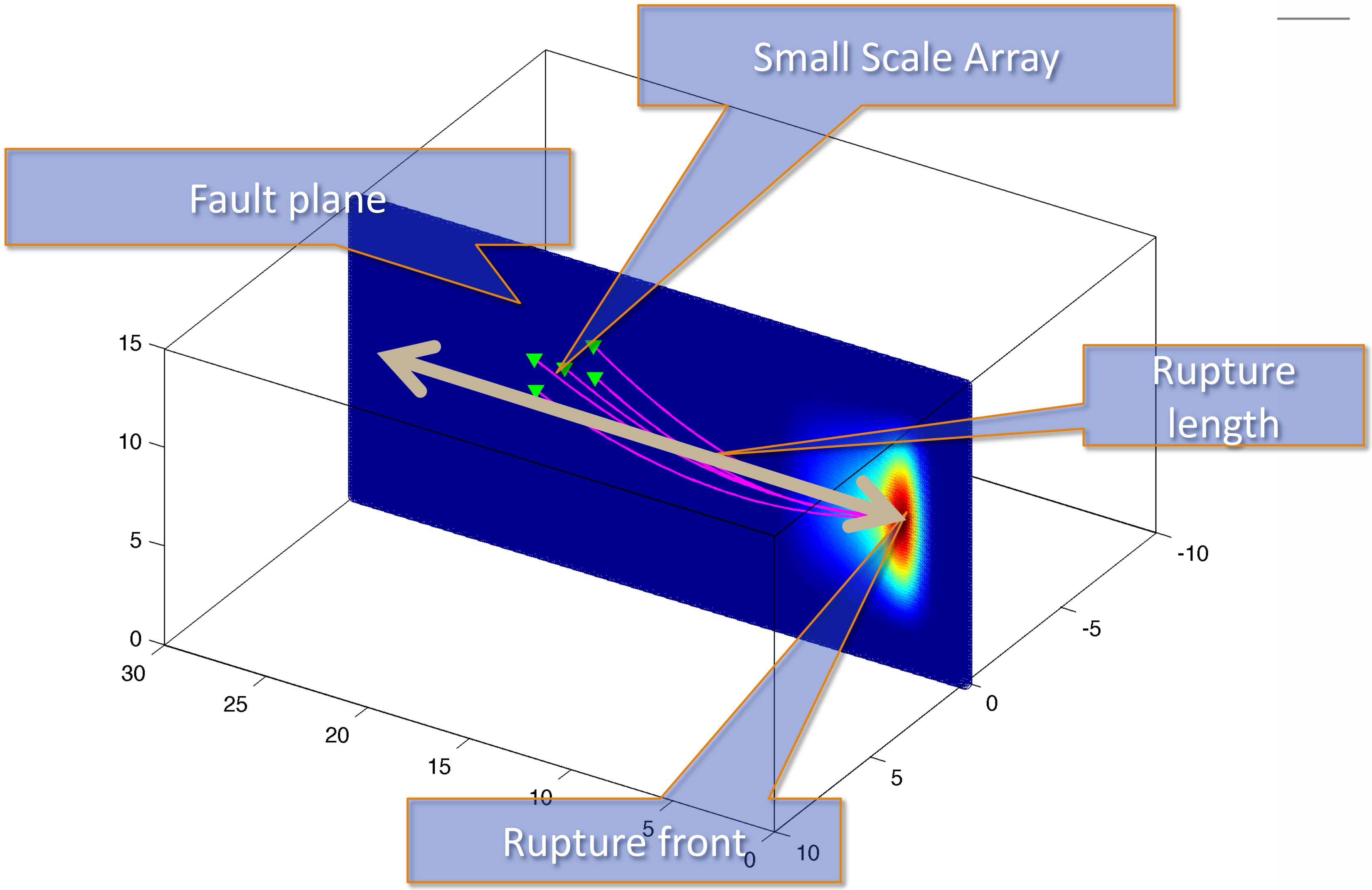


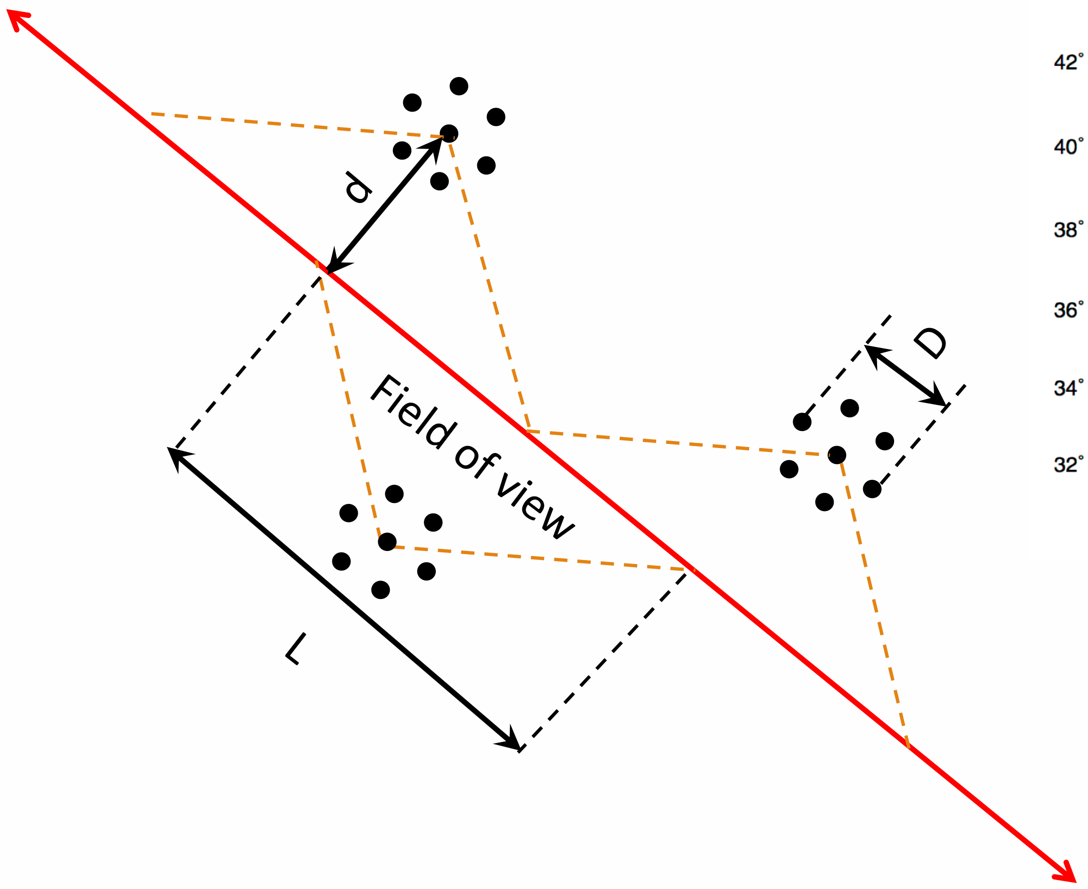
Figure 1-3 Top: Aligned waveforms sorted by epicenter distance. P onset is from time 0. Red lines show arrivals of P, PcP, and PP phases. Bottom: Carton that shows the rupture propagation. Here the amplitude of the points is normalized at each time window. Warm color indicates larger stacked amplitude.

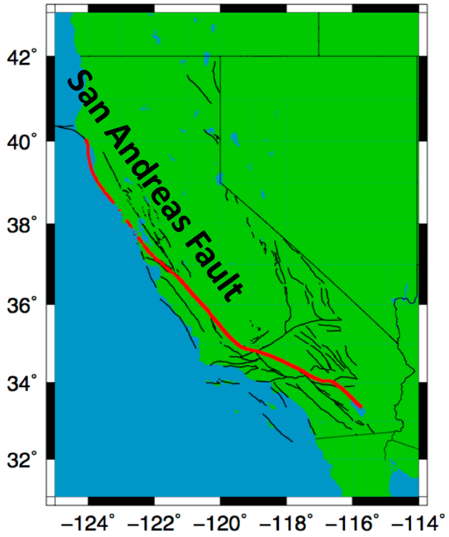
Real-time back-projection system developed by Dun Wang at ERI

