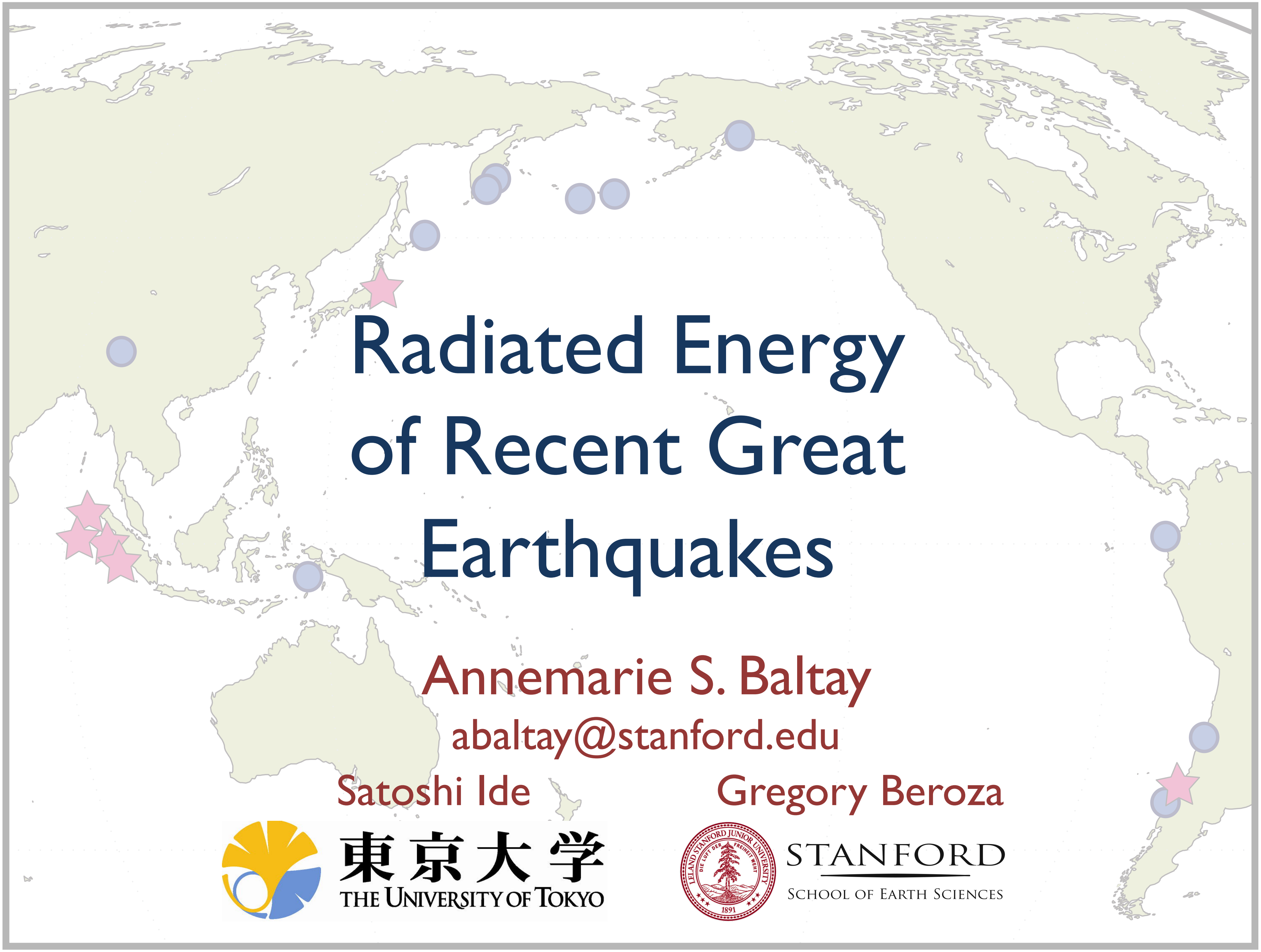


Radiated Energy of Recent Great Earthquakes

Annemarie S. Baltay
abaltay@stanford.edu

Satoshi Ide

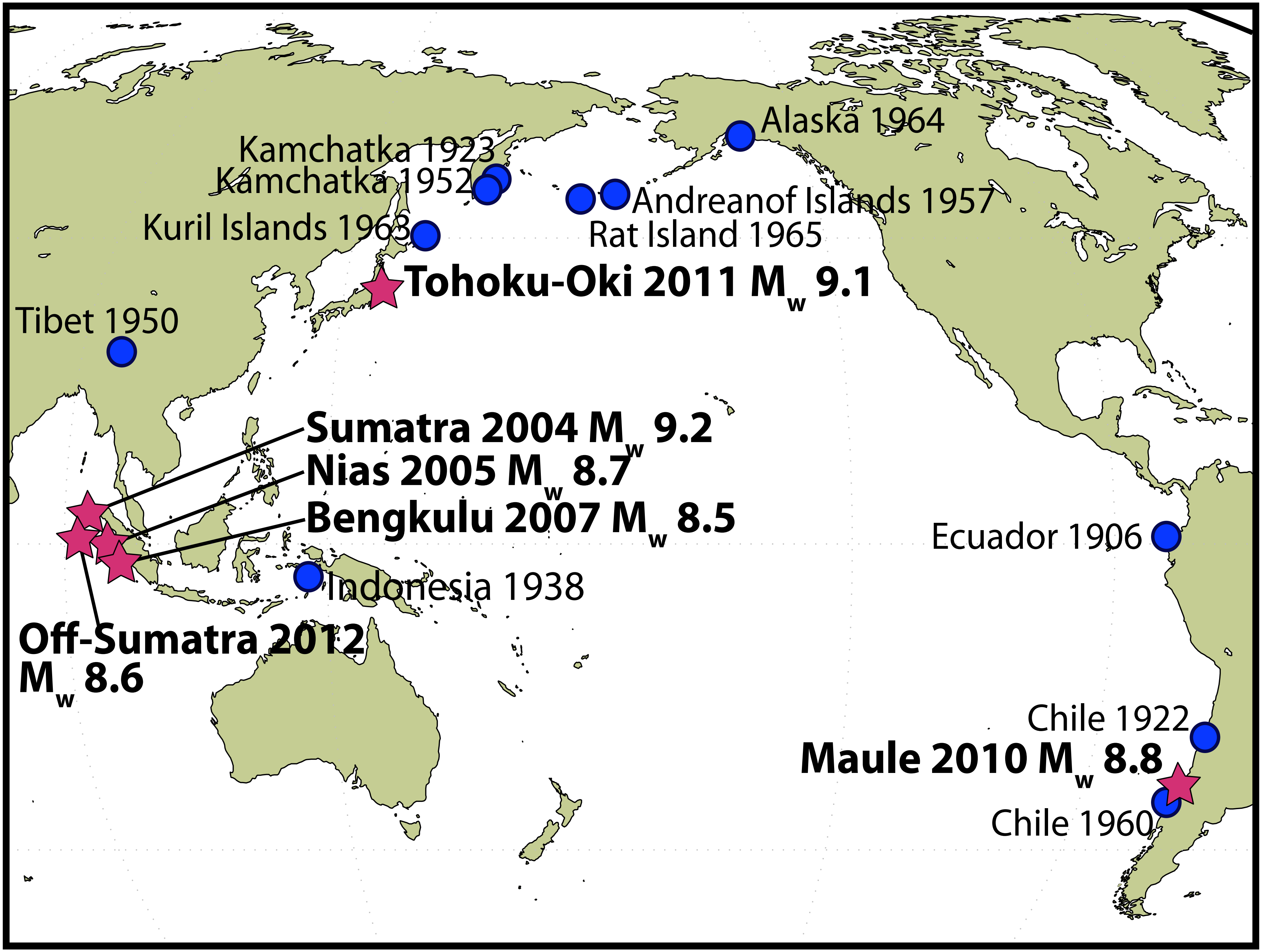
東京大学
THE UNIVERSITY OF TOKYO

Gregory Beroza

STANFORD
SCHOOL OF EARTH SCIENCES

ECGS Source Meeting • October 3rd, 2012

16 great M>8.5 earthquakes since 1900



eGf-coda Methodology for Moderate Earthquakes

(1) Create coda spectra

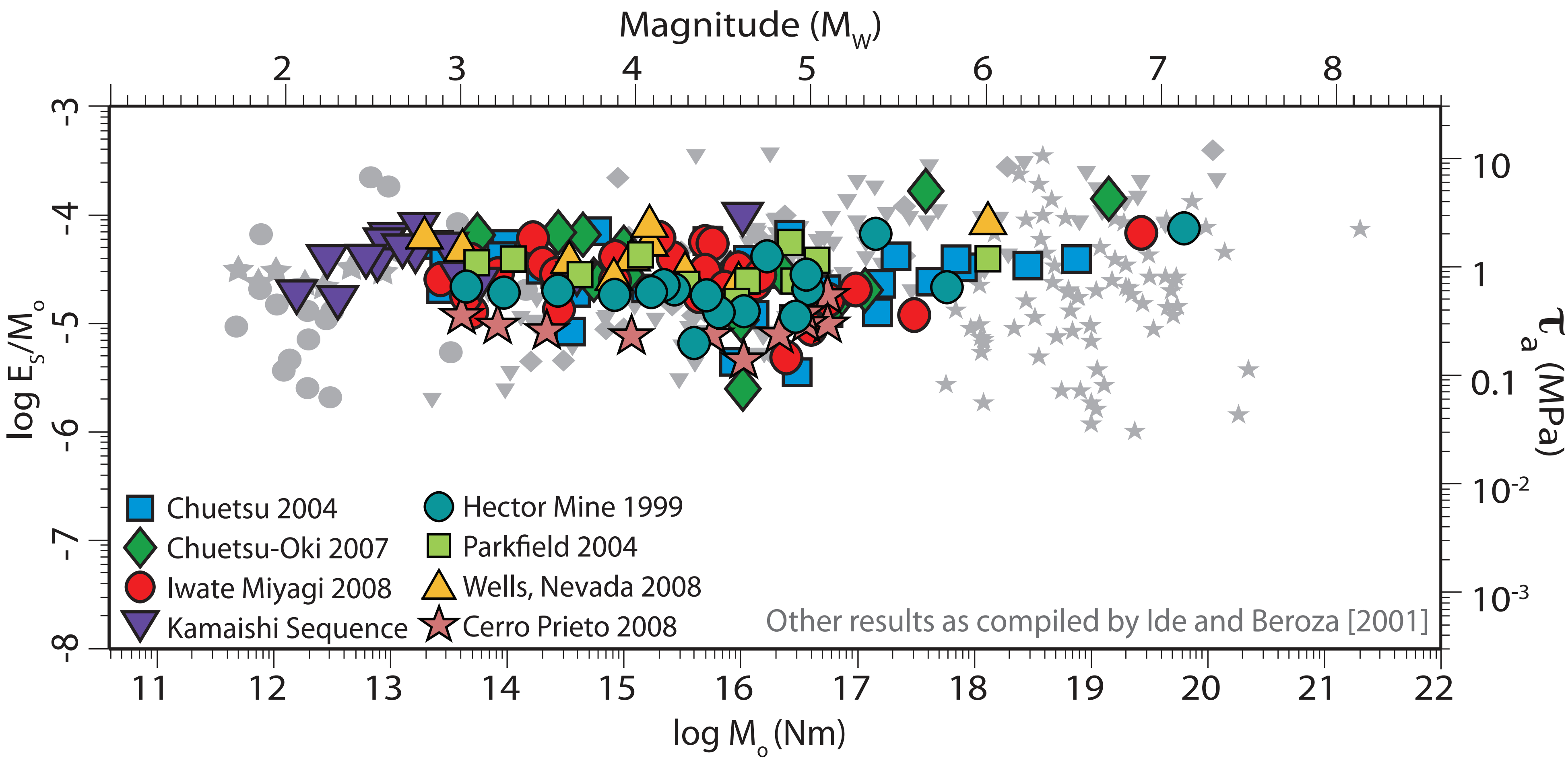
- Narrow band-pass displacement records
- Time window in each record becomes coda spectral point

(2) Empirical Green's function to remove path effects

- Small event is modeled as ideal Brune-like event
- Path effects sequentially deconvolved from larger events
- Use moment from largest event to set relative moments

(3) Source spectra → moment, corner frequency, energy

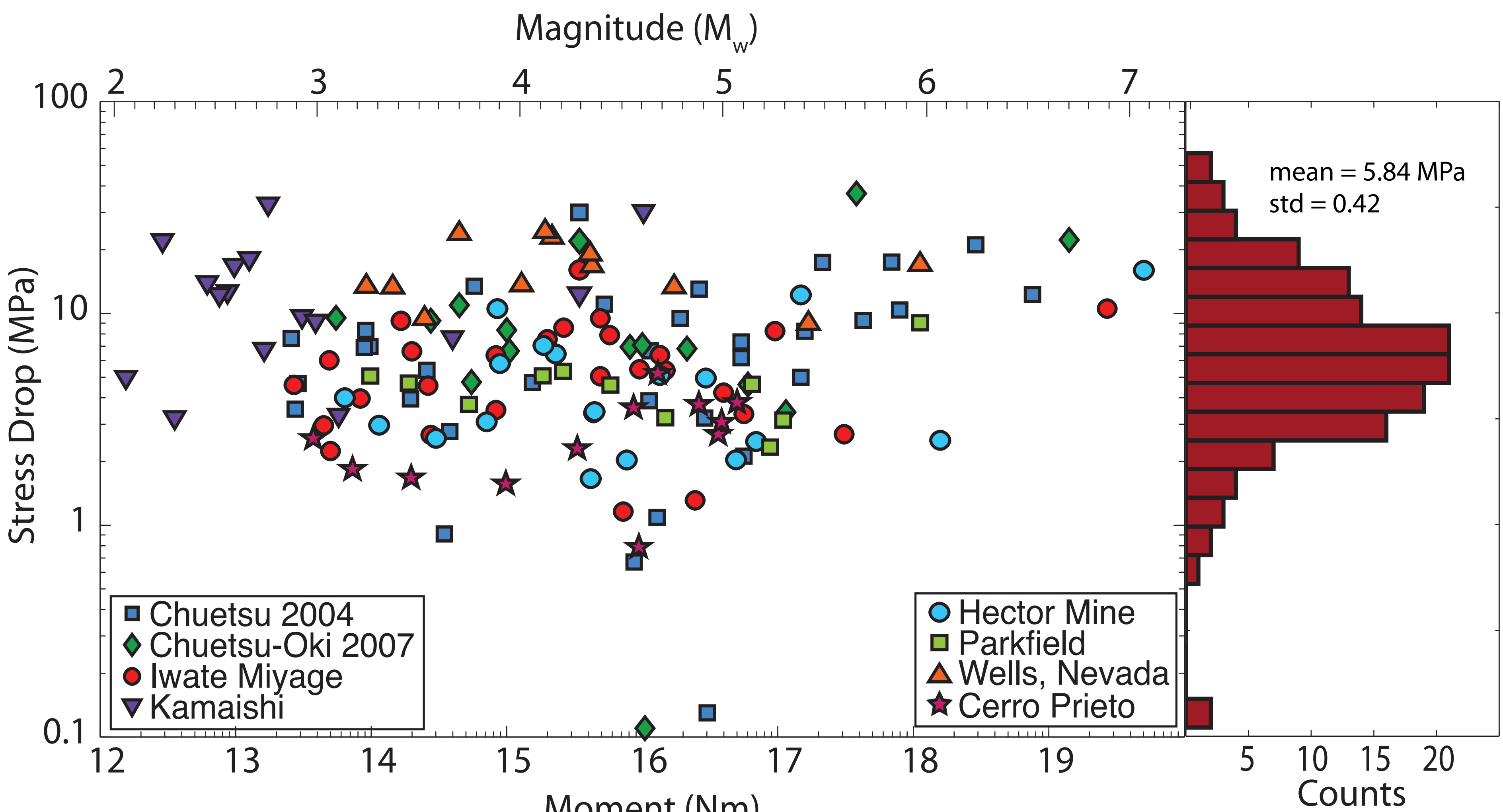
Radiated Energy and Apparent Stress



$$E_R \sim \int_0^\infty \left|\omega \cdot \dot{M}(\omega)\right|^2 d\omega \qquad \tau_a = \mu \frac{E_R}{M_O}$$

Baltay et al, 2010
Baltay et al, 2011

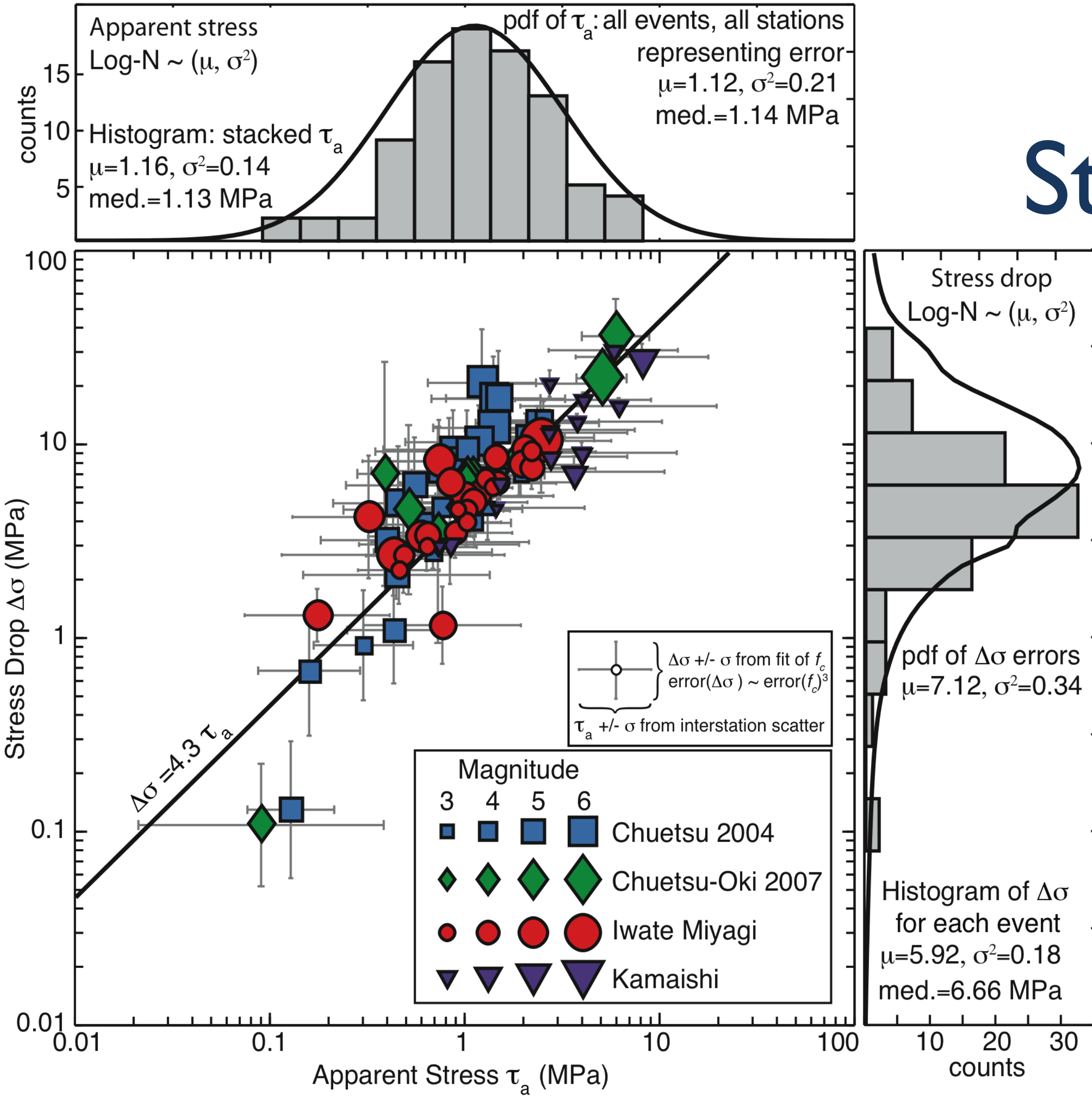
Stress Drop



$$\Delta\sigma_{Brune} = 8.47 M_o \left(\frac{f_c}{\beta}\right)^3$$

Baltay et al, 2010
Baltay et al, 2011

Apparent Stress and Stress Drop

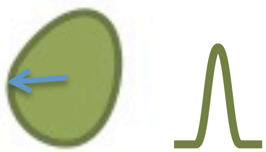


Baltay et al, 2011

- $\Delta\sigma$ and τ_a both log-normally distributed
- Follow the expected theoretical relationship