Local Arrays for Earthquake Early Warning

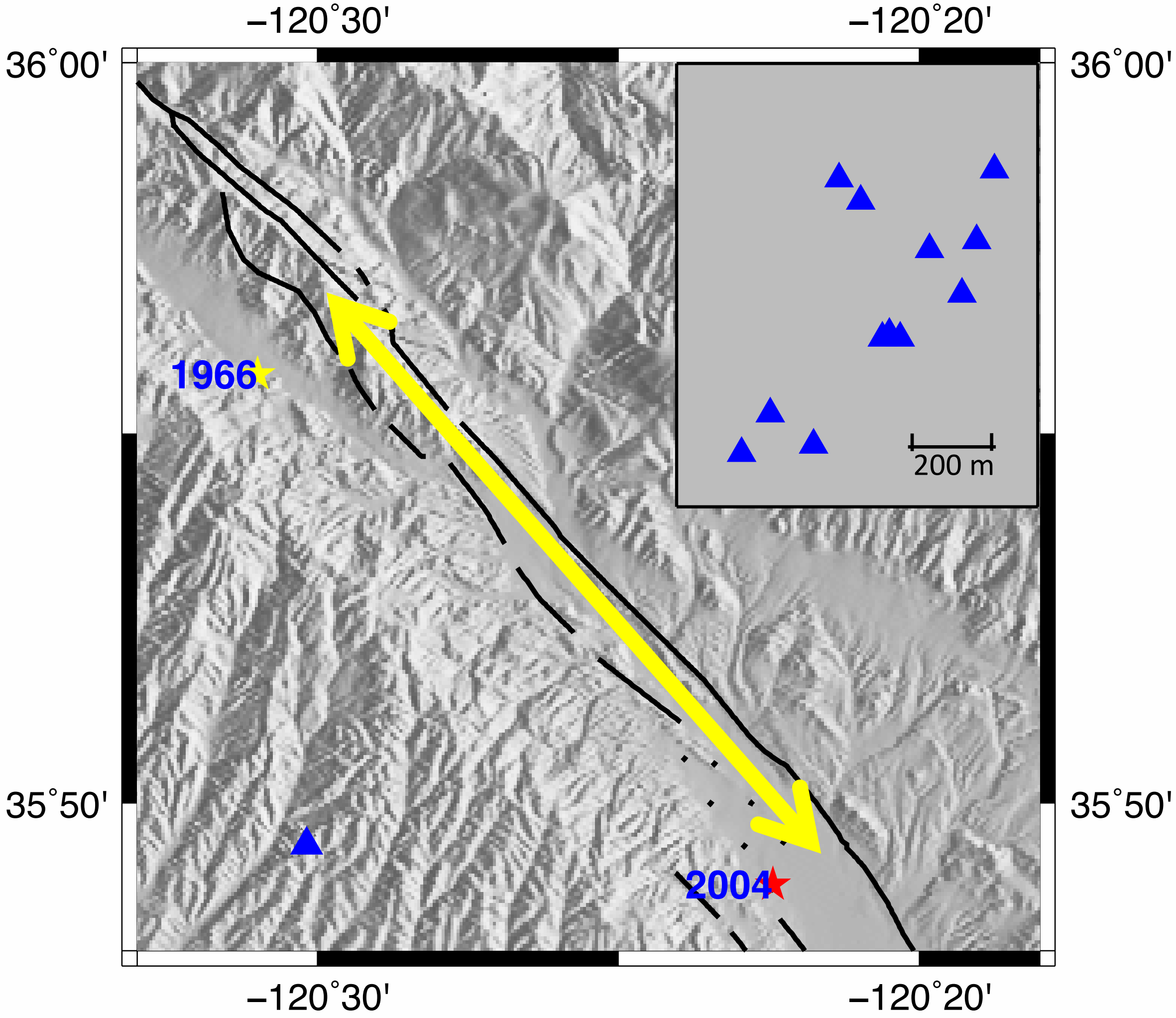


A Network of Small-scale Array Along Active Faults



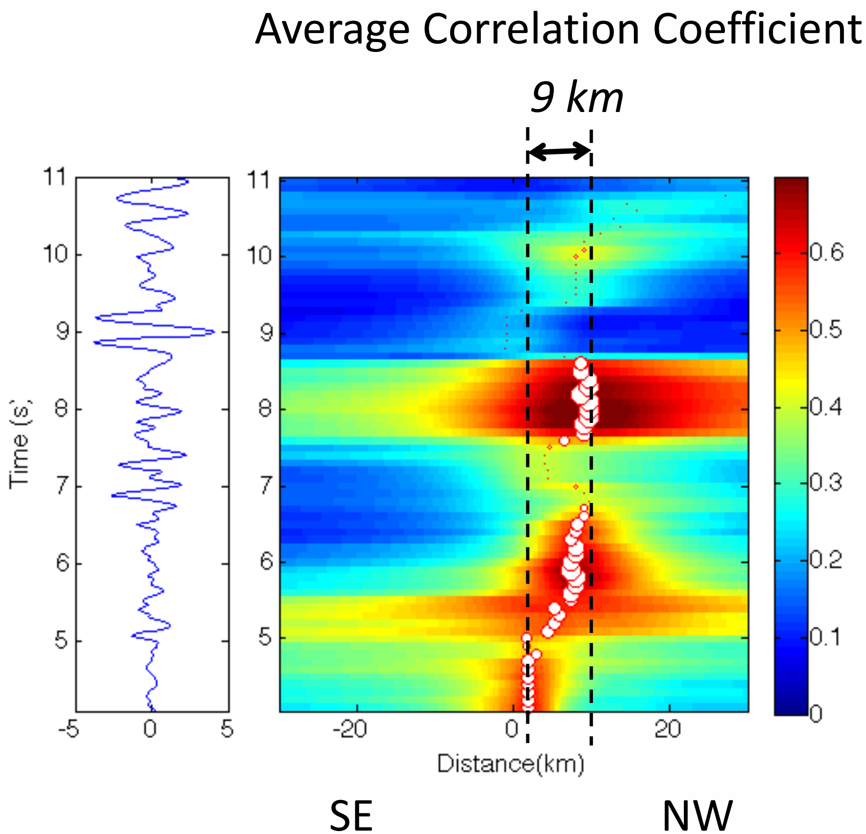


2004 Parkfield Earthquake



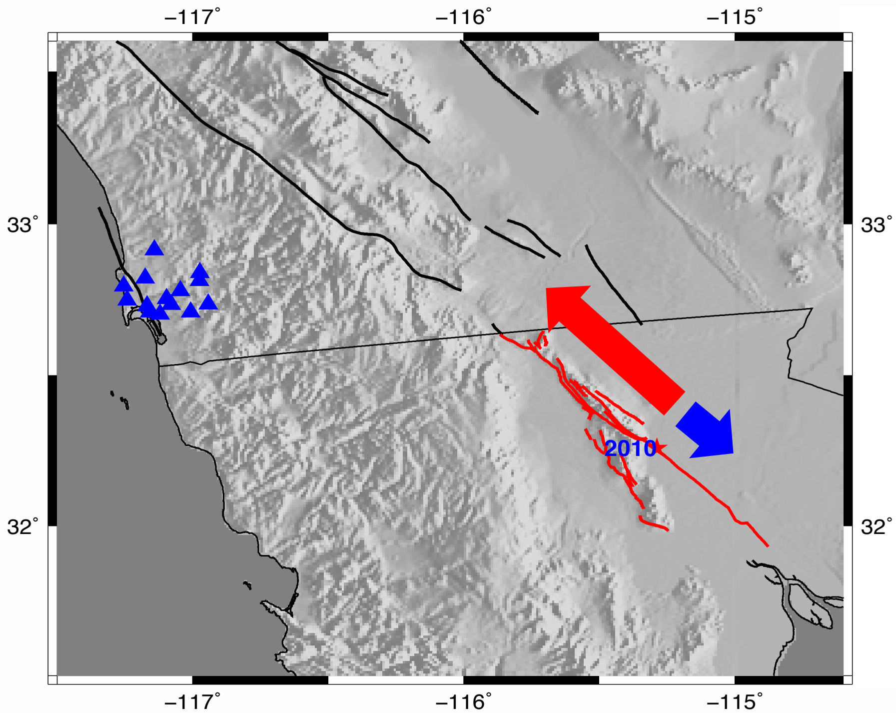
Modified from Fletcher et al, 2006

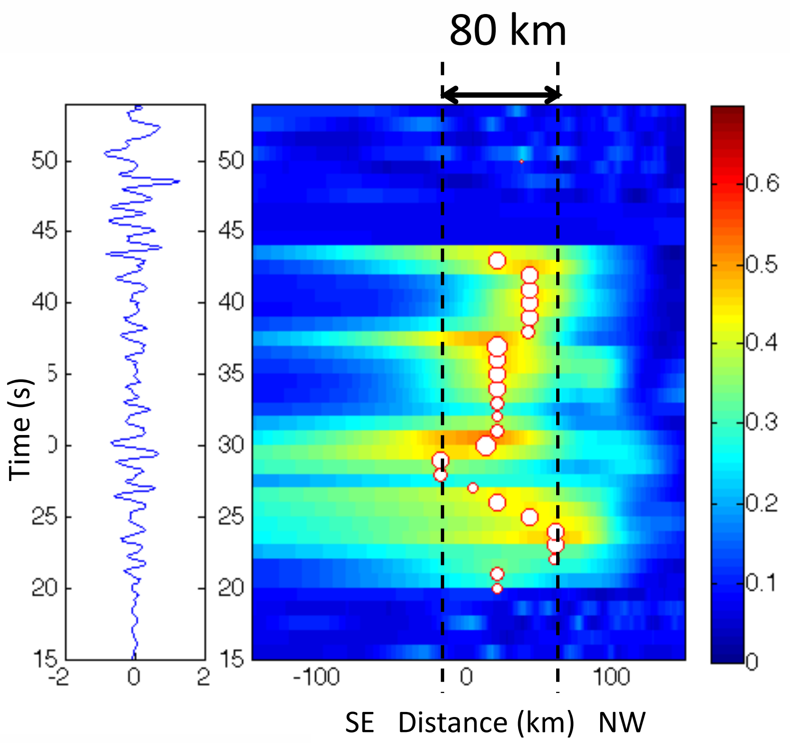
Real-Time Implementation



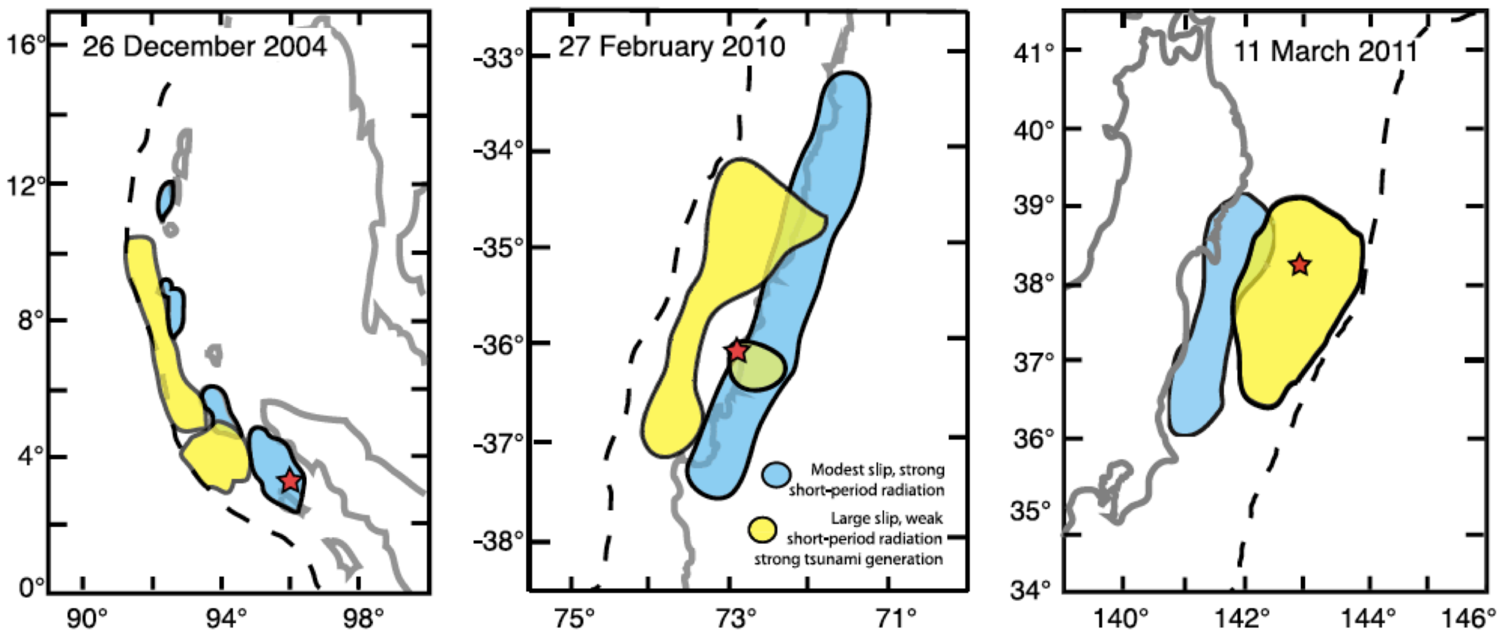
- Determine rupture length in strike-slip fault system
- Back-azimuth projected on the fault trace
- Correlation Stacking technique
- Rupture length equals to the distance between boundary seismic radiators
- Location with respect to the hypocenter indicate the directivity

2010 El Mayor-Cupacah Earthquake





Frequency-Dependent Source Radiation



Lay et al., 2012

- Low-frequency (LF) energy emanates from the shallower portion of the megathrusts.
- High-frequency (HF) energy often radiates from the deeper portion of the megathrust.

Strong Motion Generation and HF Radiation

Spatially Correlated

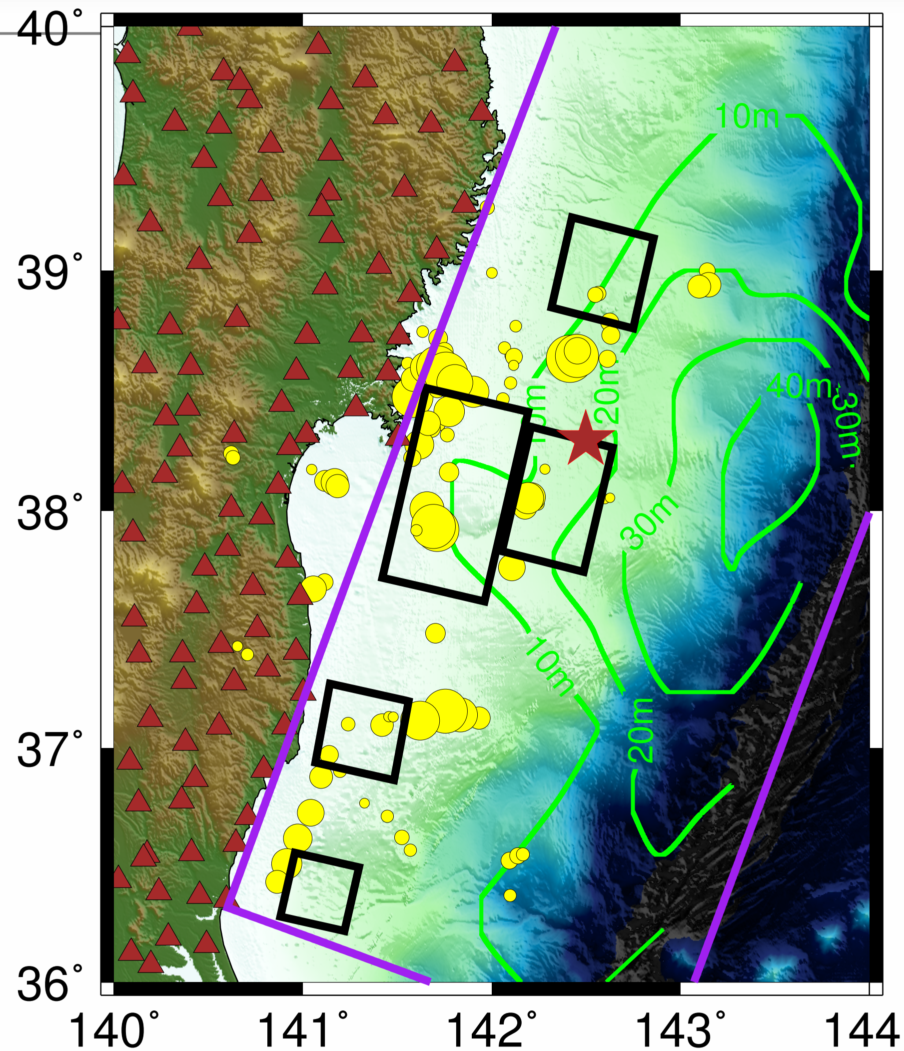
- SMGA

Strong Motion Generation Area
(Kurahashi and Irikura 2011)

- HFR

High-frequency Radiator

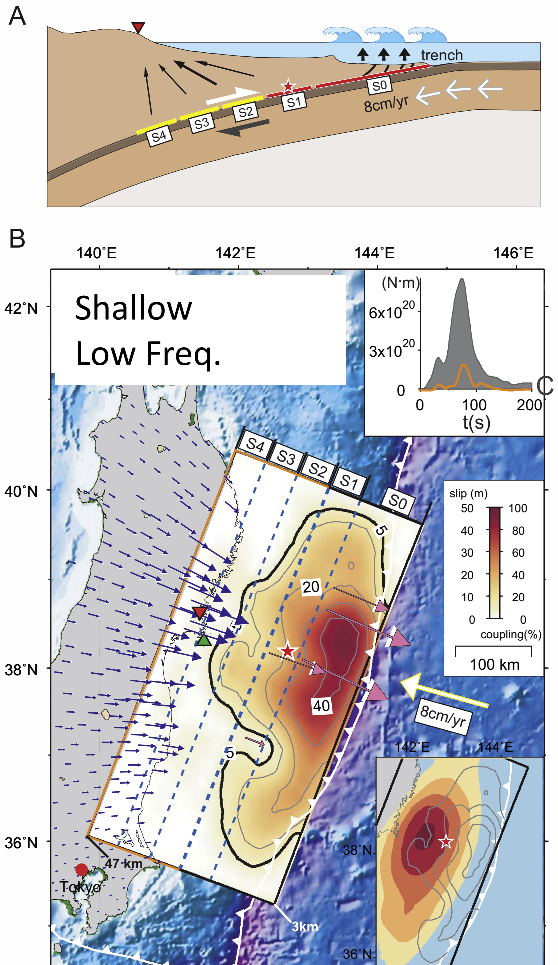
Finite Fault model (Wei at.el. 2012)