Teleseismic empirical Green's functions

M_w 3

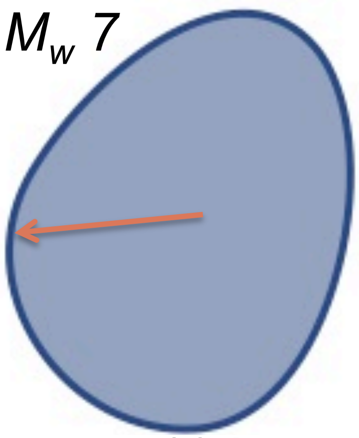


r = ~100 m

R upto ~200 km

r<<R

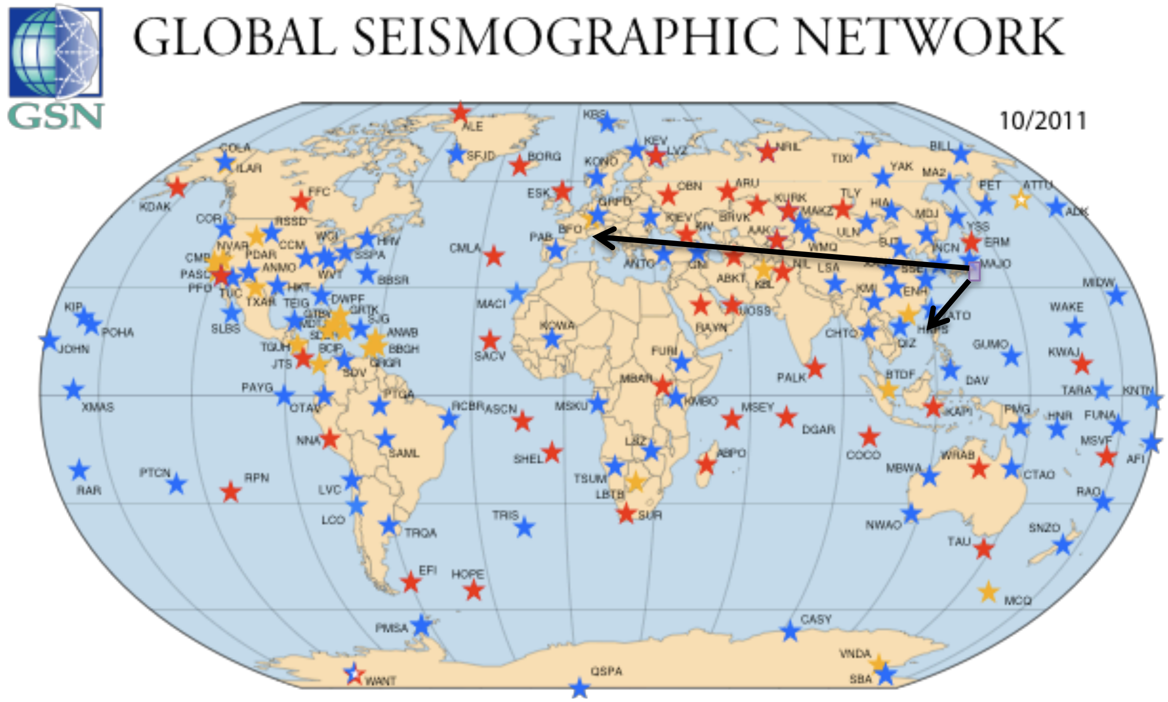
M_w 7



r = ~10 km

R ~3000 km to ~10,000 km

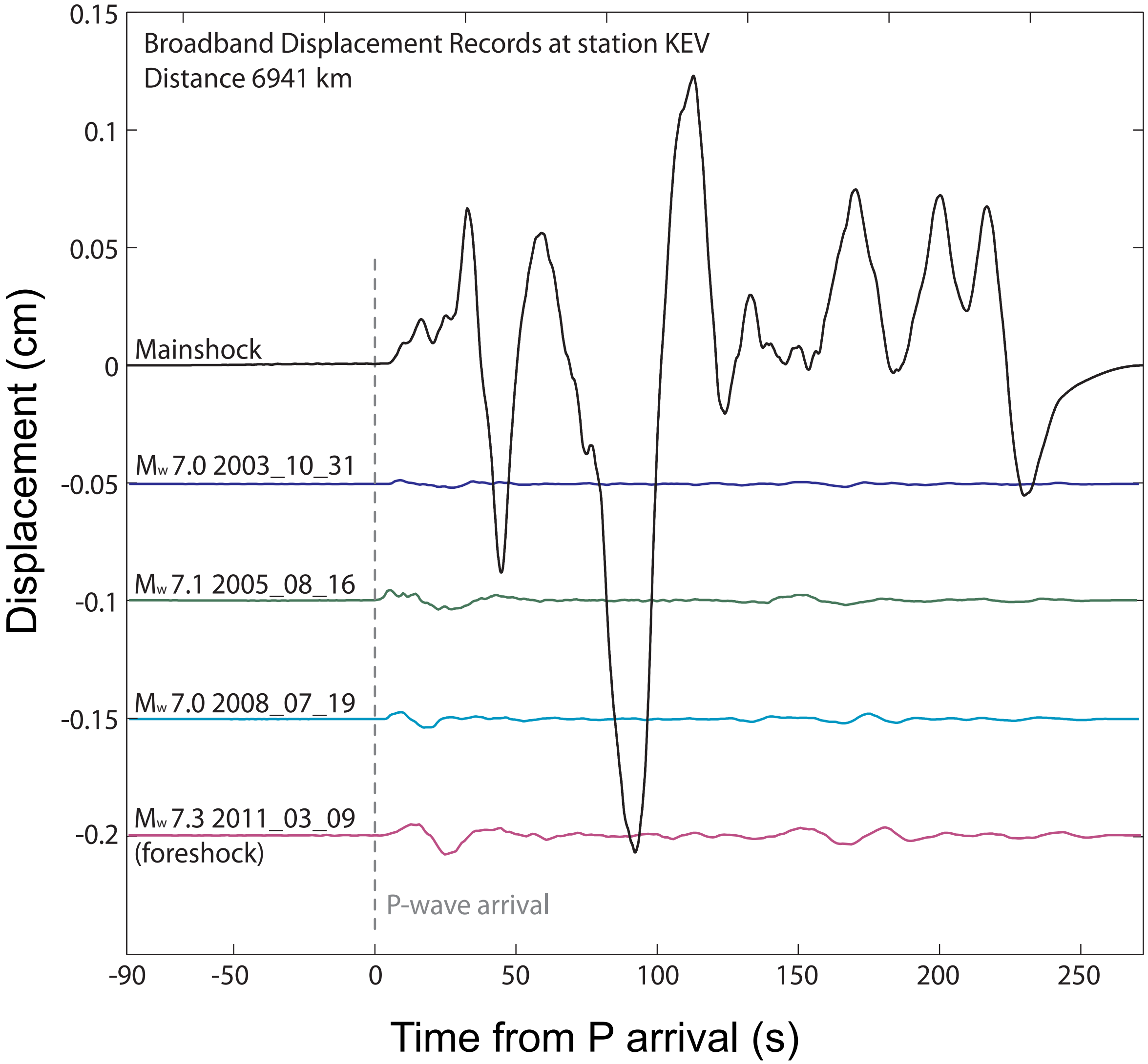
r<<R

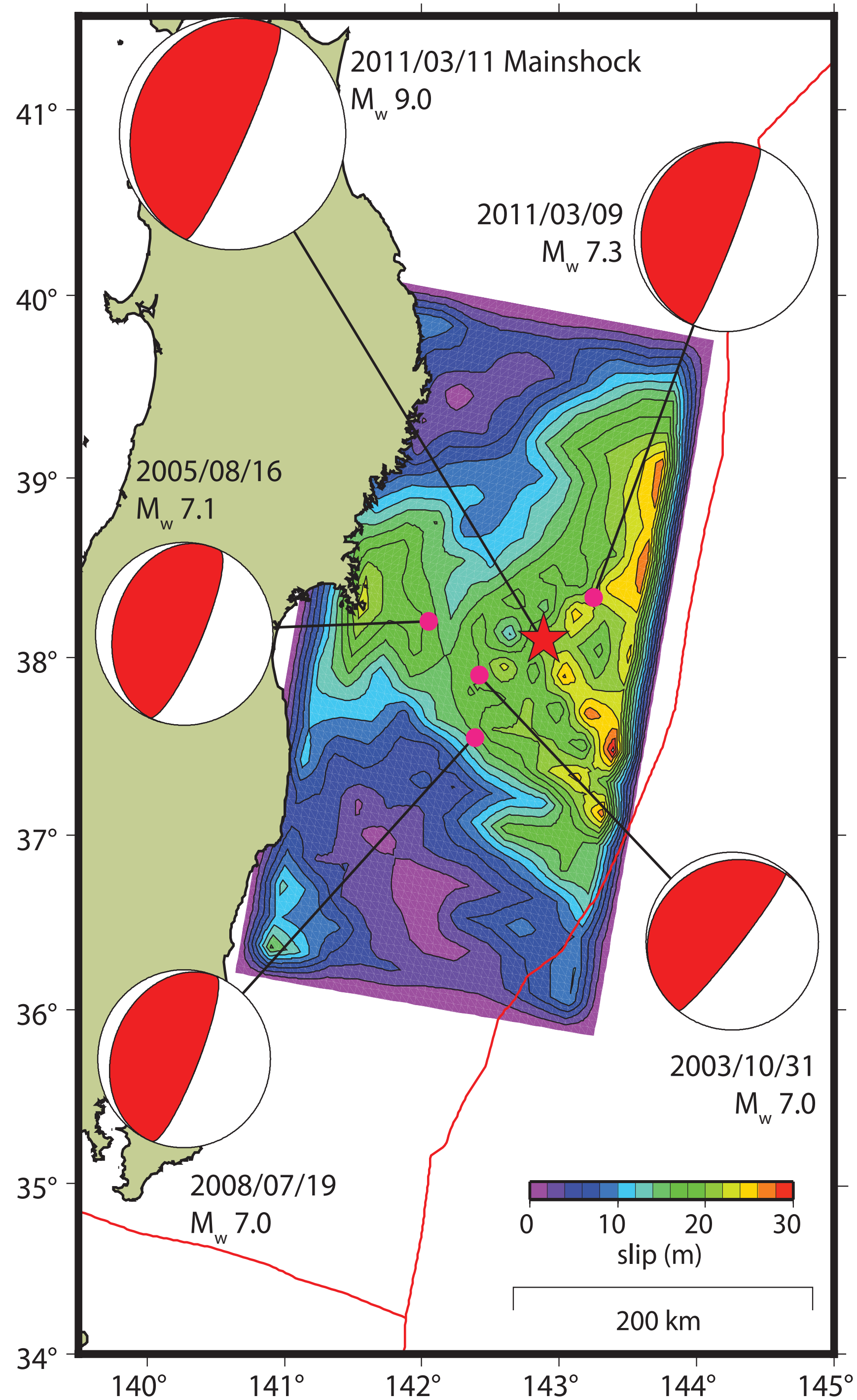


Can't use local eGf method to analyze large M>7.5 earthquakes