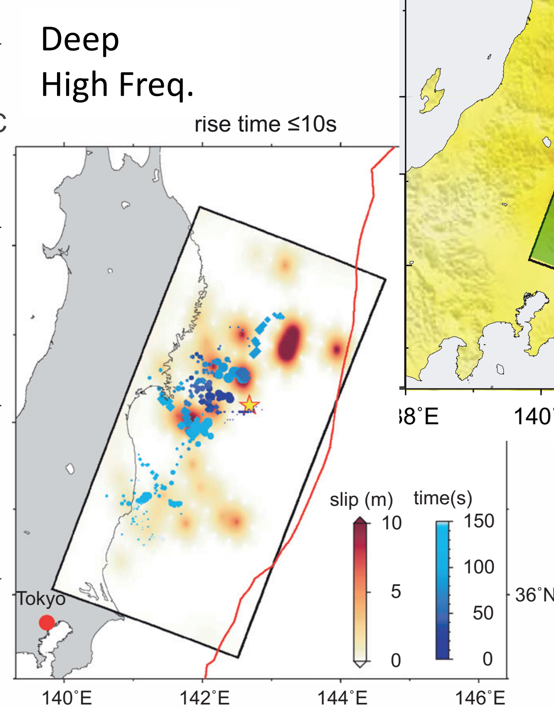
Strong motion of the Tohoku earthquake

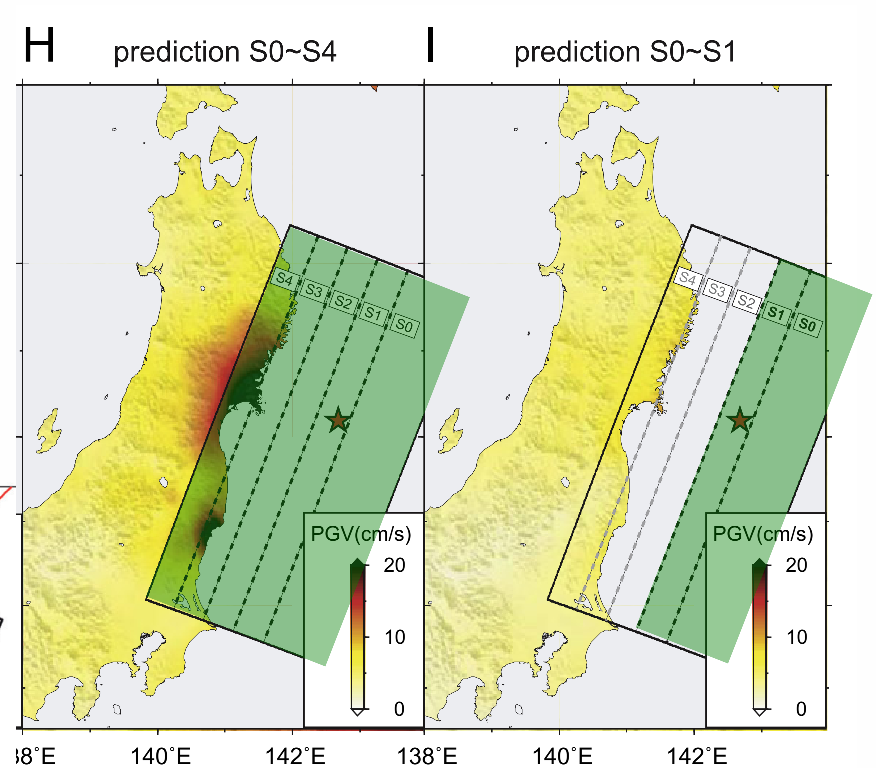
Full slip   Deep slip only

Slip inversion with different patches along dip



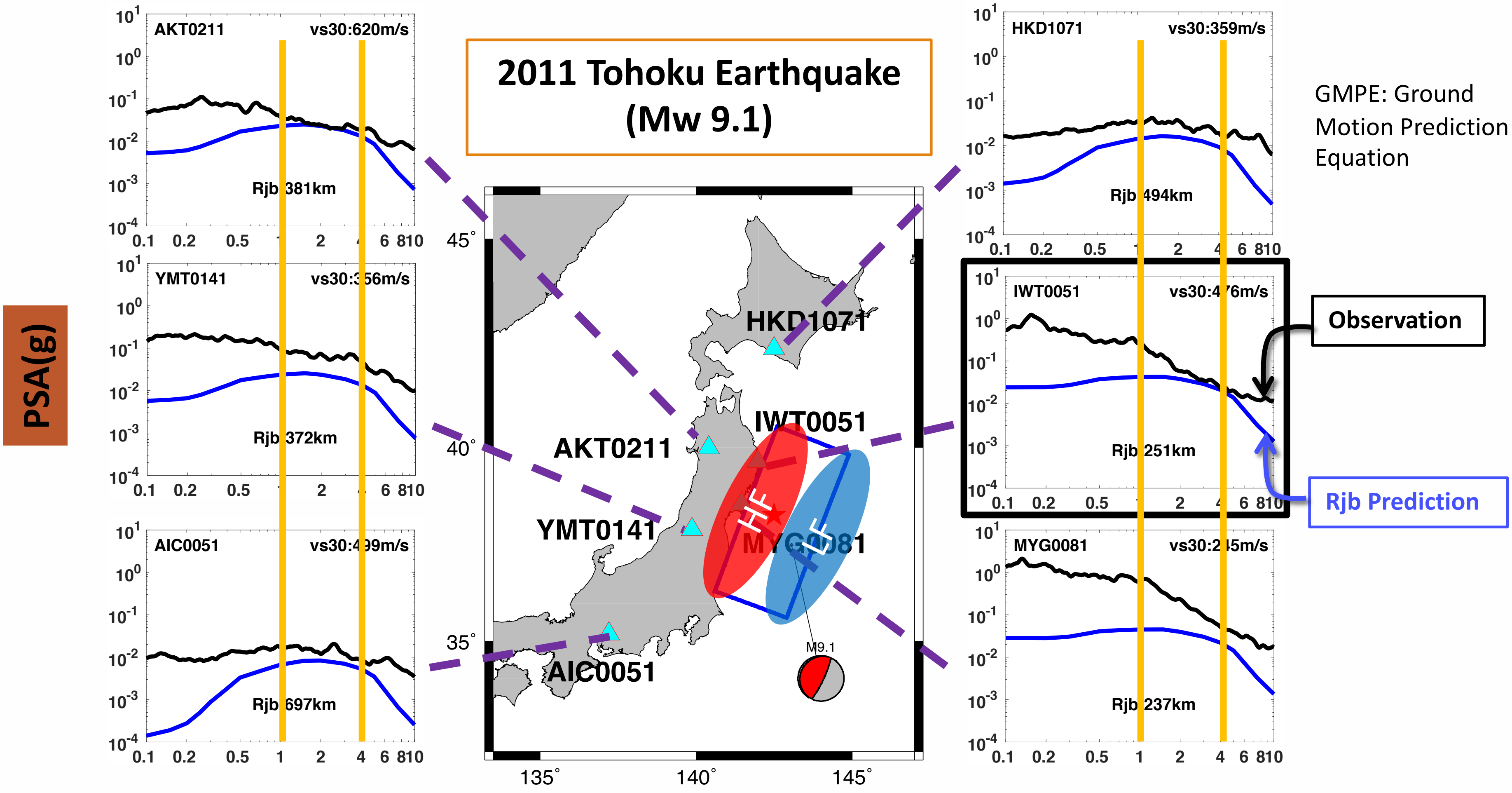
Wei et al., 2012





Strong shaking mostly caused by deep slip

Ground Motion Intensity Underestimation



Rjb: Joyner-Boore distance

PSA: Pseudo spectral acceleration

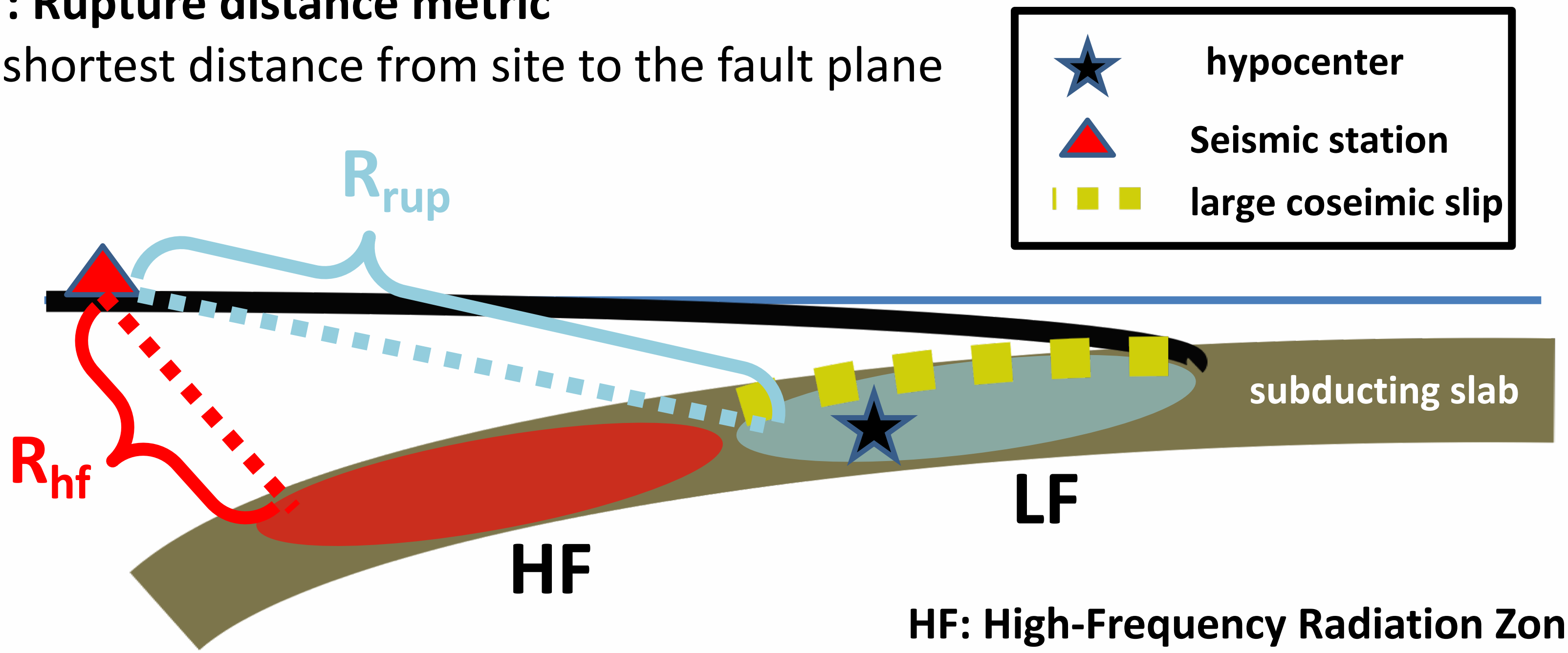
High-Frequency Distance Metrics

R_{hf}: high-frequency distance metic

- shortest distance from site to high-frequency zone

R_{rup} : Rupture distance metric

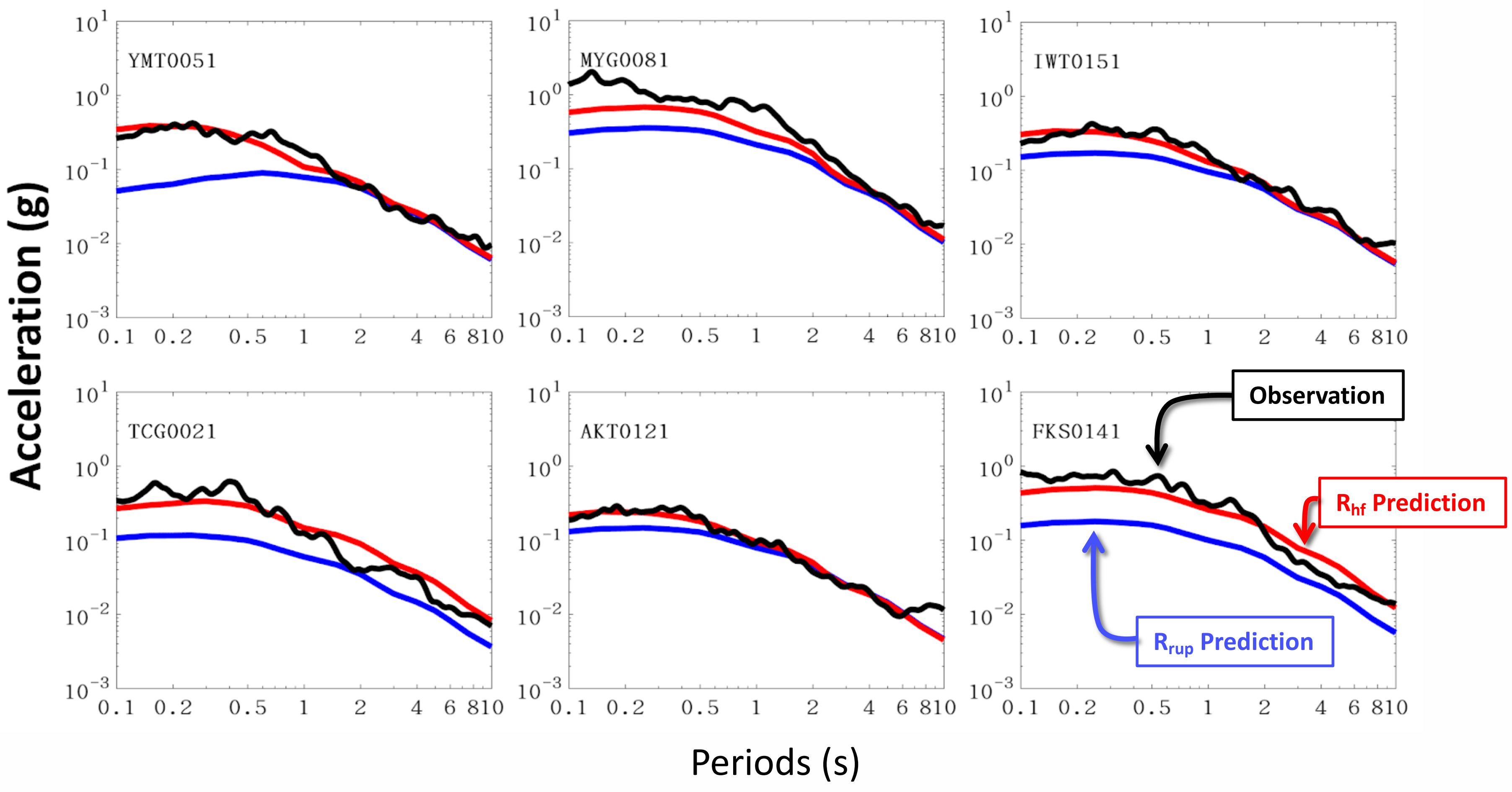
- the shortest distance from site to the fault plane



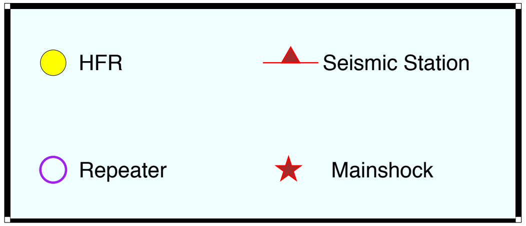
HF: High-Frequency Radiation Zone
LF: Low-Frequency Radiation Zone

(Feng and Meng, 2018)

More Accurate Ground-motion Predictions

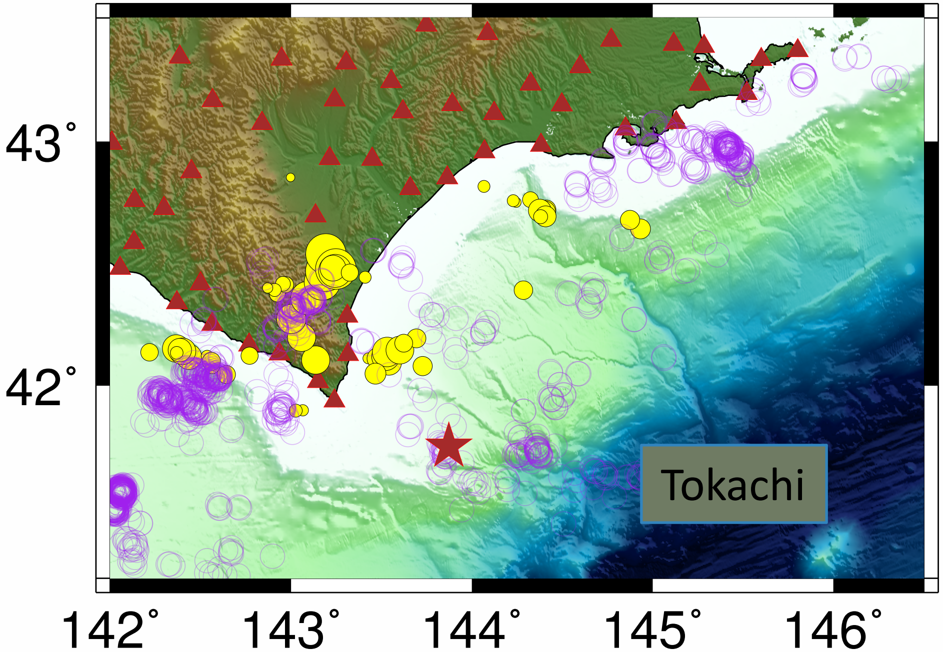


Future Large Megathrust Earthquake

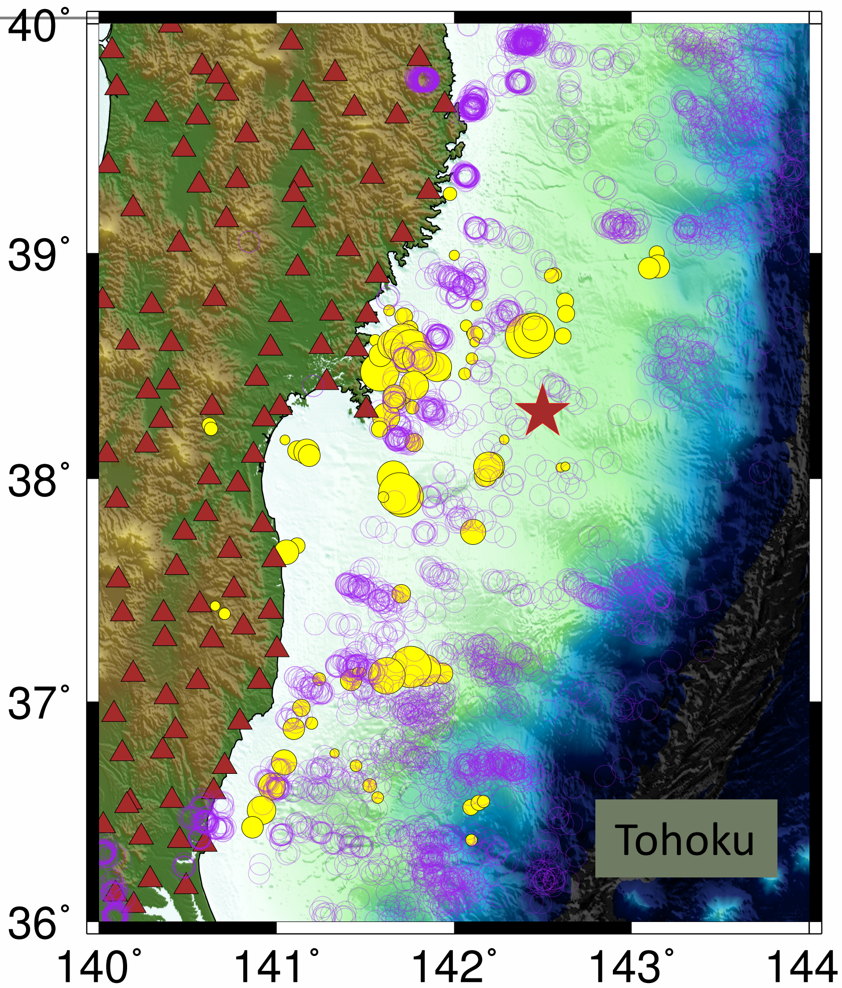


Repeaters (Uchida at.el. 2016)

SMGA (Kurahashi and Irikura 2011)



Finite Fault model (Koketsu at.el. 2004)

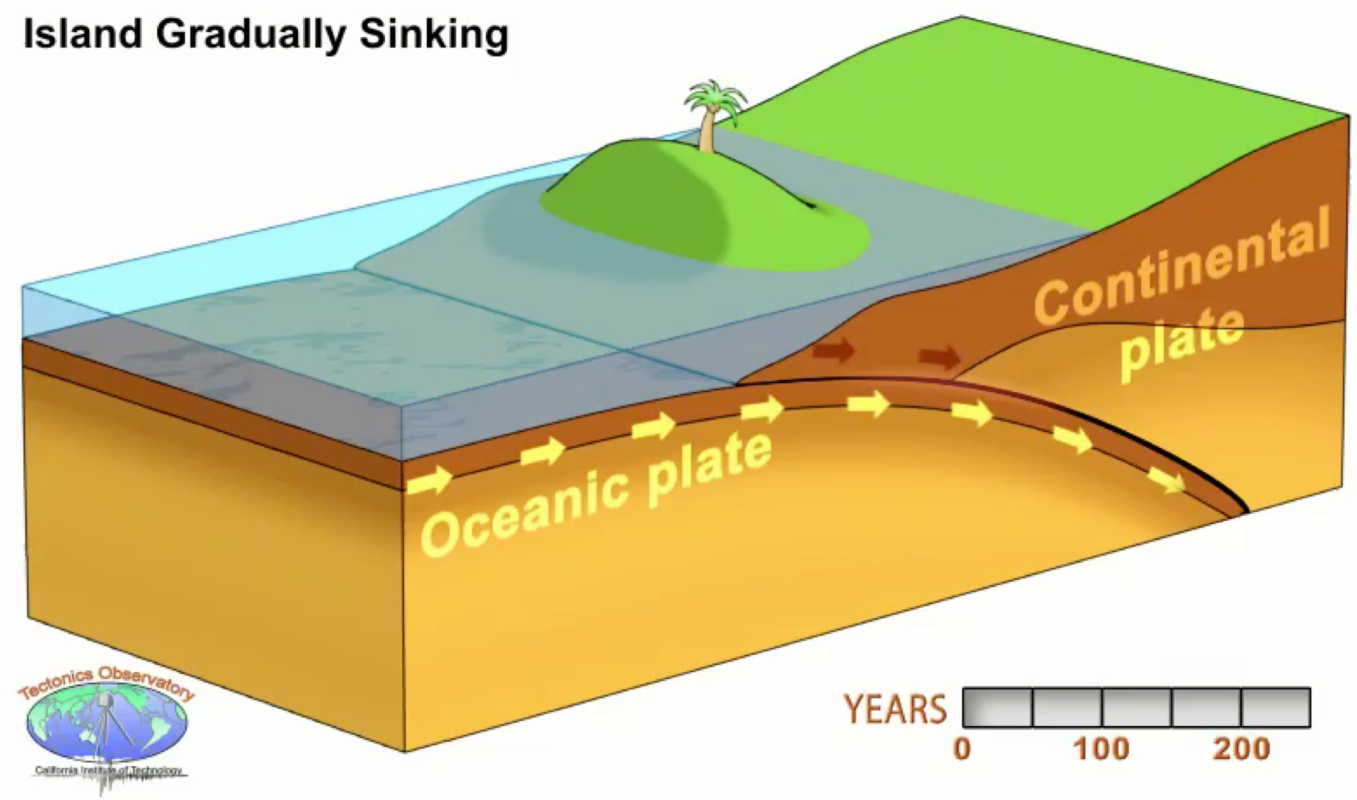


Finite Fault model (Wei at.el. 2012)

Los Angeles Area

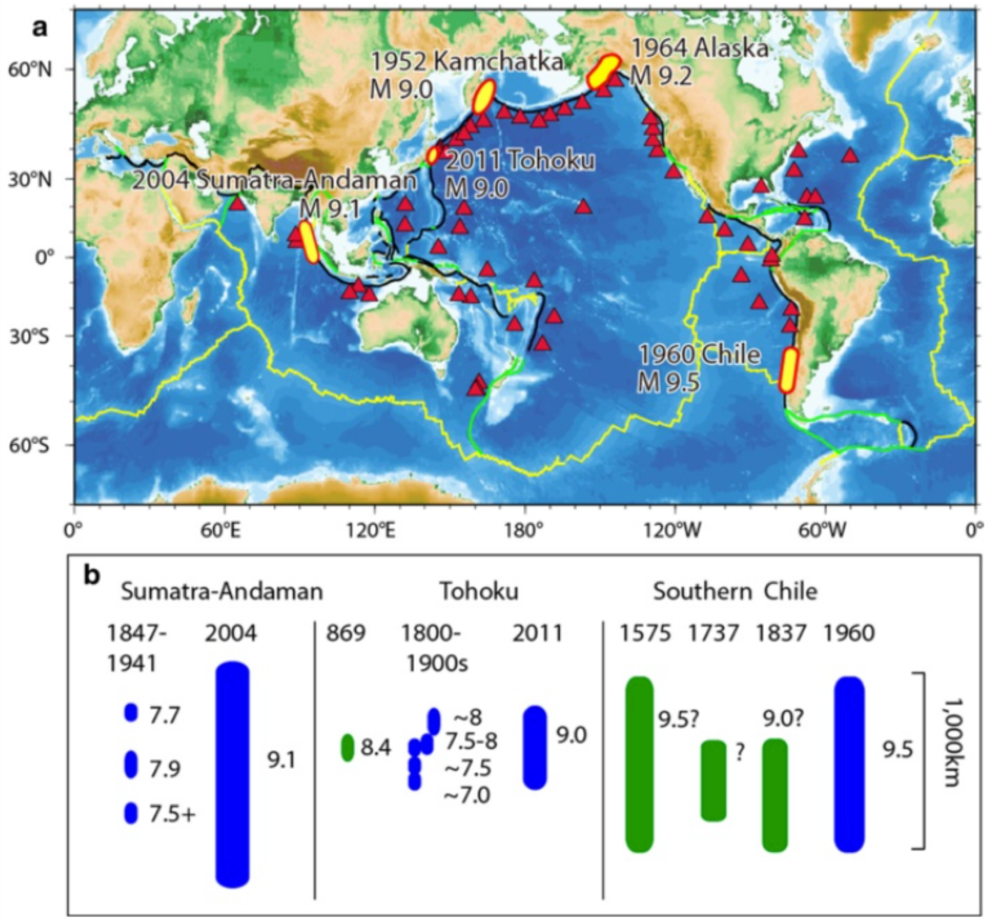
Tsunami Induced by Large Megathrust earthquakes

1. Interseismic elastic deformation
2. Earthquake and elastic rebound of over-riding plate
3. Tsunami wave formation and propagation



http://www.tectonics.caltech.edu/

Giant Tsunami-genic Earthquakes in the World



Satake, 2014

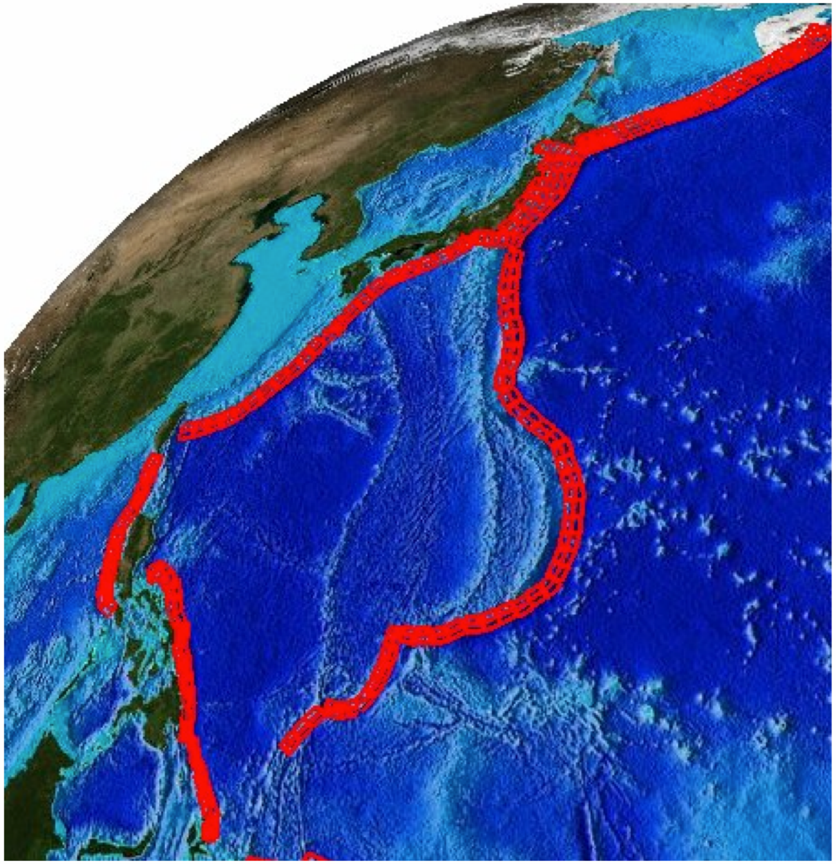
March 11th, 2011

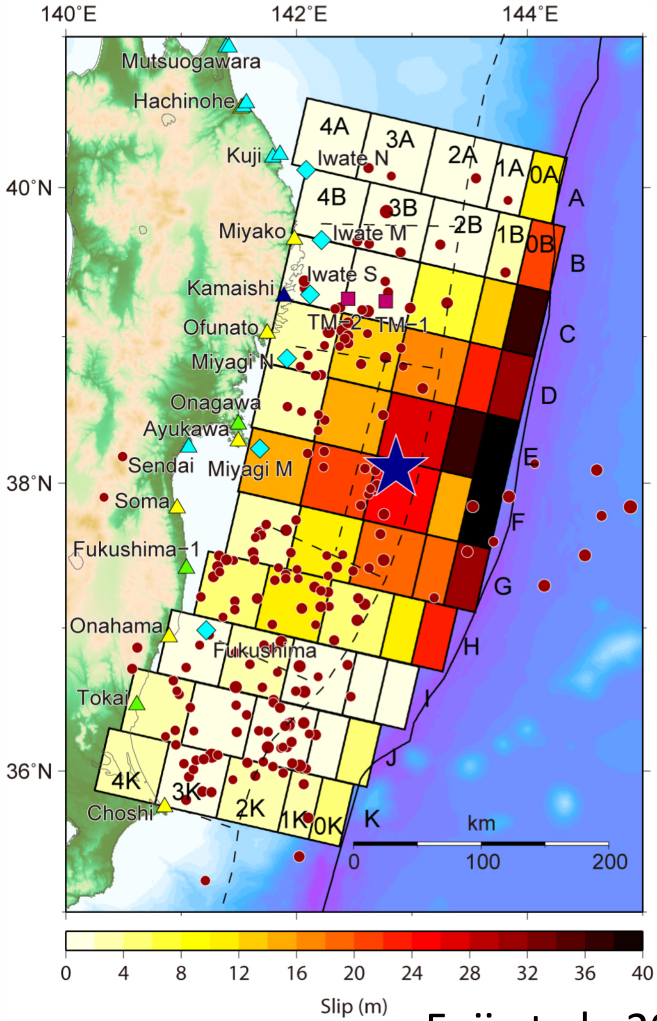
Magnitude 9 Tohoku-oki, Japan earthquake and tsunami

… Aftermath of a big tsunami!

2011 M9.0 Tohoku Earthqauke

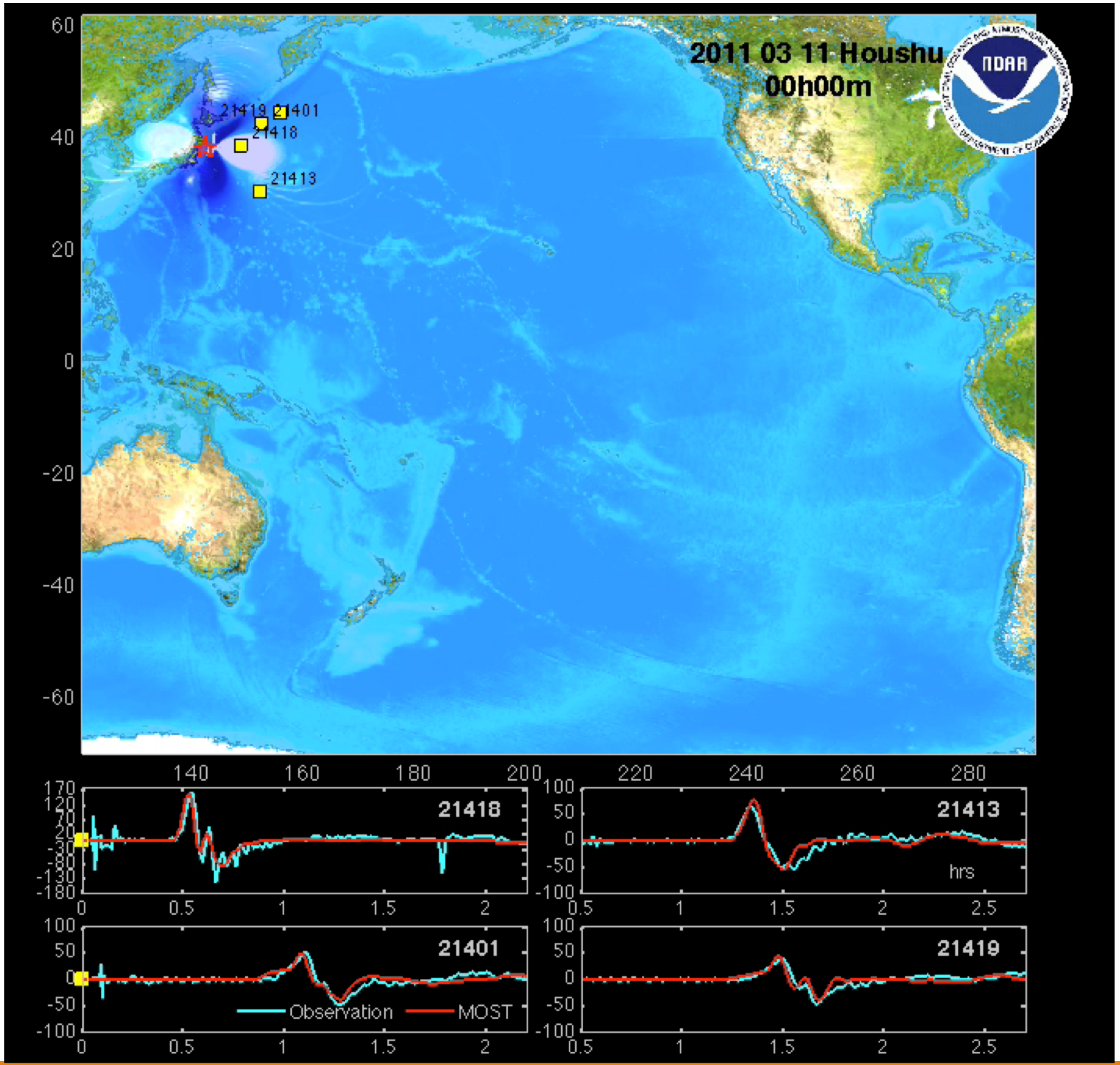
NOAA unit tsunami sources of 100 km by 50 km





Fuji et al., 2011

2011 Tohoku Tsunami simulation



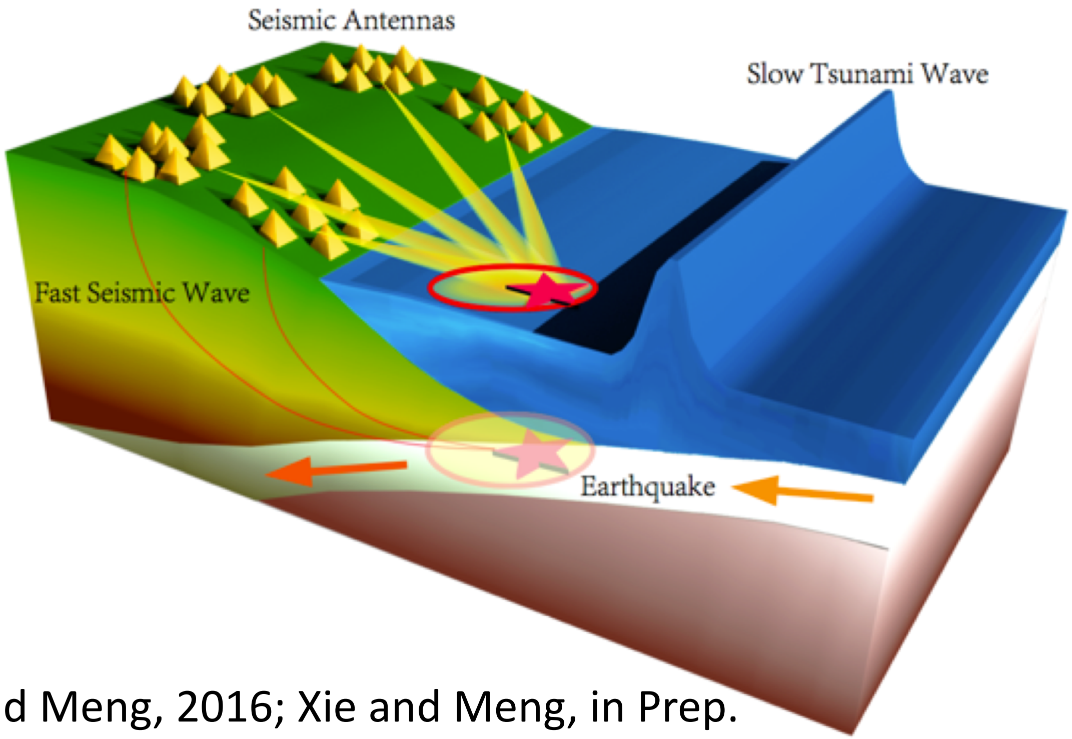
Tide gage data

Challenges in Tsunami Warning

- Typical tsunami warning system is based on direct tsunami waveform measurements.
- Good for Far-field (across ocean), but too slow for near-field.
- Teleseismic inversion is faster but uncertain.
- Near-field seismic recordings suffer a well-known saturation problem.
- W-phase get robust moment but does not provide finite source effect.
- Real time GPS requires post-processing to remove the contamination due to the atmospheric effects.

Need to get robust estimation of **finite dimension** in real time !

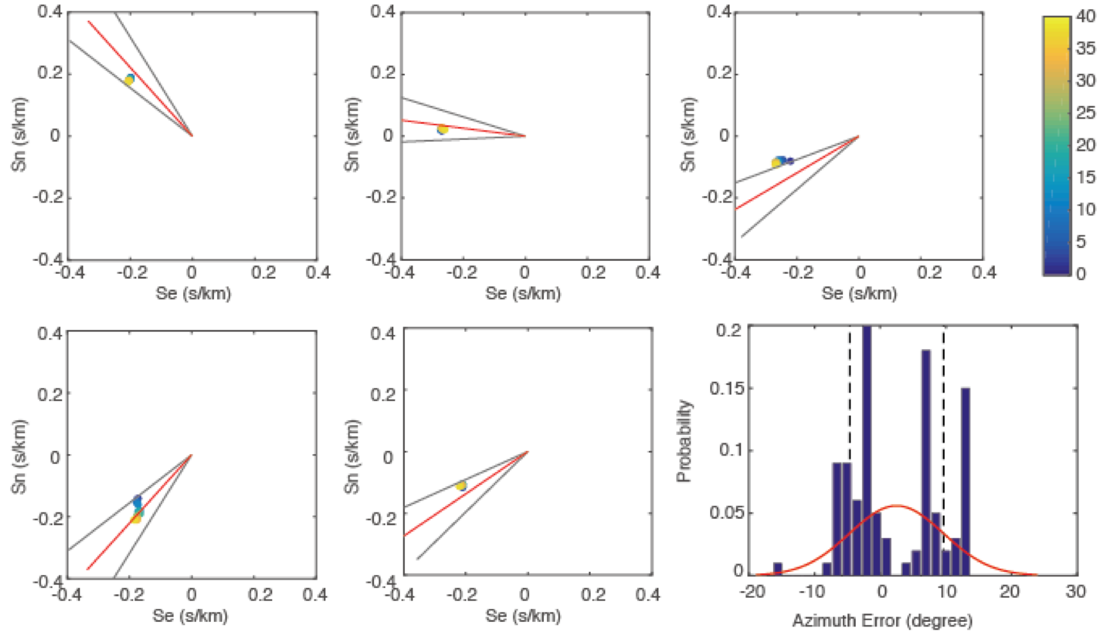
Seismic Antenna for Tsunami Warning

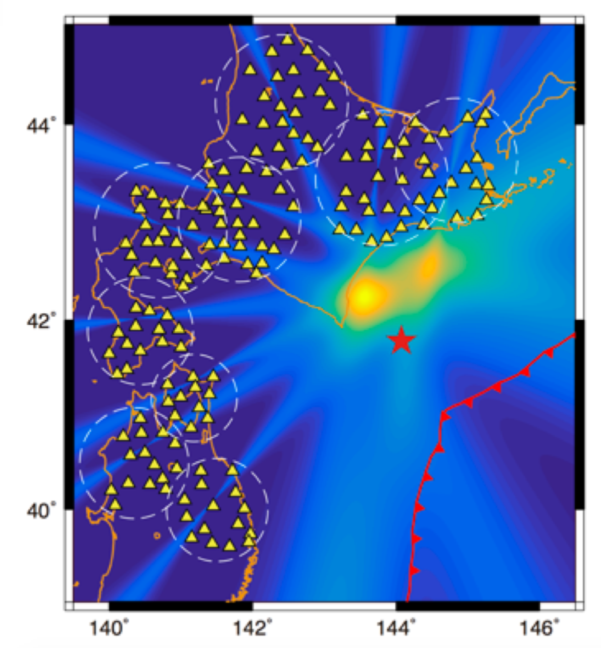


An and Meng, 2016; Xie and Meng, in Prep.

- Conducting long-period (10 s – 50 s) BPs with local stations.
- Constructing simplified source model: estimating rupture area and calculate slip based on W-phase inversion.
- Predicting amplitude and arrival time of tsunami wave.