Assume a ~ M 6.5 – 7.5 can be modeled as ideally Brune → teleseismic eGf method

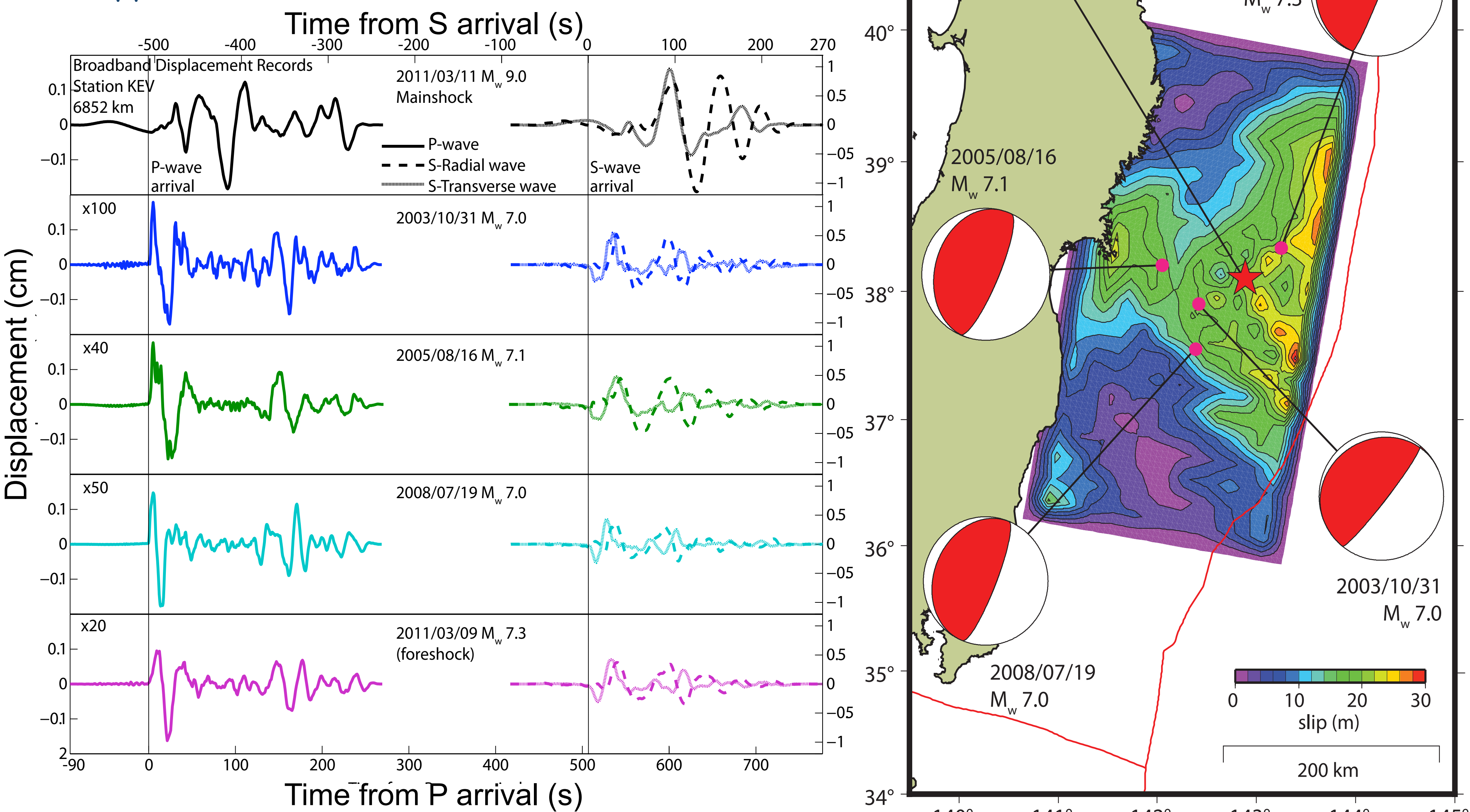
Tohoku-Oki 2011
M_w 9.1





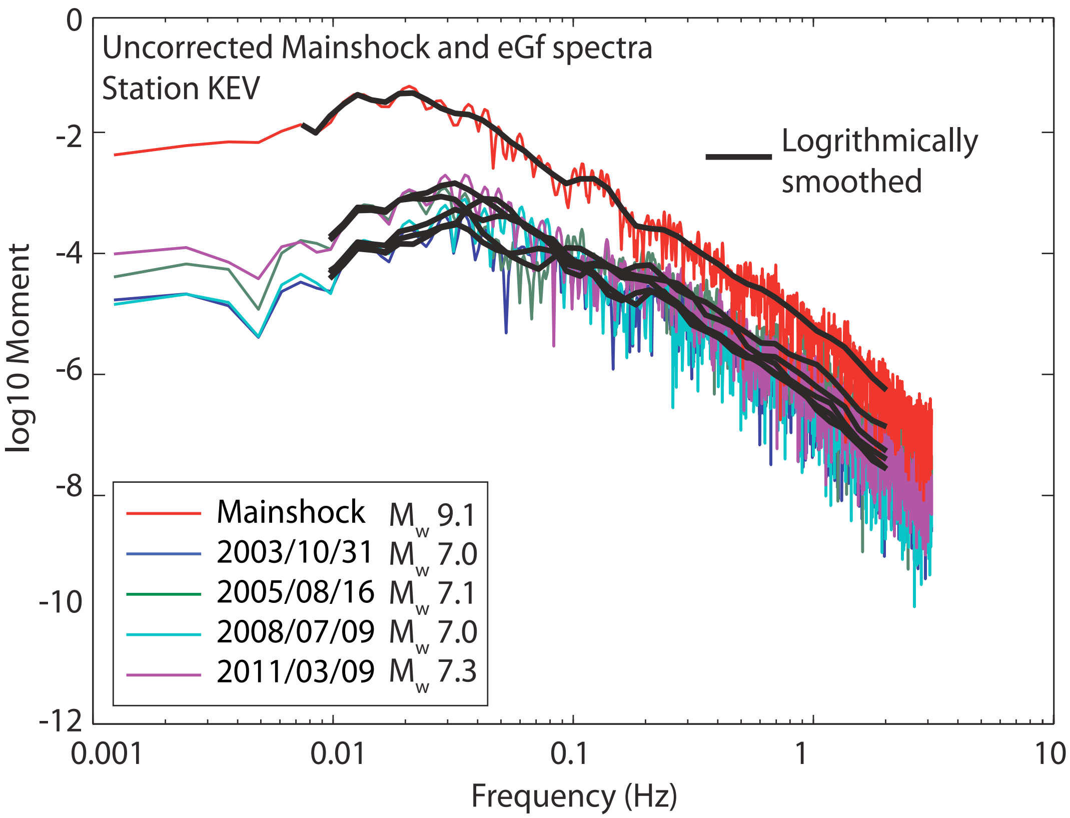
Ide et al, 2011

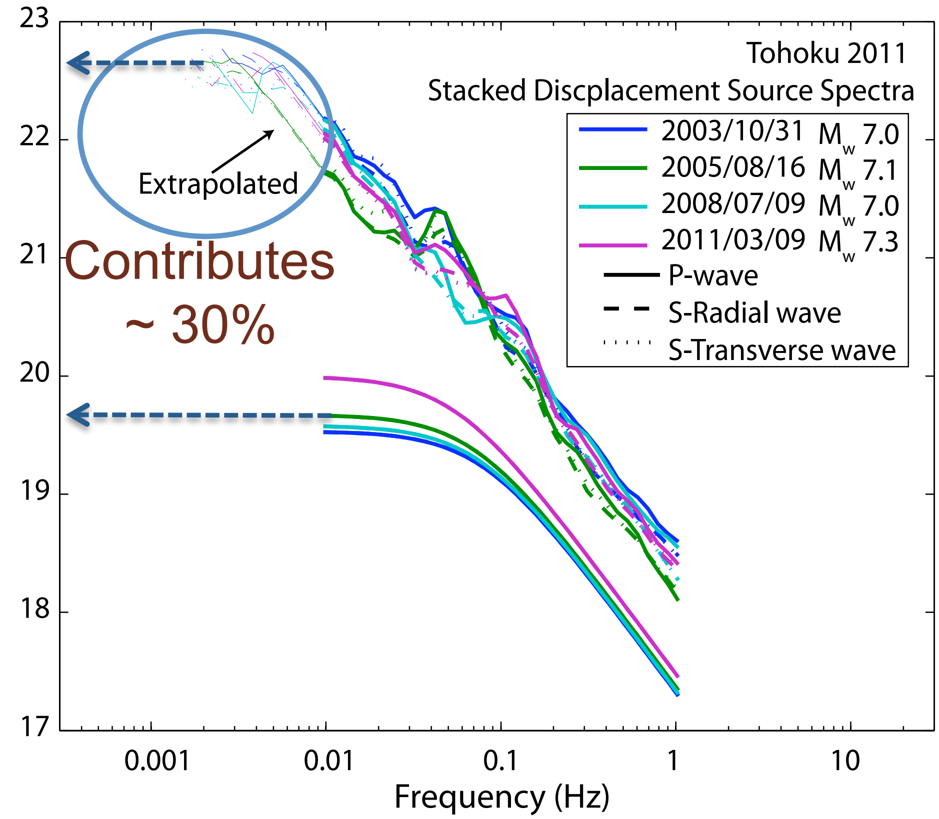
Tohoku-Oki 2011
M_w 9.1



Ide et al, 2011

eGf Deconvolution





$$E_R \sim \int_0^\infty \left| \omega \cdot \dot{M}(\omega) \right|^2 d\omega$$