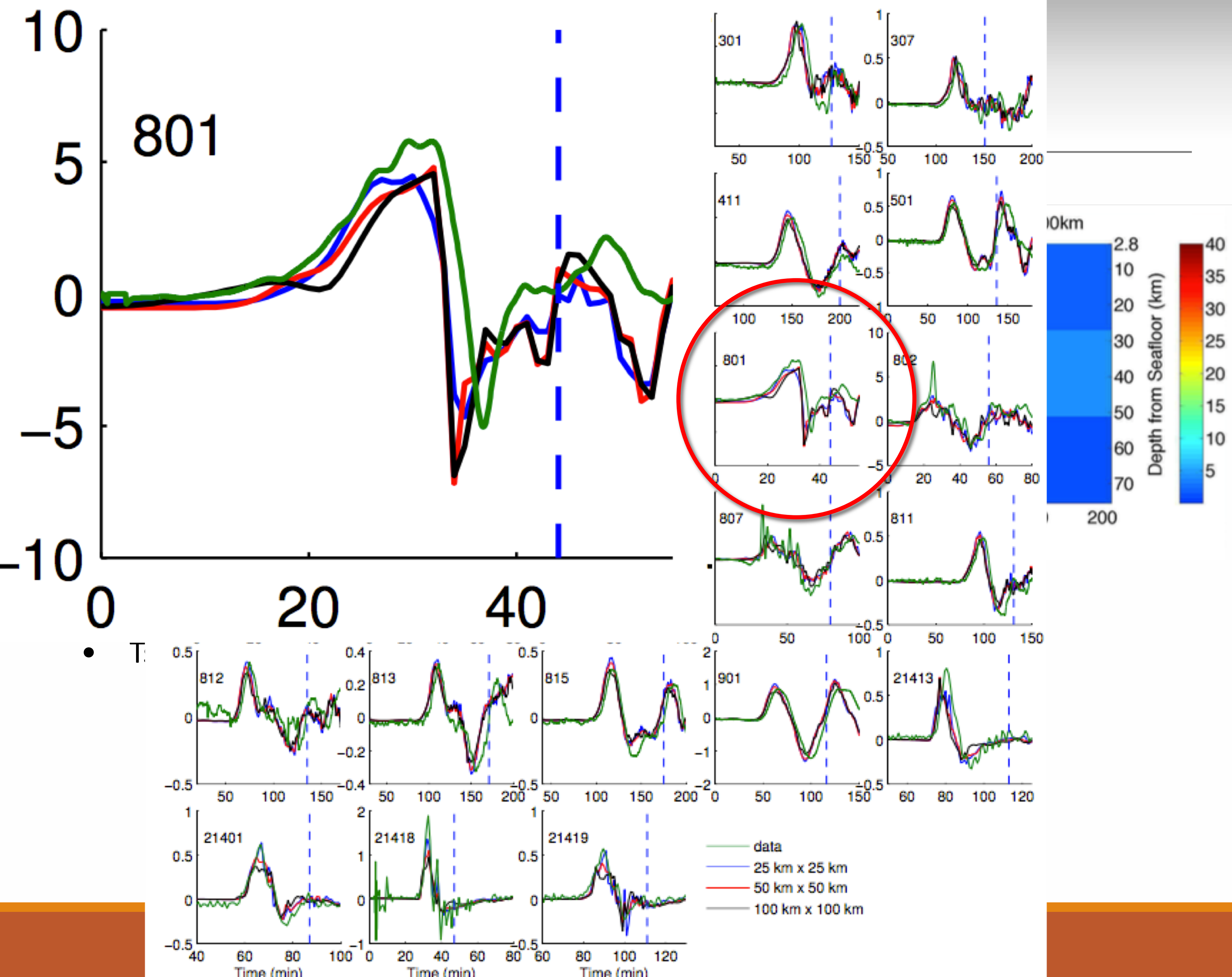
A Multi-Array Tracking Approach





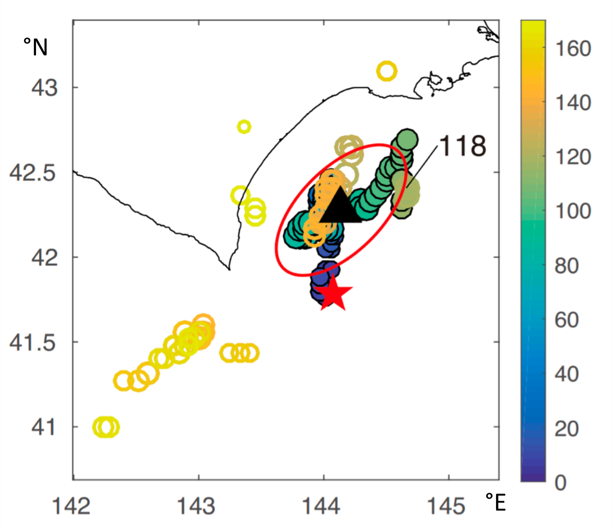
2003 M8.3 Tokachi Earthquake

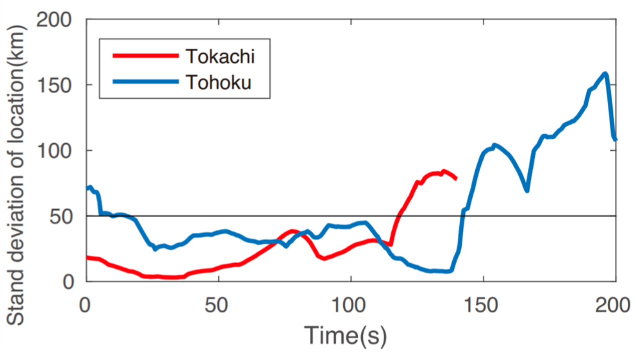
- Source slowness are determined at each strong-motion cluster .
- Smoothing of the back-azimuth due to uncertainty and angular spreading.
- Source location by intersecting the back-azimuths.


801
301
307
411
501
801
802
807
811
812
813
815
901
21413
21401
21418
21419
data
25 km x 25 km
50 km x 50 km
100 km x 100 km
Time (min)
Depth from Seafloor (km)
200

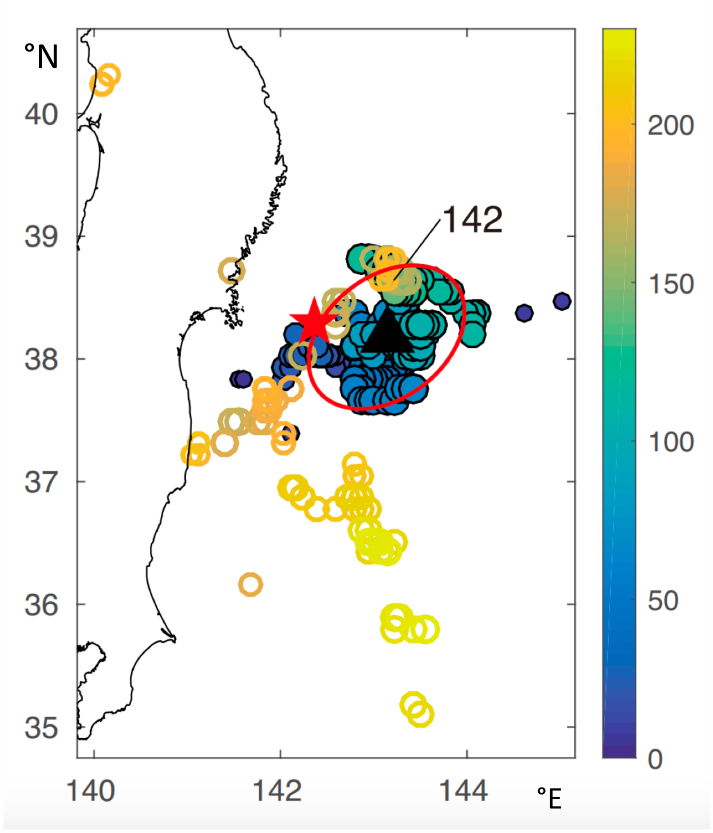
Automatic Determination of When Earthquakes Stop

2003 M8.3 Tokachi Earthquake



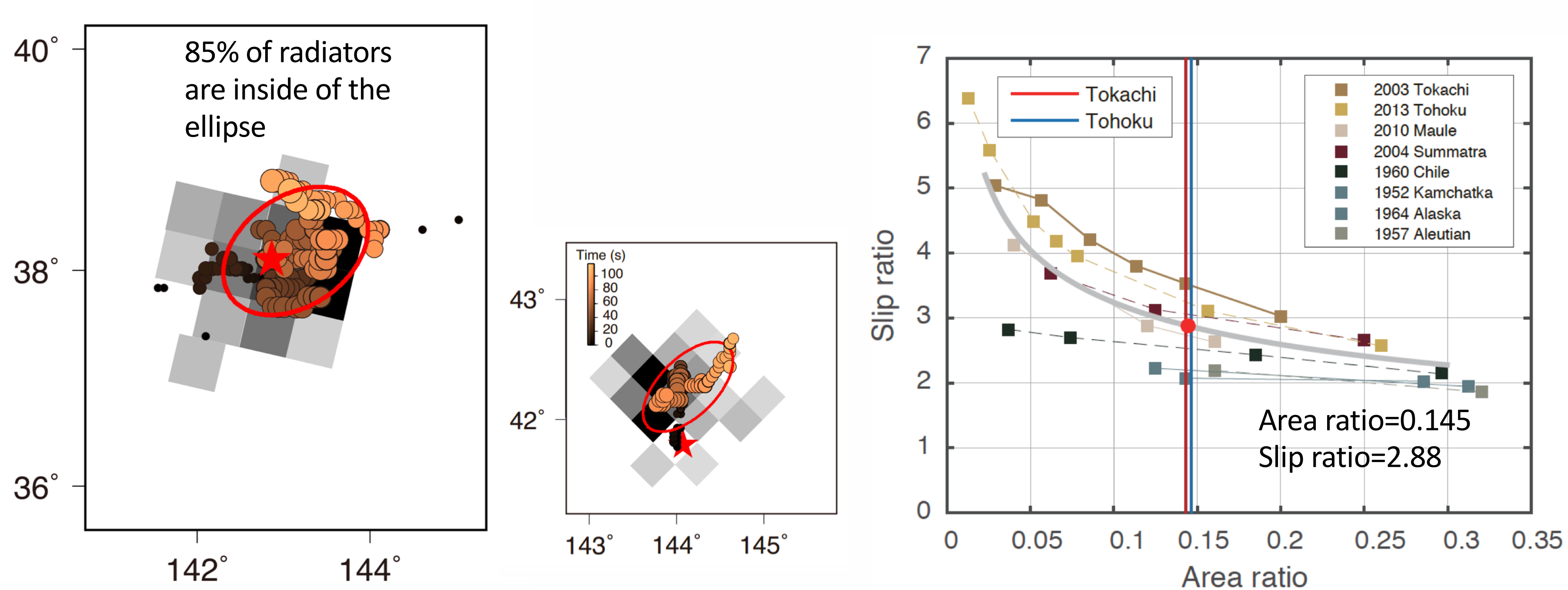


2011 M9.0 Tohoku Earthquake



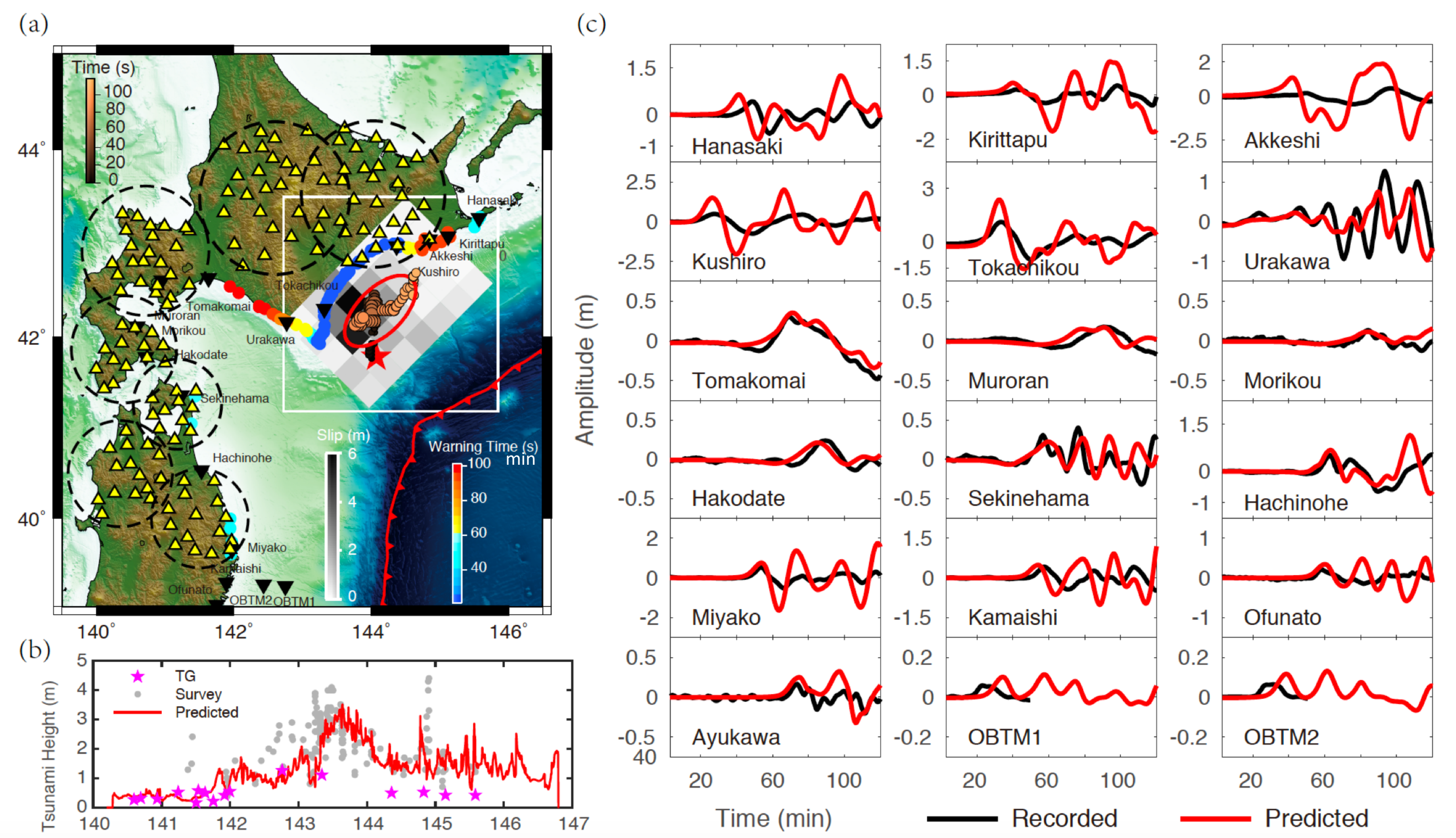
The seismic radiators are cut off when their locations are too scattered

Slip Estimation

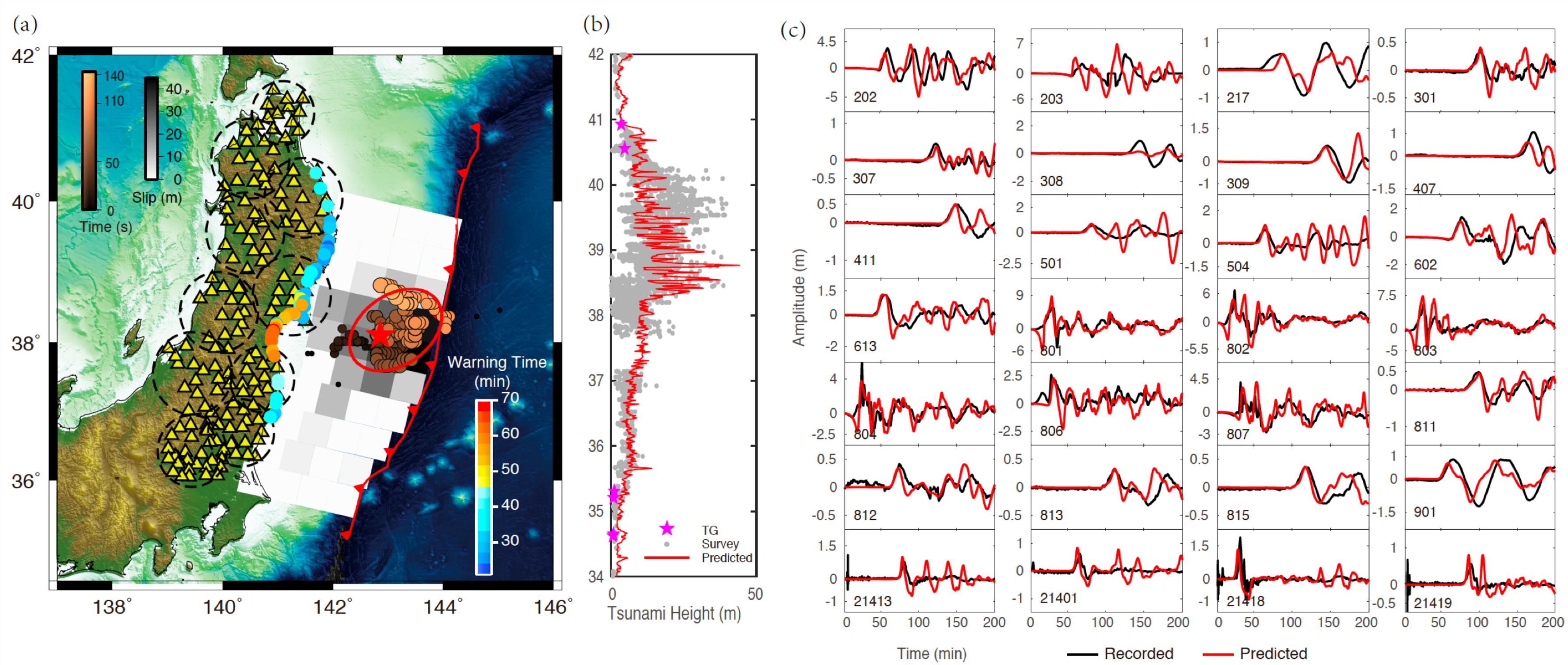


- BP-estimated rupture region represents the area of large slip instead of the entire source zone.
- We establish an empirical relations between the degree of slip concentration versus normalized source area.

2003 M8.3 Tokachi Earthquake

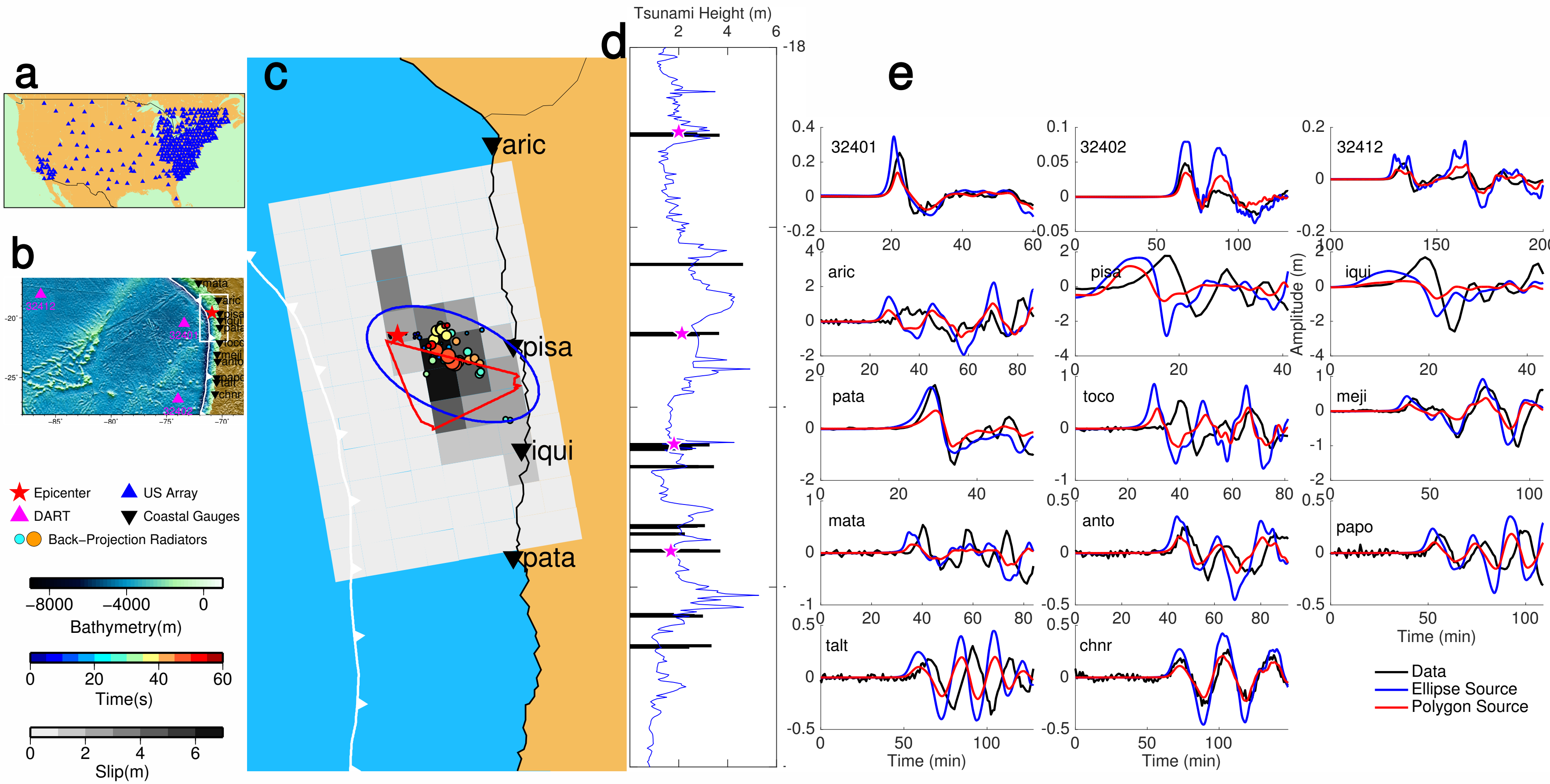


2011 M9.0 Tohoku Earthquake



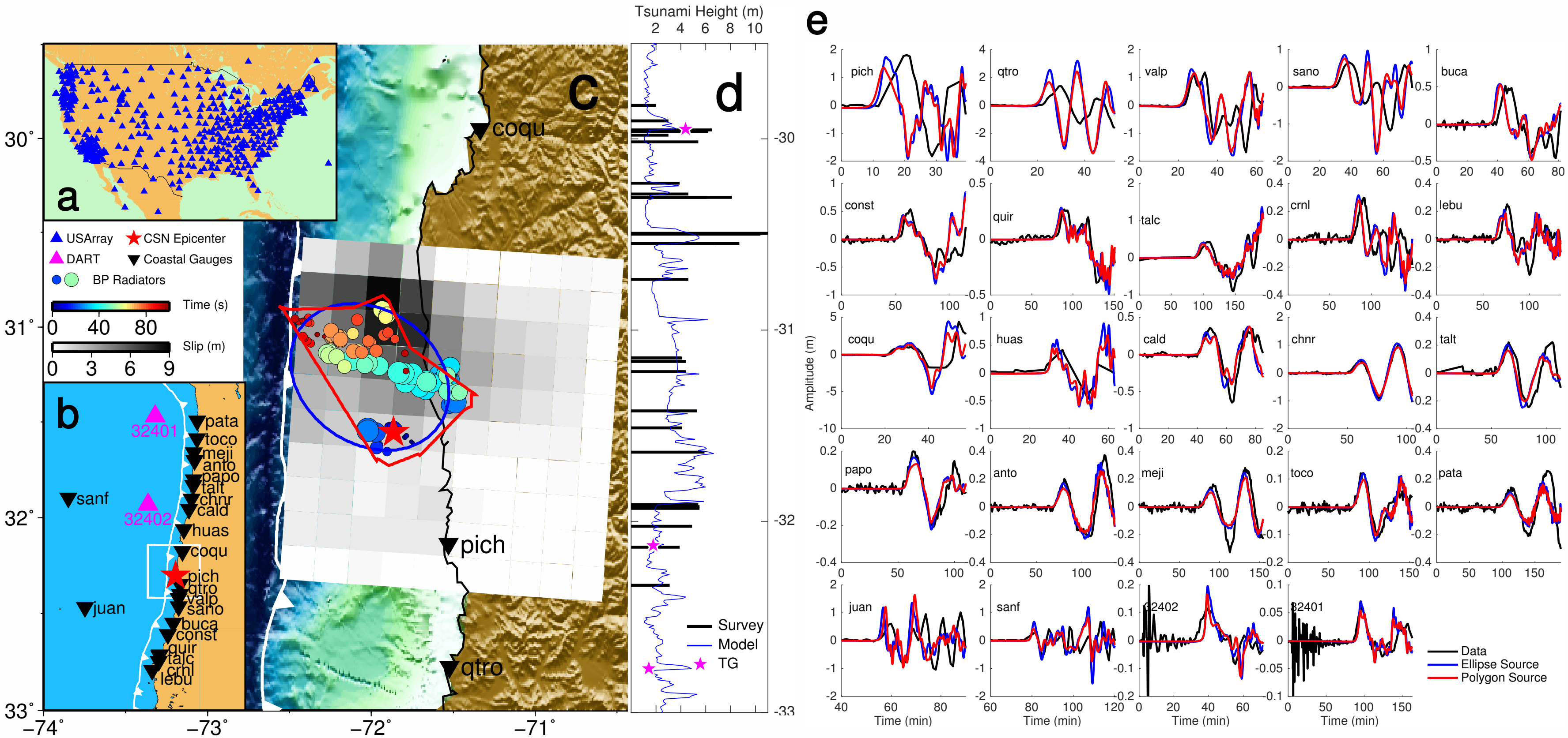
Xie and Meng, Submitted to GRL.

2014 M8.2 Iquique Earthquake



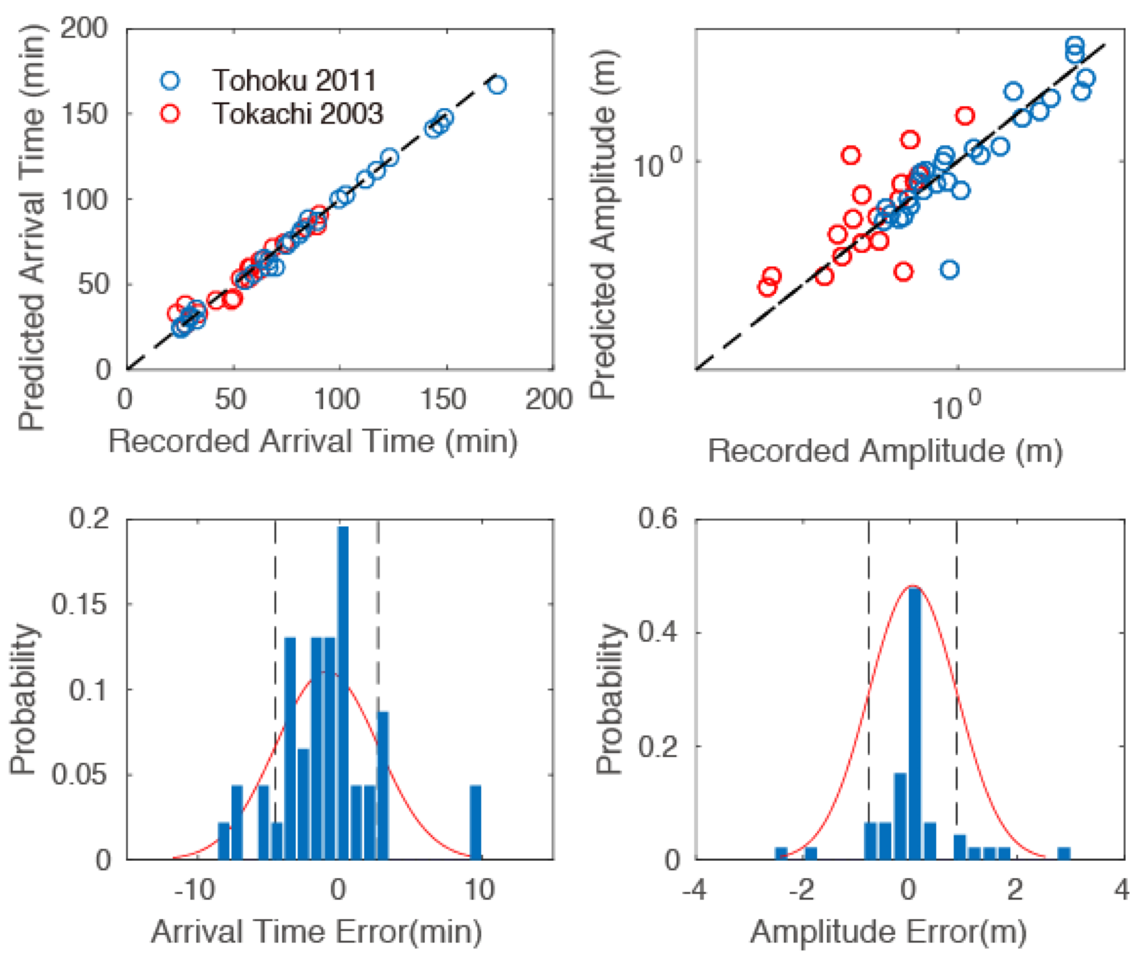
An and Meng., 2016

2014 M8.3 Illapel Earthquake

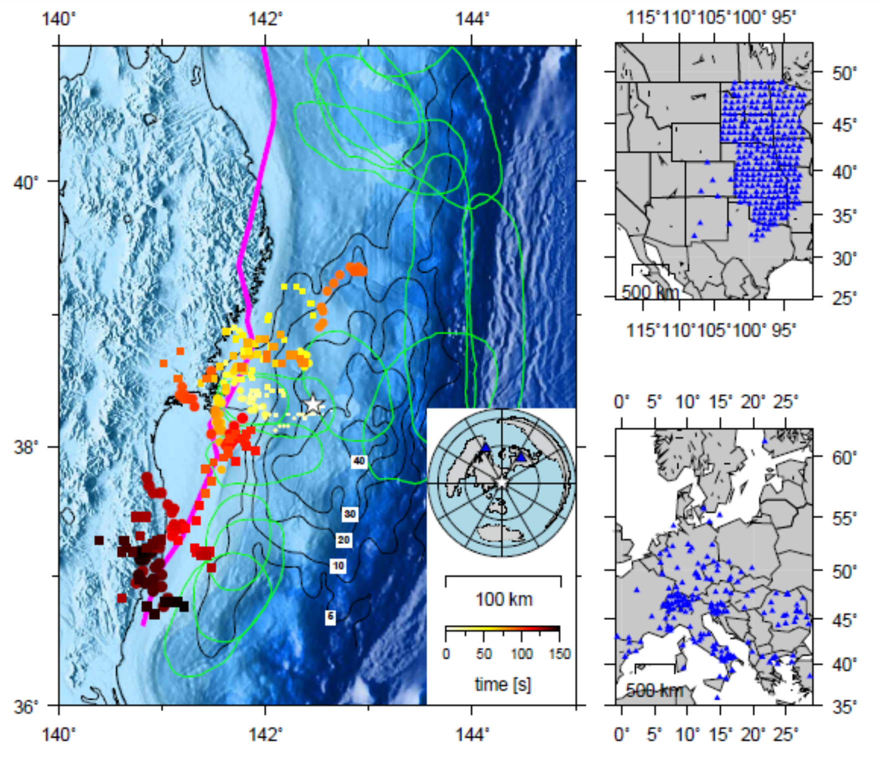


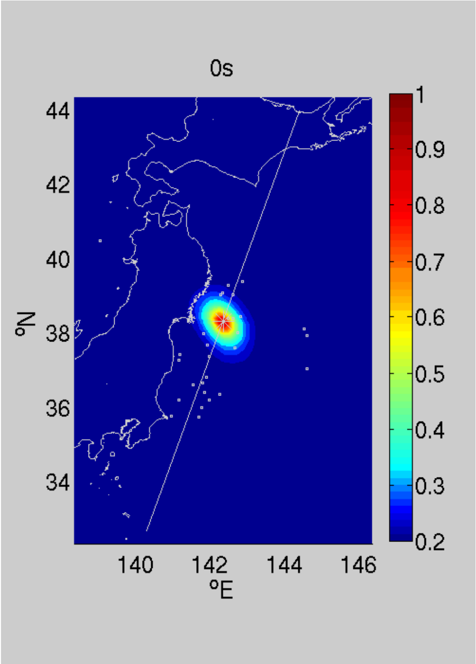
An and Meng., 2016

Predictions Vs Observations



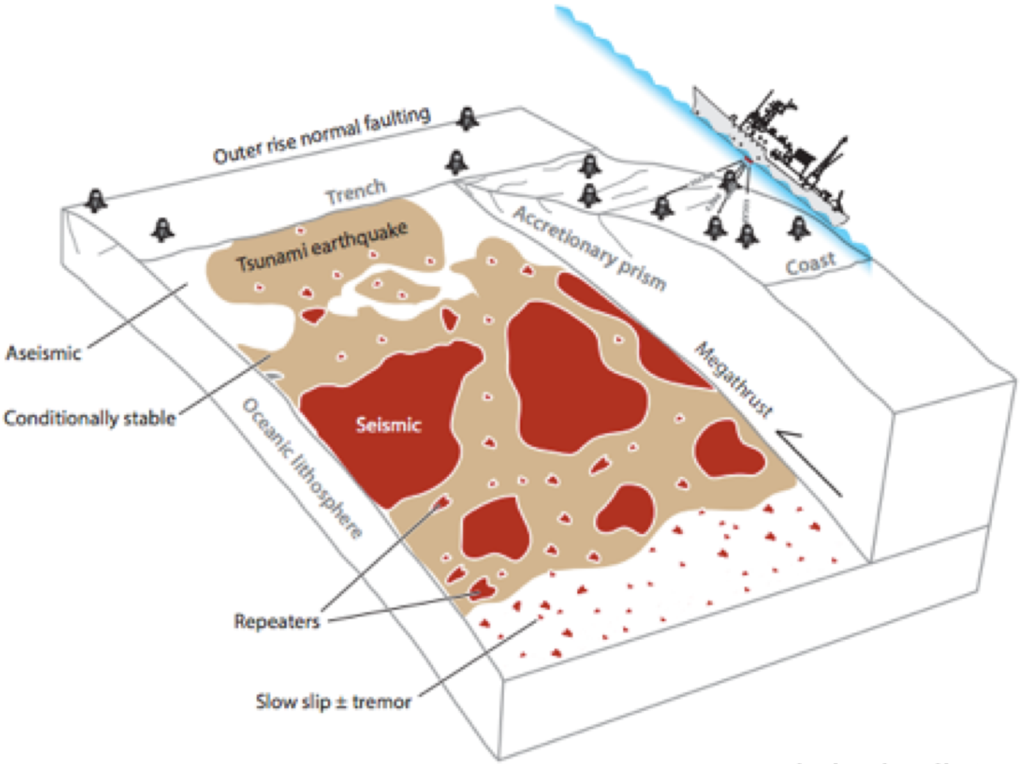
Earthquake Source Imaging By Back-projection of Array Data





2011 Tohoku-Oki earthquake (Meng et al,2011)

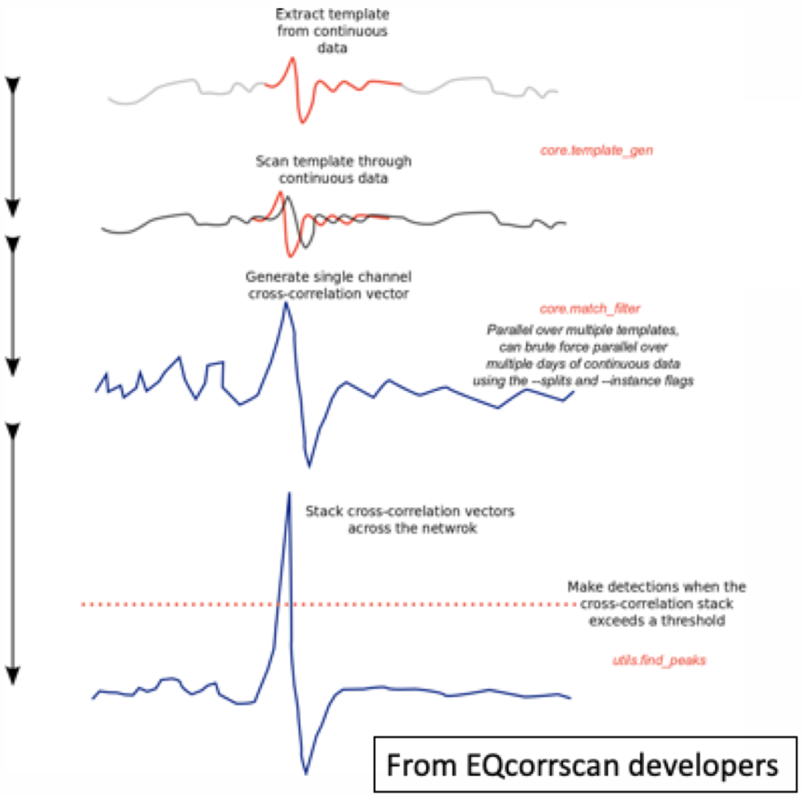
Off-shore Seismicity Detection



Bürgmann and Chadwell, 2014

- Sea floor geodesy instruments are expensive with sparse distribution.
- Resolution of off-shore slip is not well constrained by the inland GPS.
- Slow slip often accompanied by small earthquakes. Study small off-shore earthquakes would help us have a better understanding of slow slips.