Corner frequency of mainshock is not well resolved

→ Can't measure $\Delta\sigma$

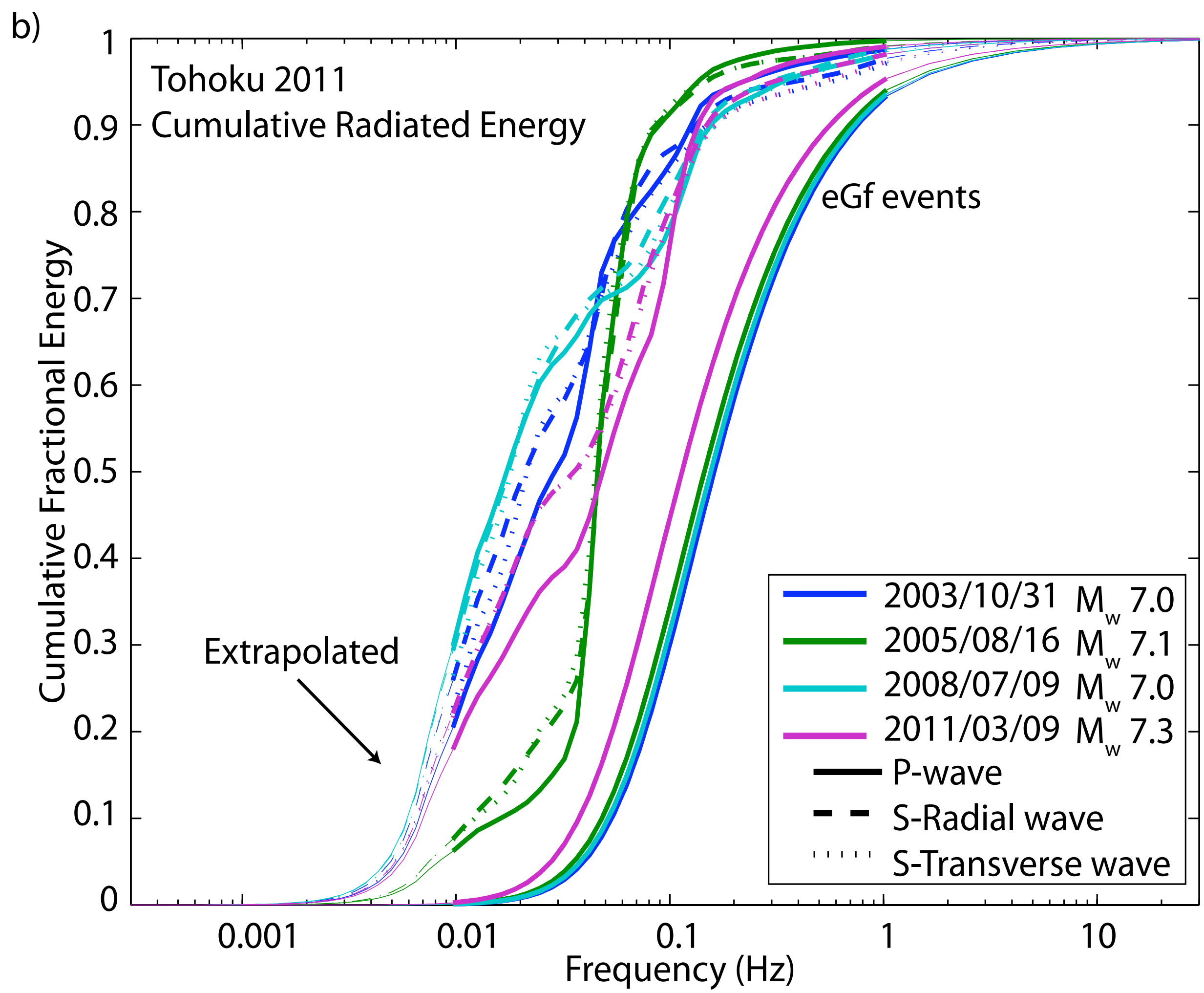
Ide et al, 2011

Frequency-Energy Accumulation

- Most energy in 0.01-0.1 Hz band, given very large size/ low corner frequency

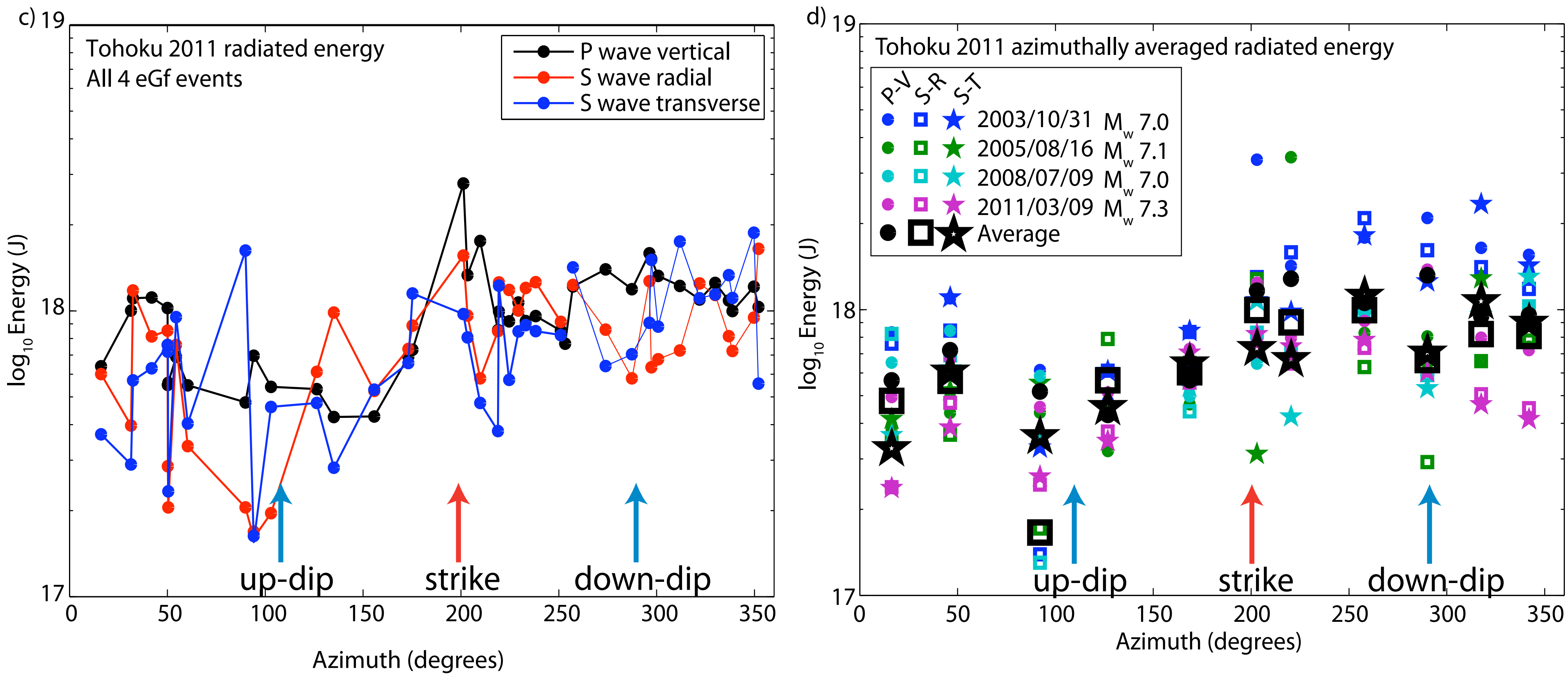
- High frequency contribution is negligible (as expected)

- P and S waves are similar for each eGf



Ide et al, 2011

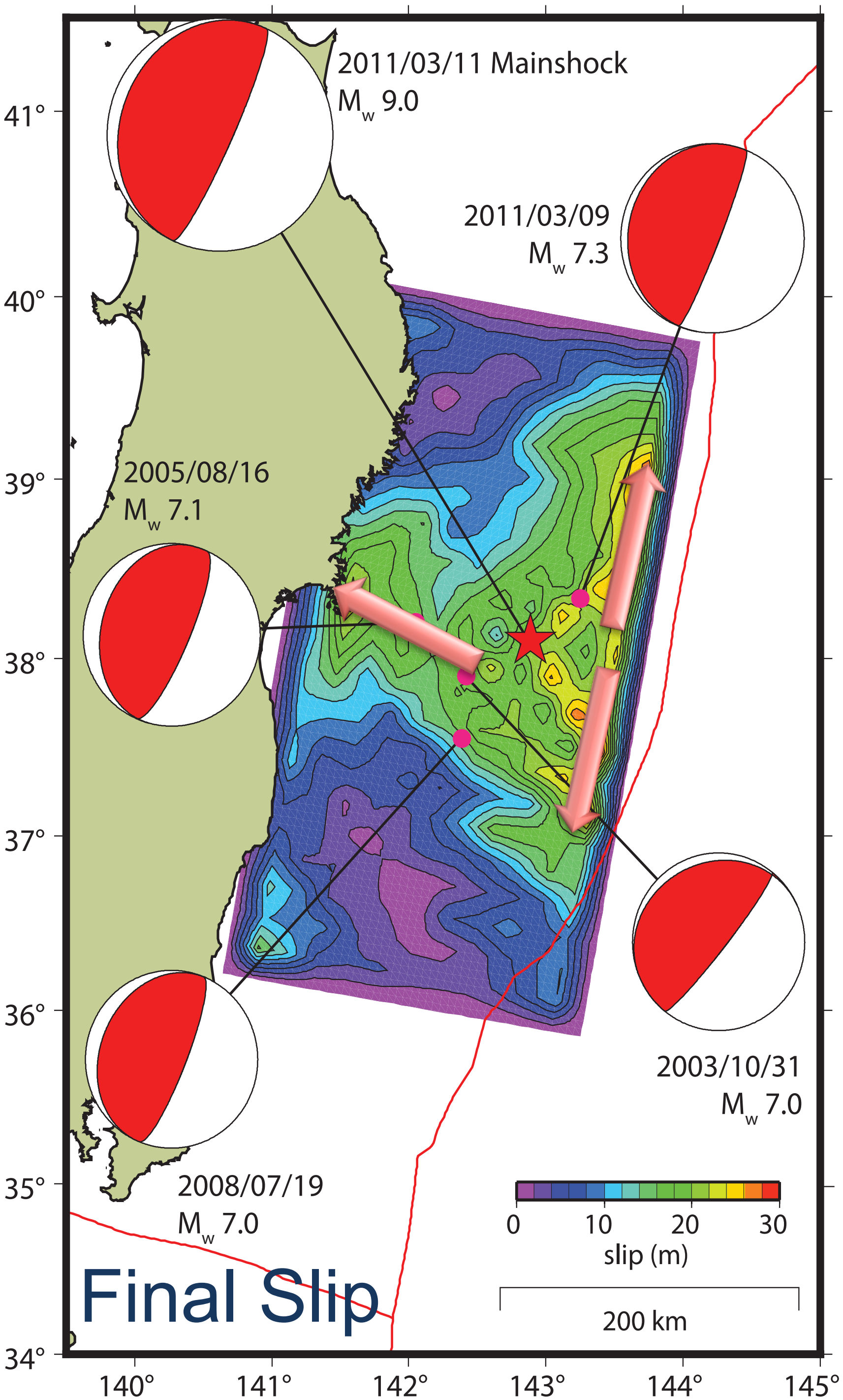
Directivity of Seismic Energy



$E_s = 7.06\text{x}10^{17}$ J $E_s/M_o = 1.57 \times 10^{-5}$ $\tau_a = 0.61$ MPa

→ Typically, expect higher energy in direction of rupture propagation

Ide et al, 2011

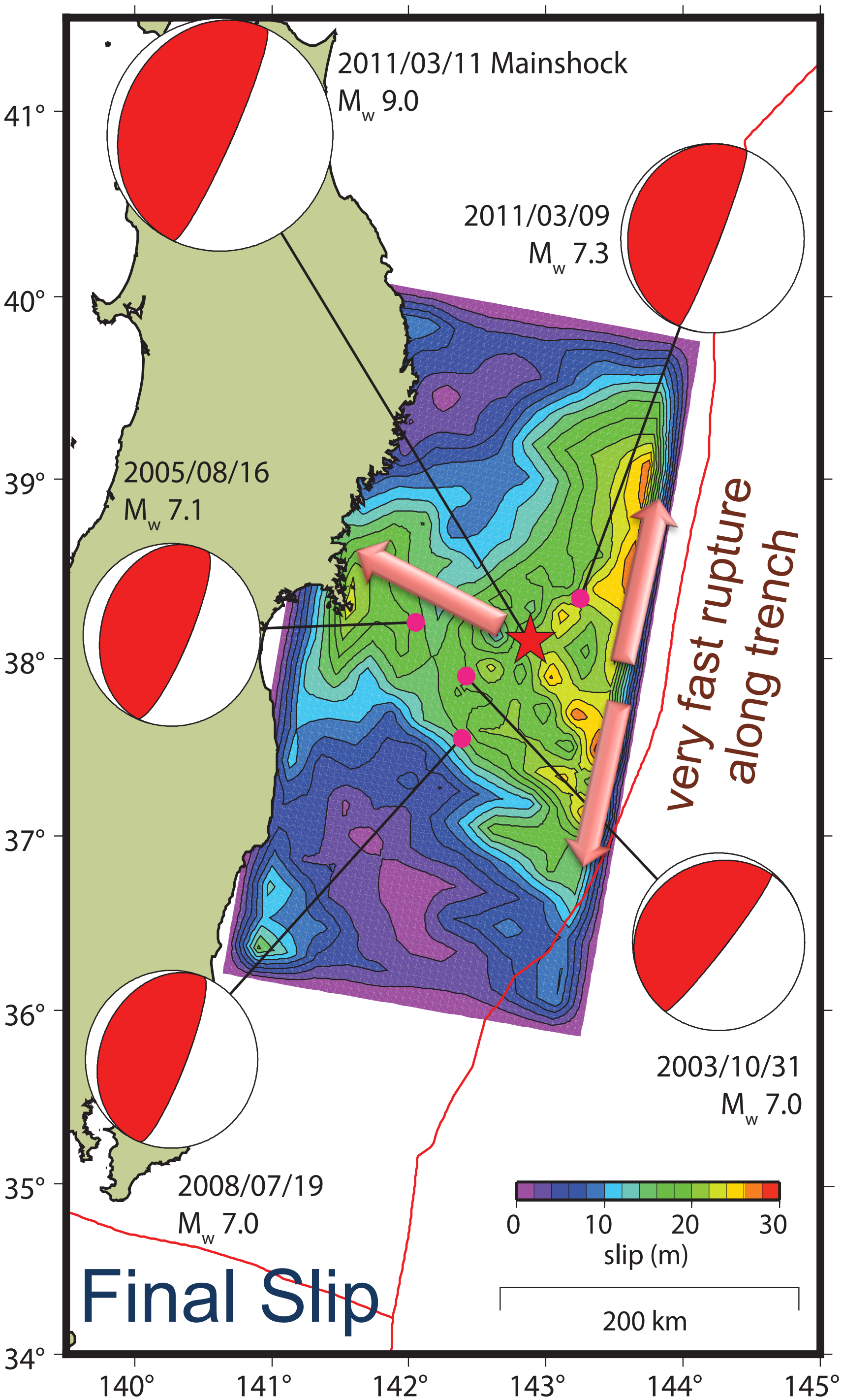


Ide et al, 2011

Slip Evolution

- Slow start
- Down-dip propagation from
  ~20 s to 40 s
- Rapid, along trench propagation
  ~50 s to 70 s with large slip