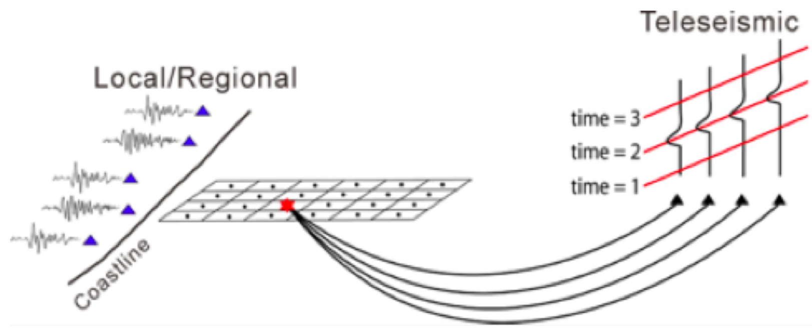
Combing Back-Projection and Matched-Filter

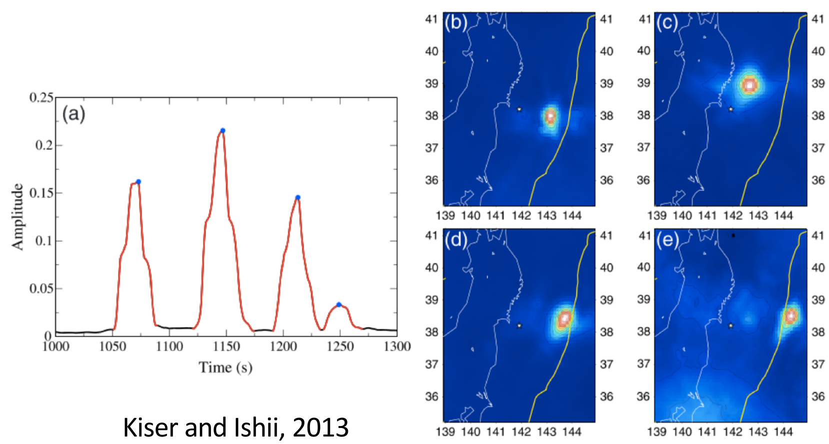


From EQcorrscan developers

Match Filter: searches for similar patterns by cross-correlating waveforms of known template events with continuous seismic recordings

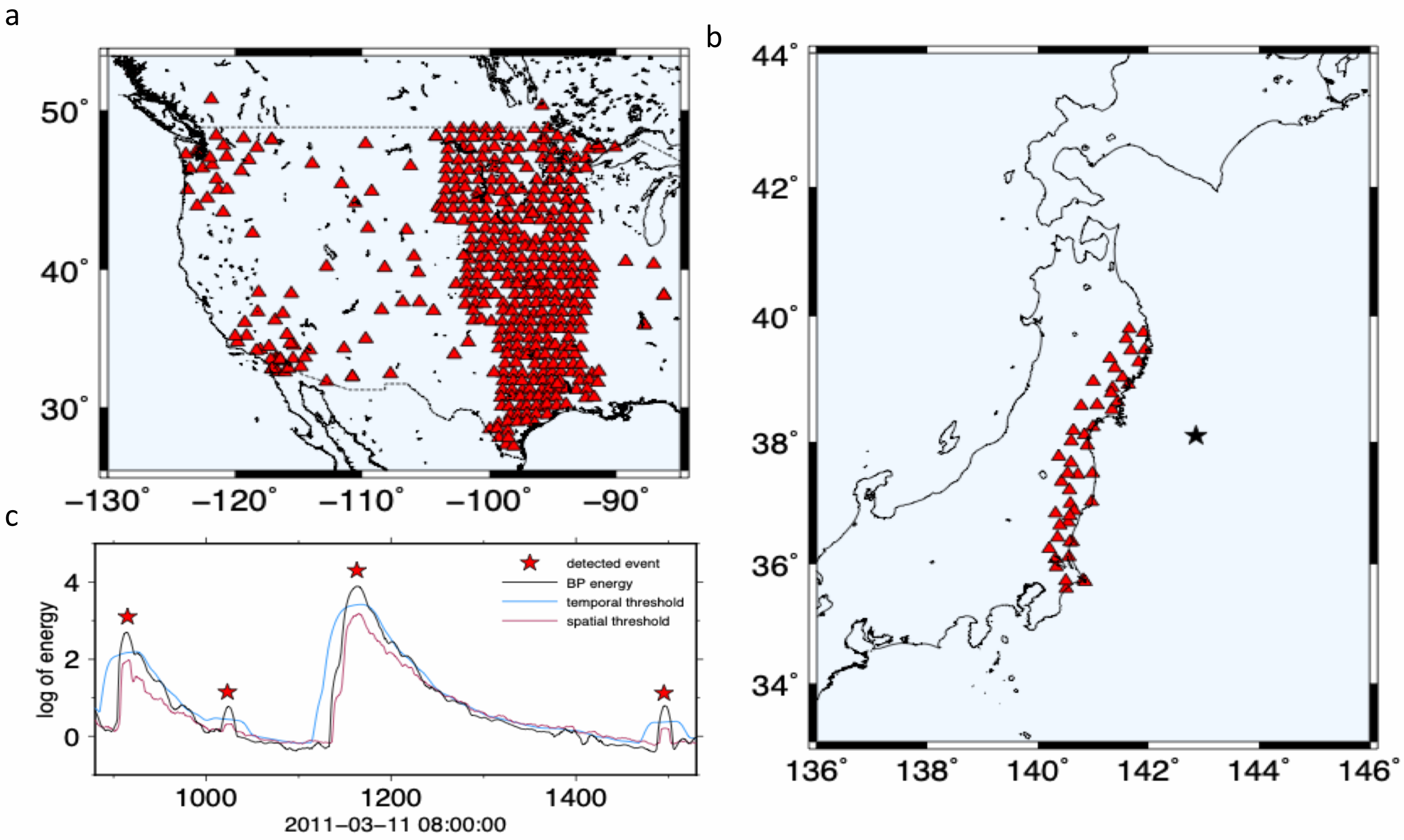
Back-projection: an earthquake-rupture imaging technique, back tracing seismic waves, provide spatiotemporal distribution of energy pulse



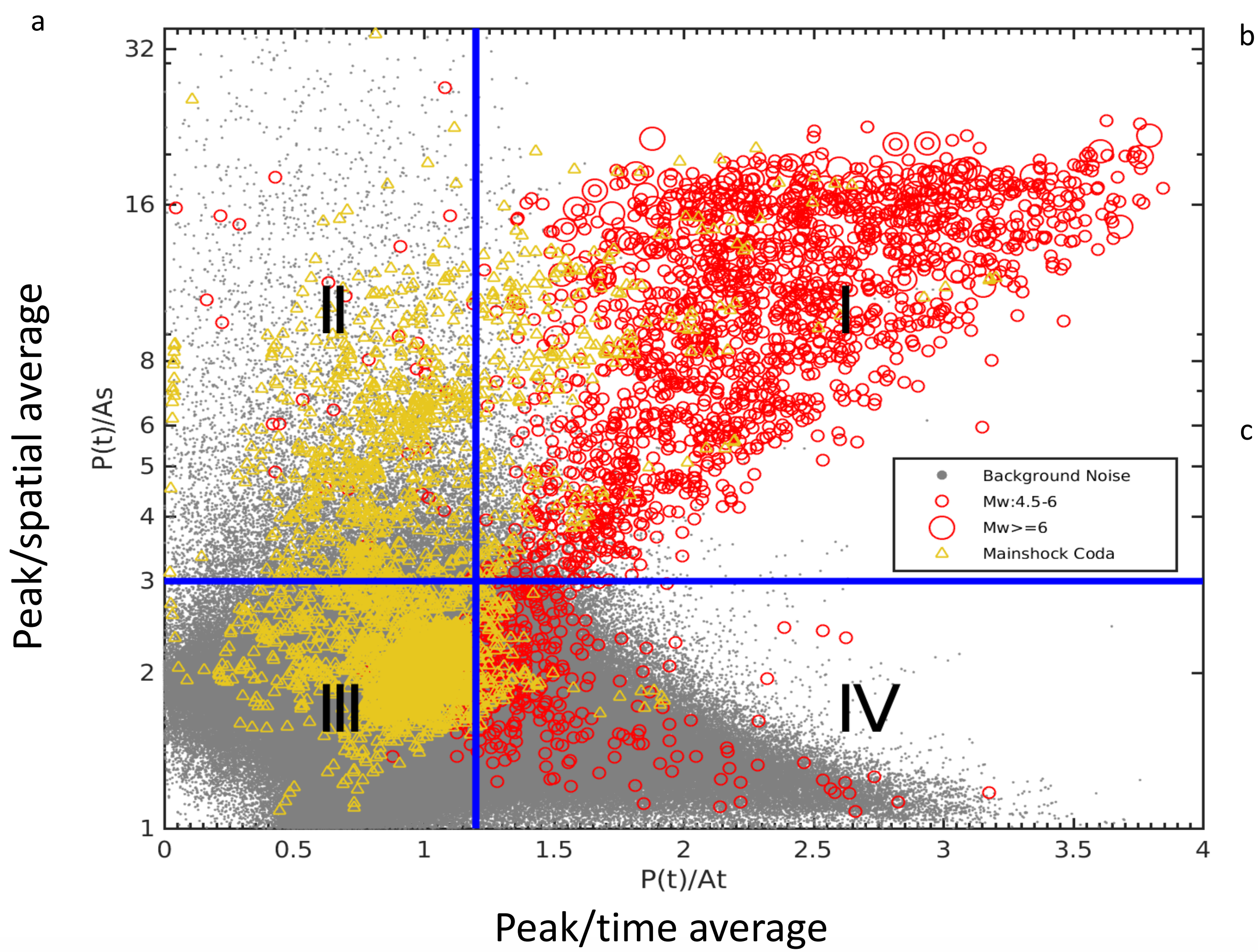


Kiser and Ishii, 2013

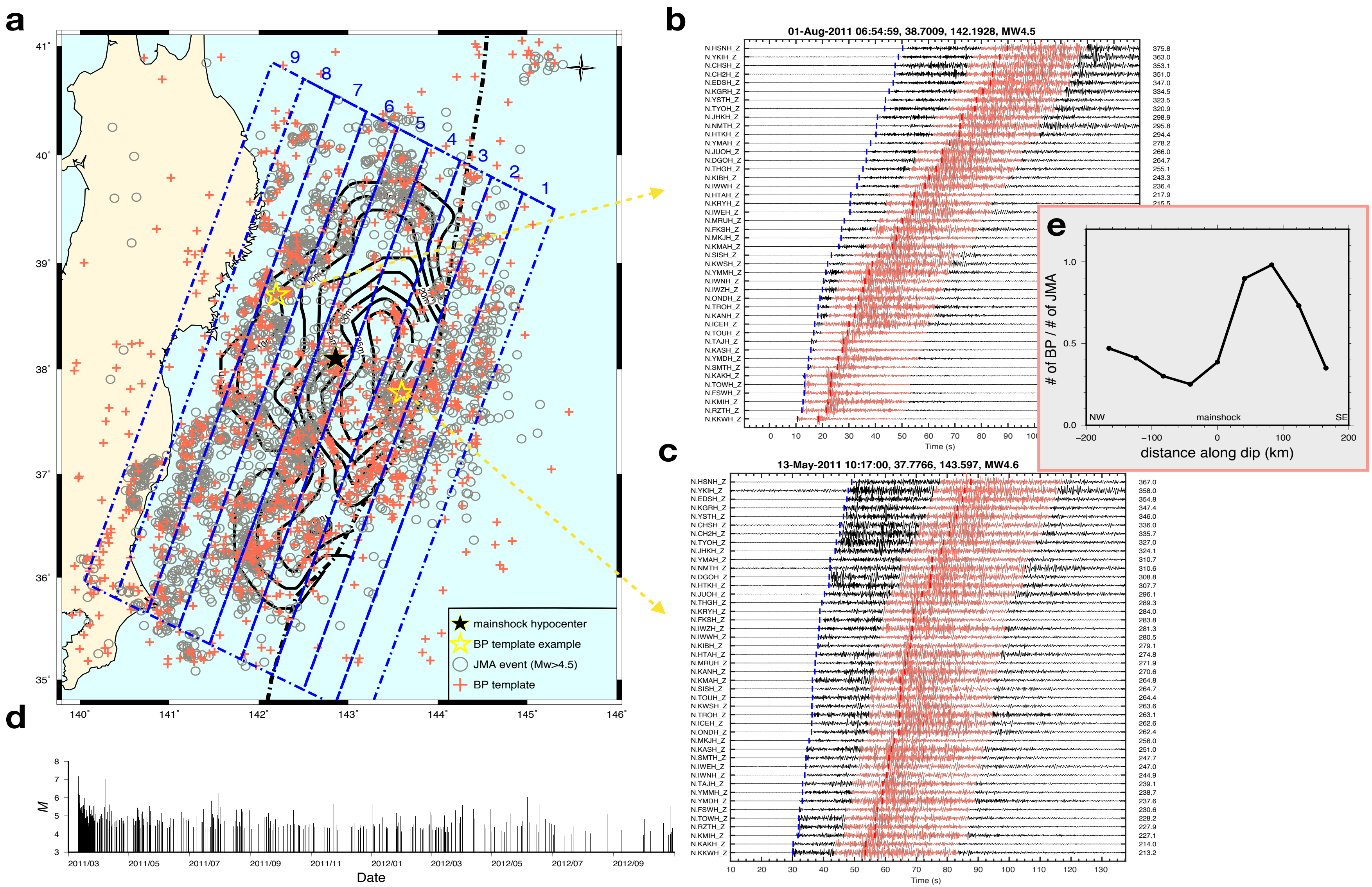
Case study: Detecting One-year Aftershocks of the Tohoku Earthquake