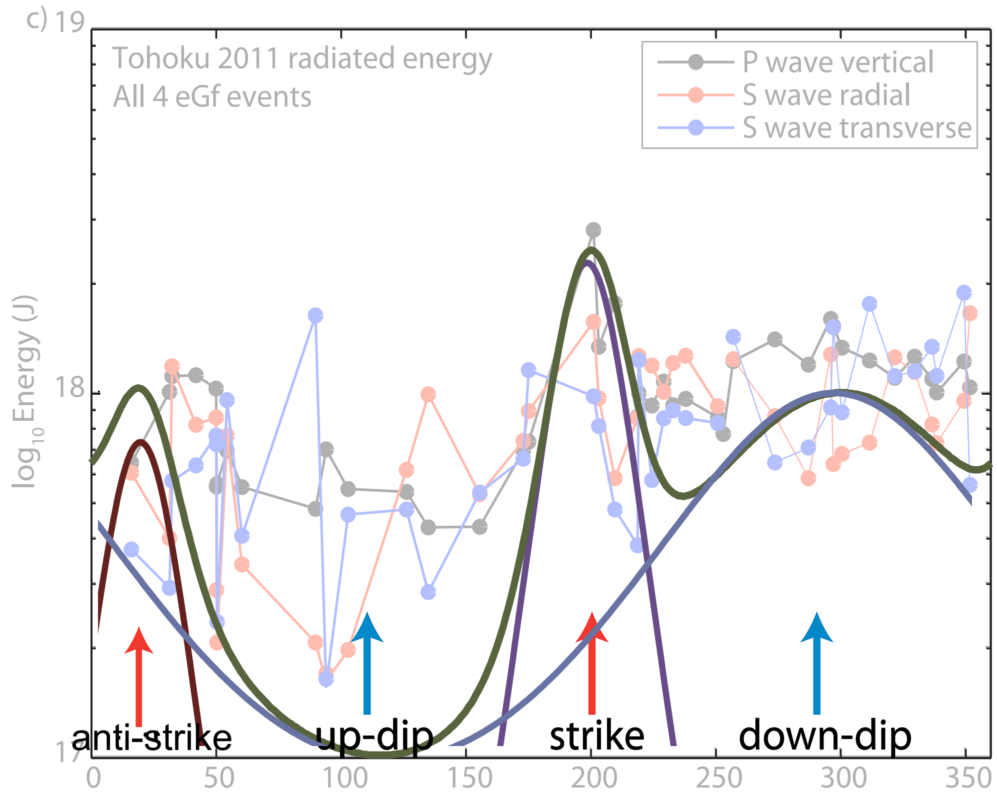
Line Sources



Ide et al, 2011

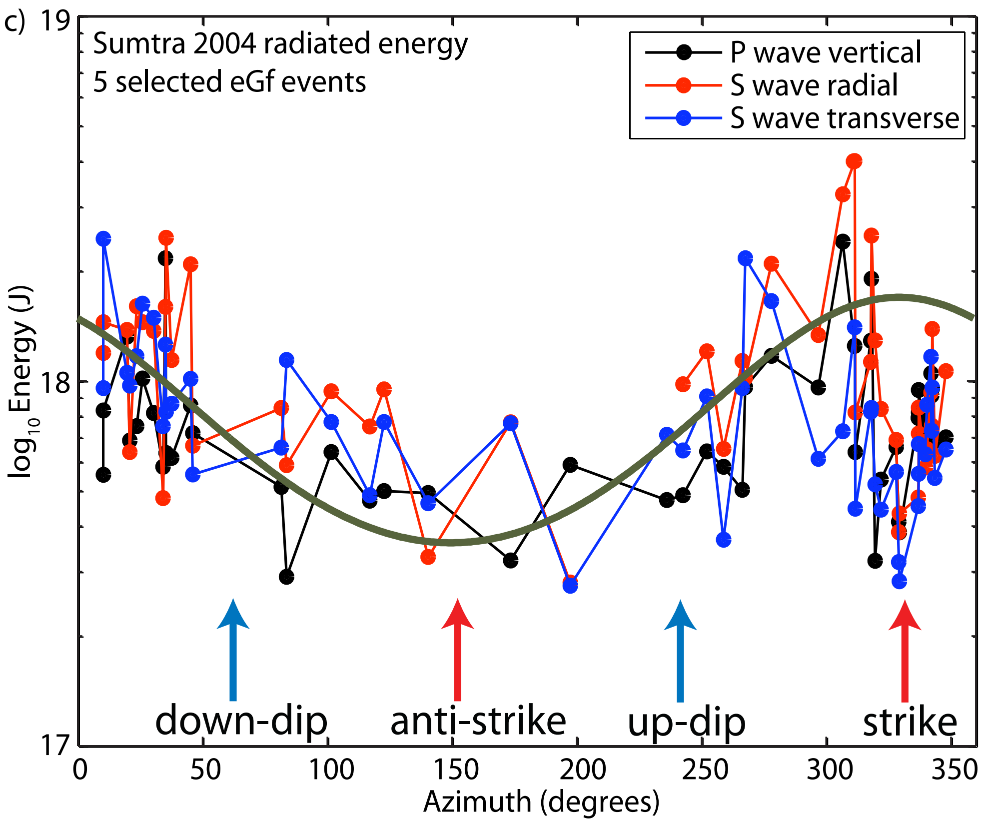
Model simple Haskell line sources

- Rupture direction
- Rupture dimensions
- Rupture velocity
- Amplitude

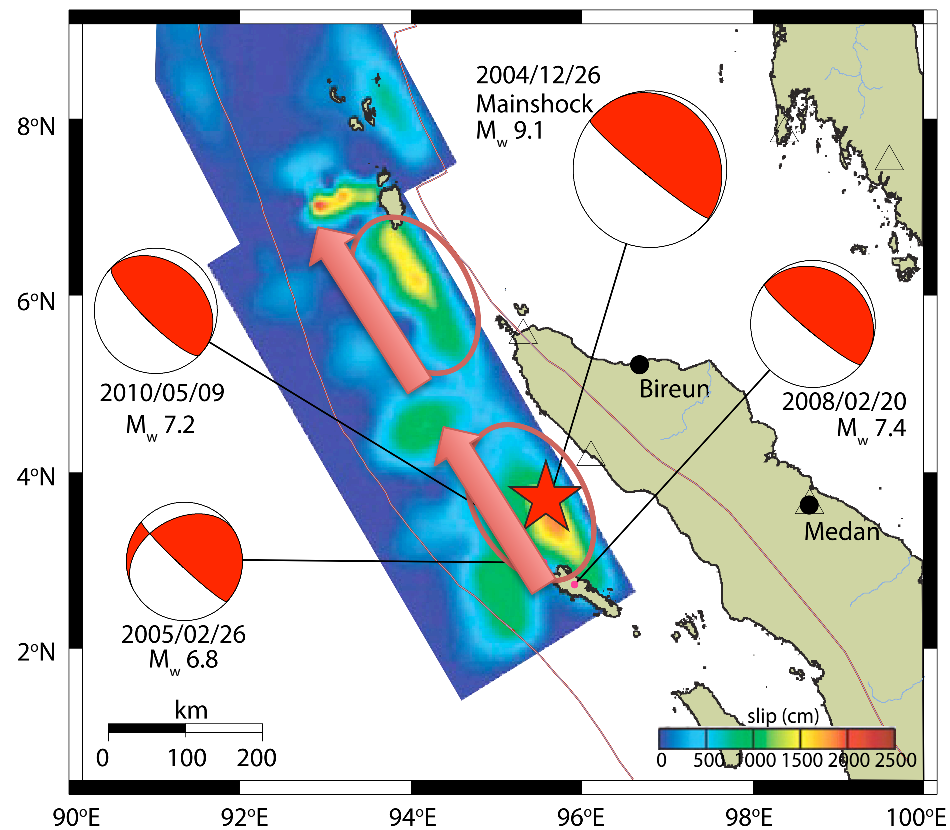


Simple model of rupture captures gross directivity pattern

Sumatra 2004 M_w 9.2



2 Haskell line sources
with half of the moment each



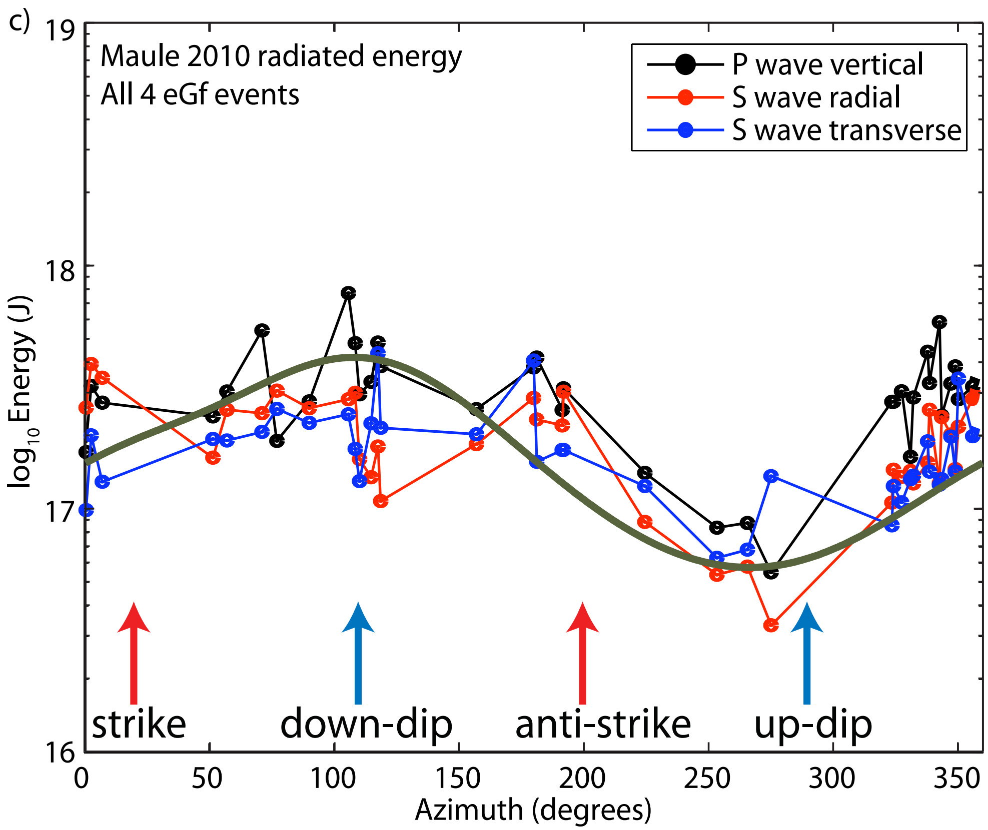
Mean from 3 egf events, 3 components, and 46 stations