Detection Threshold Selection

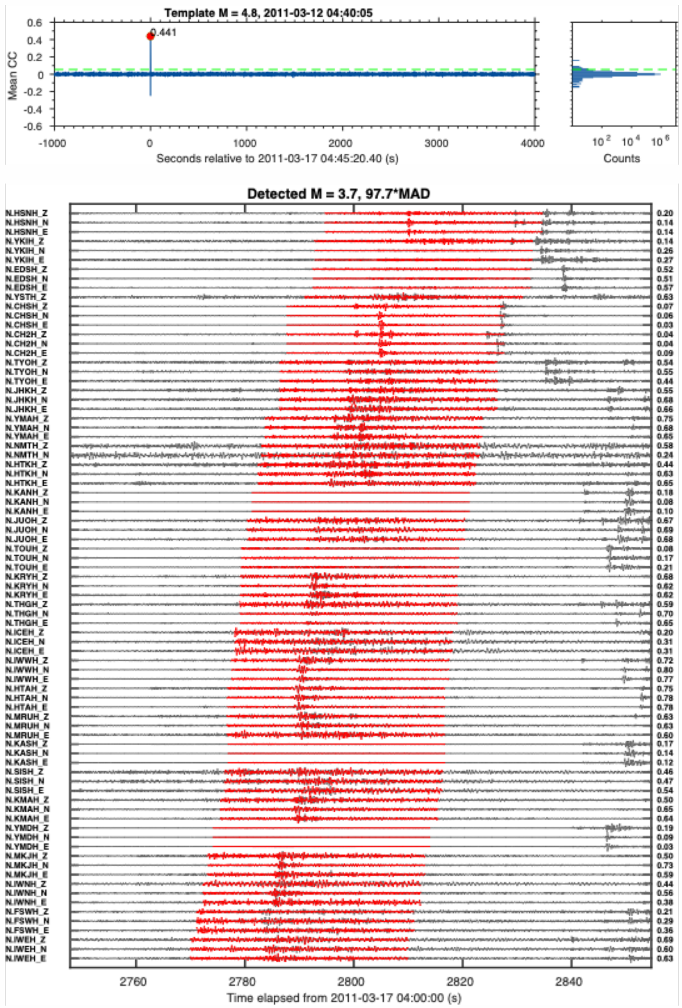


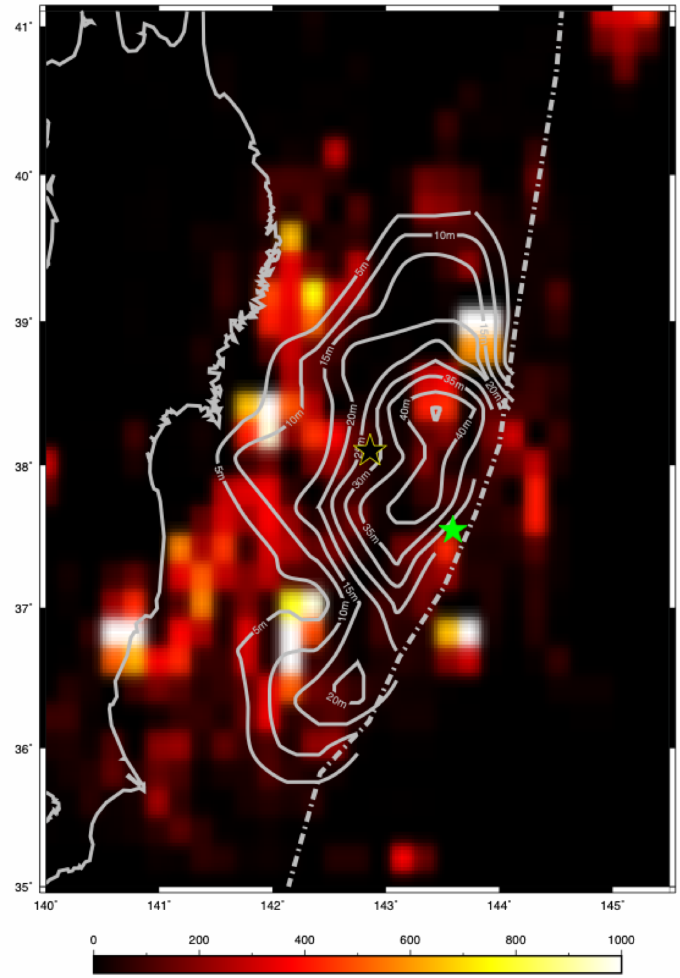
New BP Templates



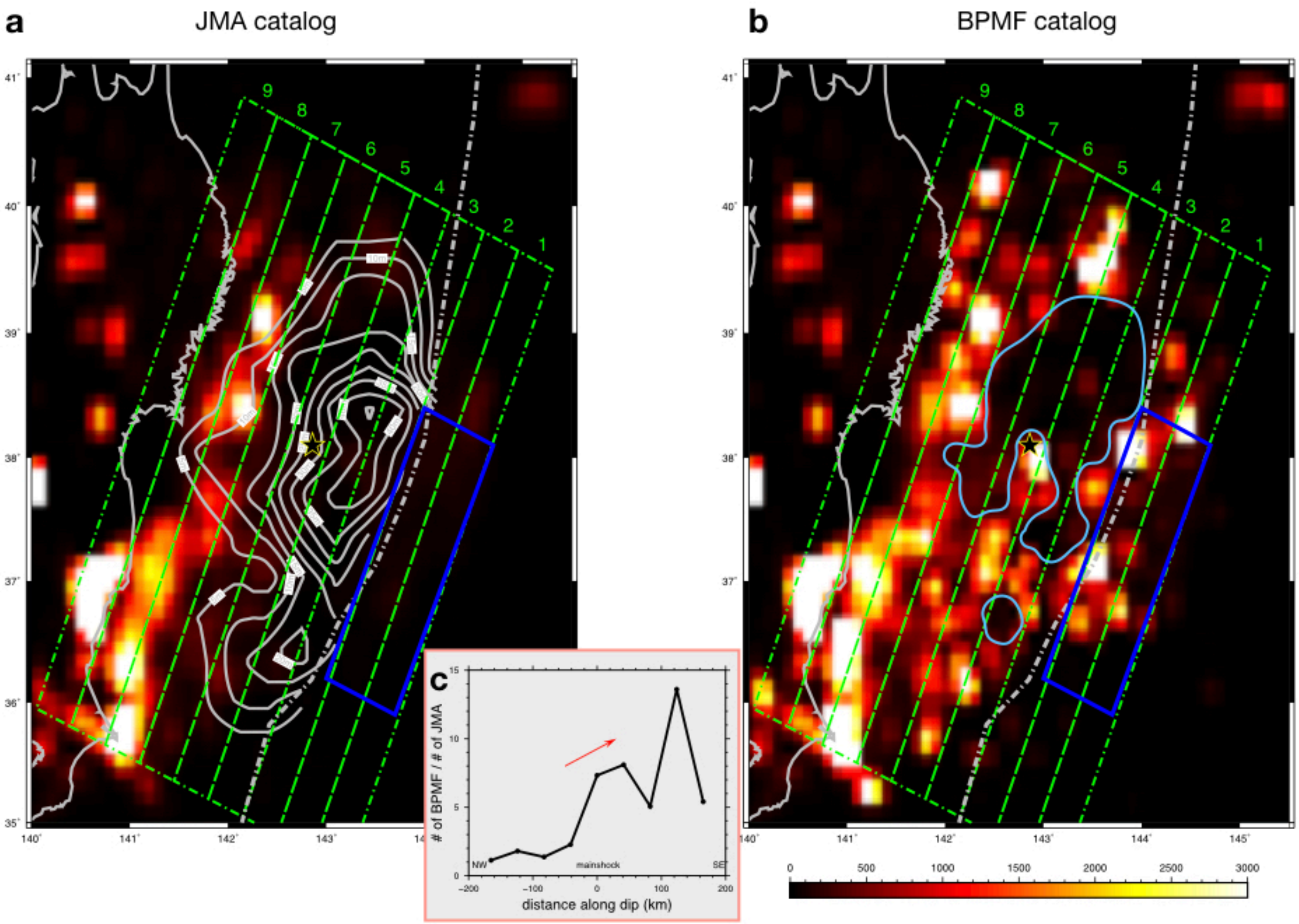
BP finds 100% more M>4.5 events offshore.

Matched-filter with New BP Templates

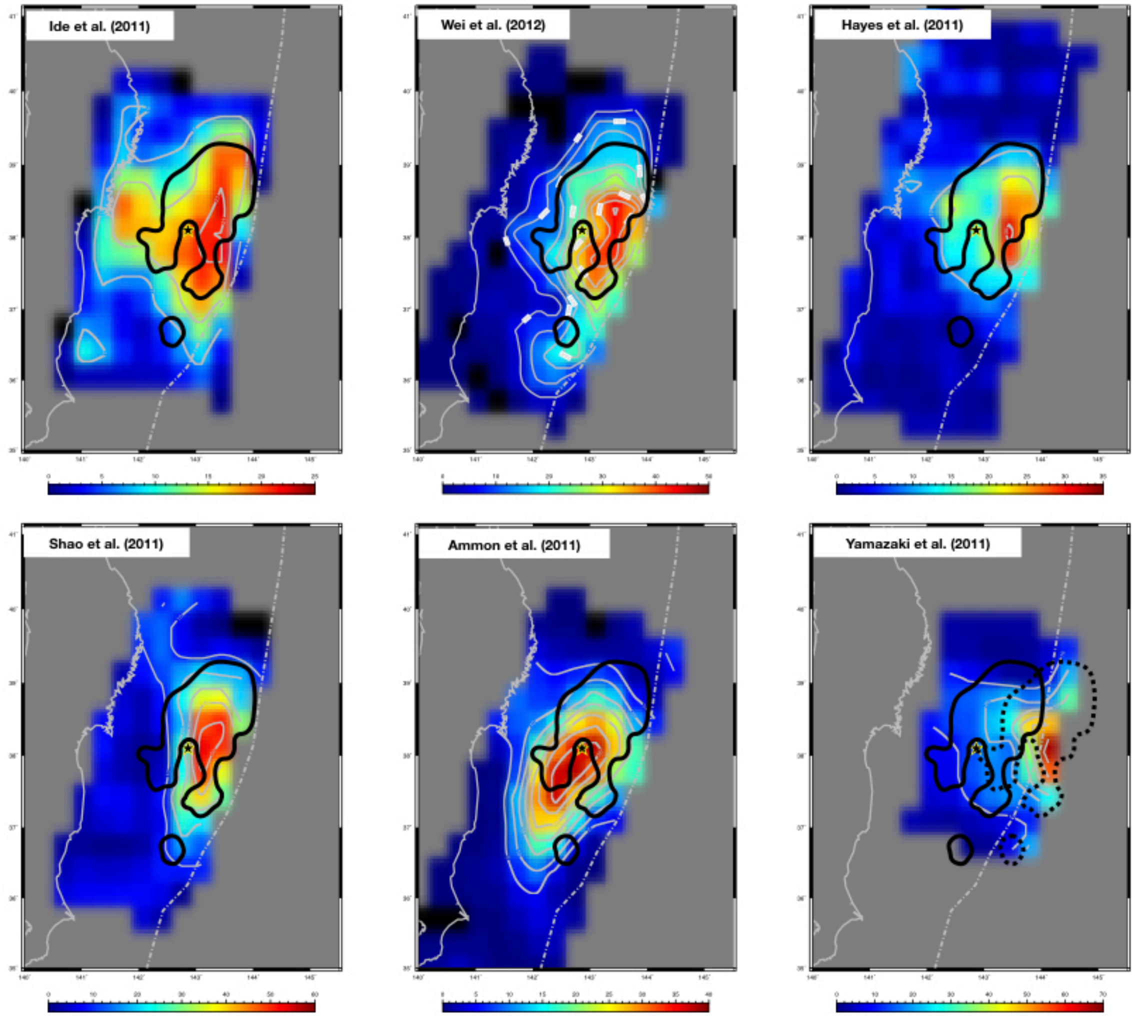




Earthquake Density Distribution

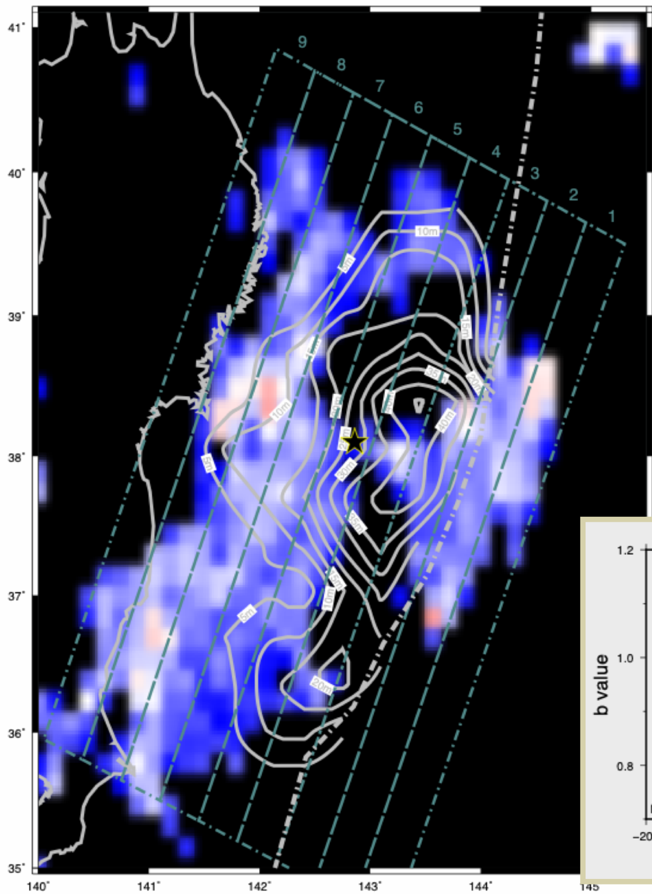


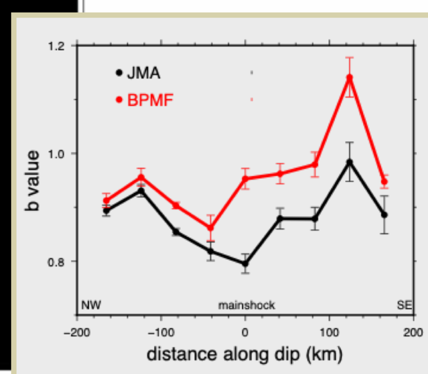
Comparison with Finite Fault Models



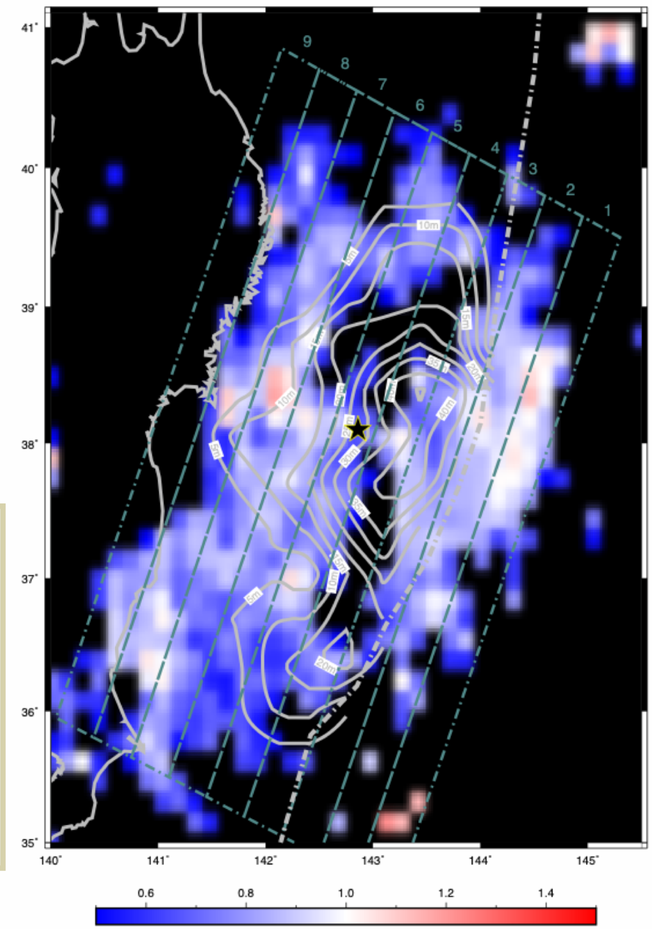
b Value Distribution

JMA catalog



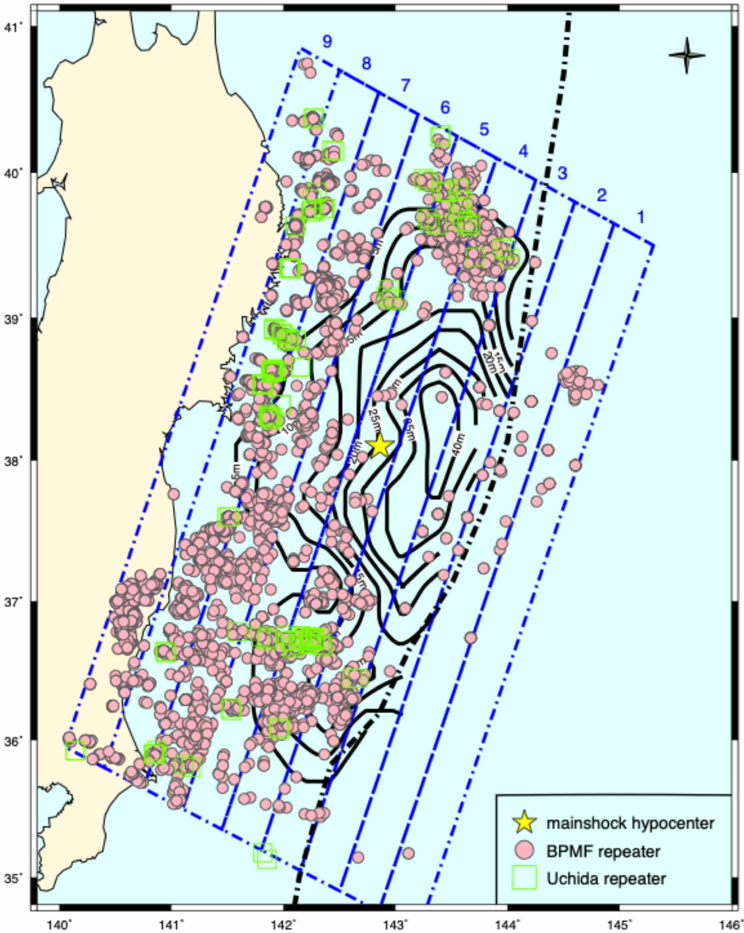


BPMF catalog



Repeating Earthquakes

All



M>4