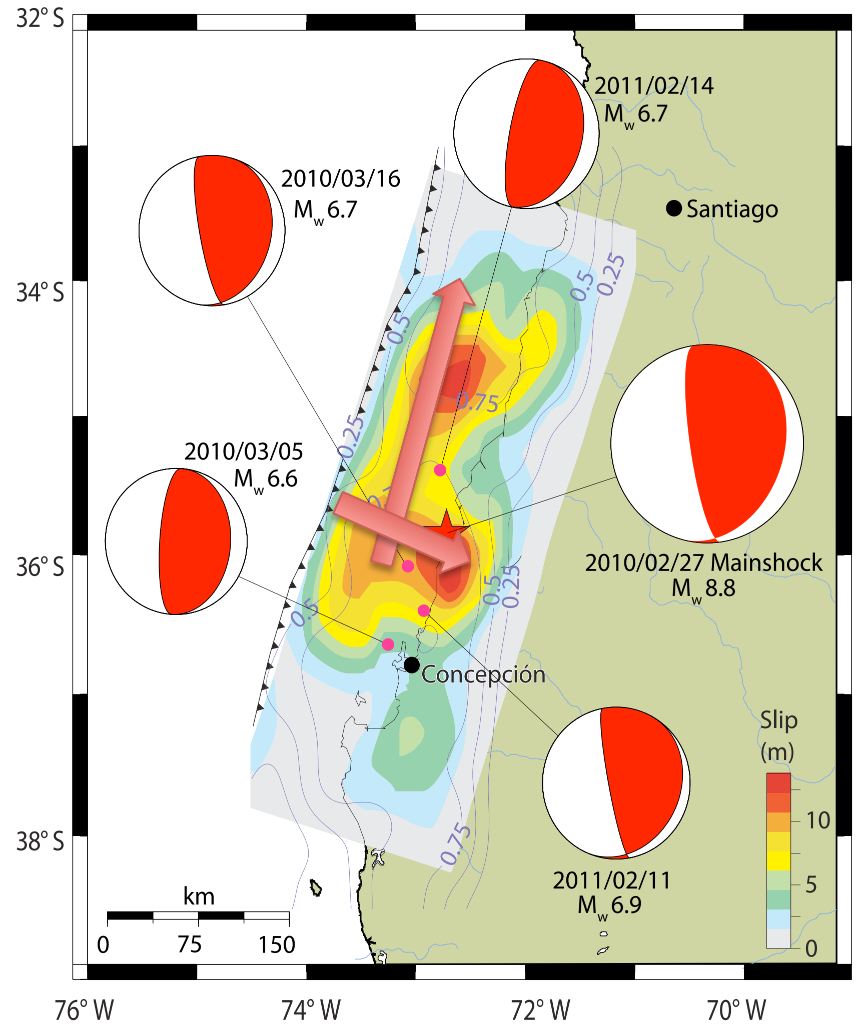
$E_s = 7.25 \times 10^{17}$ J $E_s/M_o = 1.1 \times 10^{-5}$ $\tau_a = 0.43$ MPa

Slip inversion from
Ammon et al, [2005]

Maule, Chile 2010 M_w 8.8

Source along strike with 50% of moment
Secondary down dip



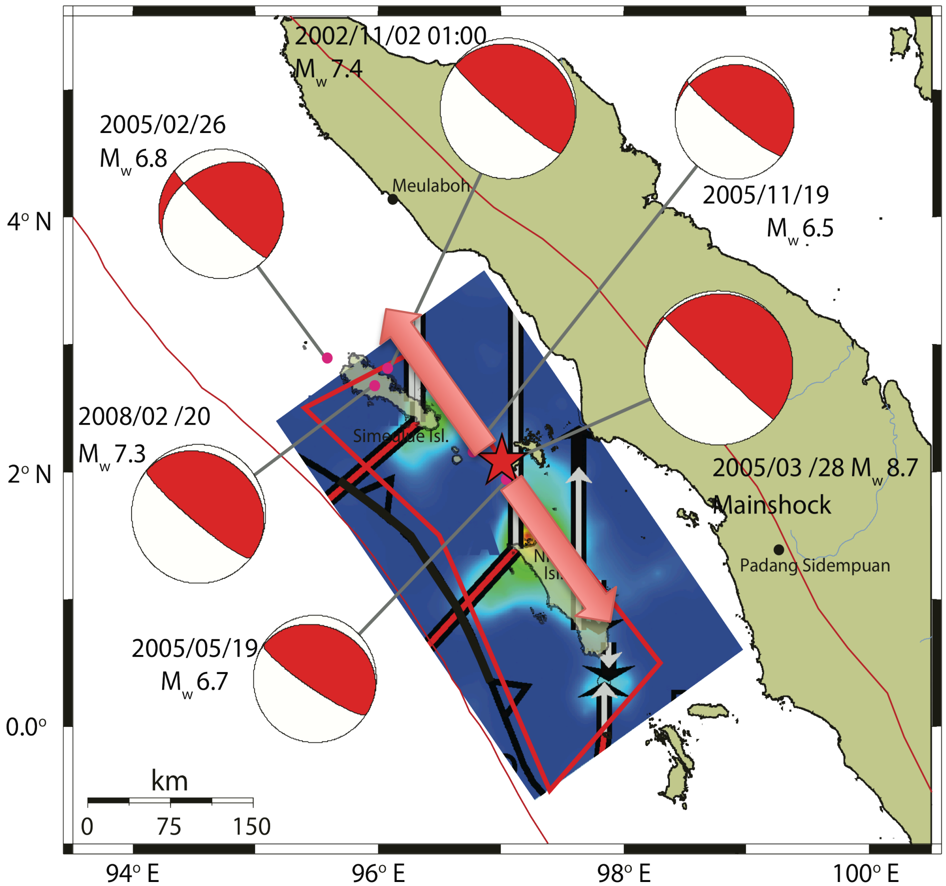


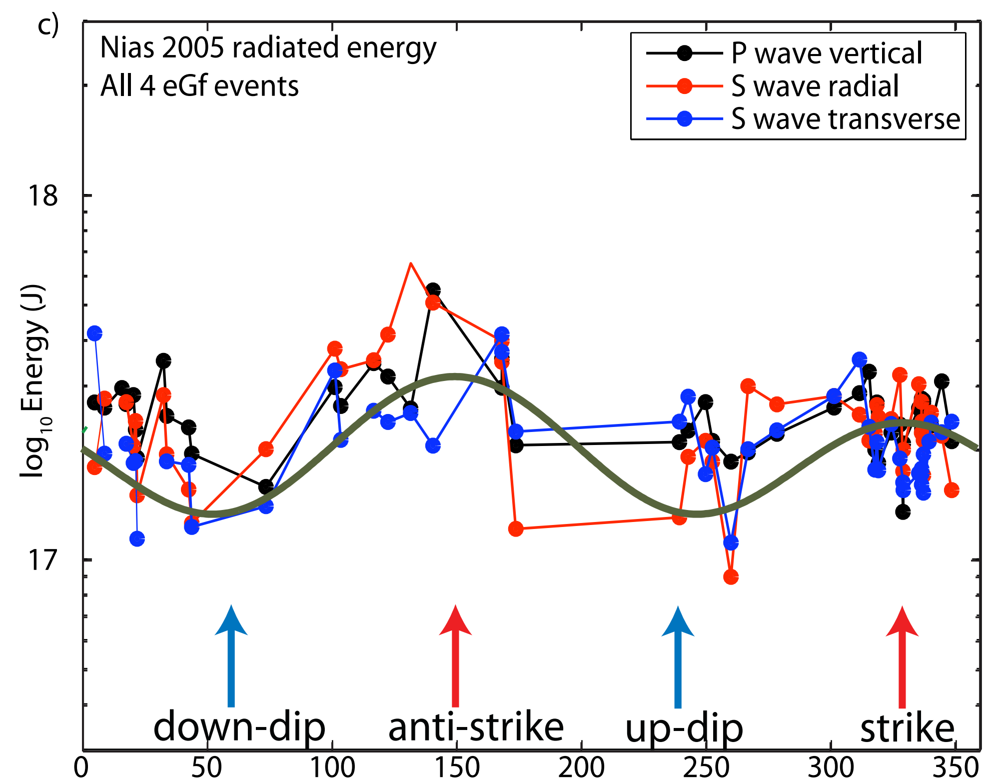
Mean from 4 egf events, 3 components, 35 stations

$E_s = 1.86 \times 10^{17}$ J $E_s/M_o = 1.0 \times 10^{-5}$ $\tau_a = 0.40$ MPa

Slip inversion from Hayes *2010*

Nias, Sumatra 2005 Mw 8.7





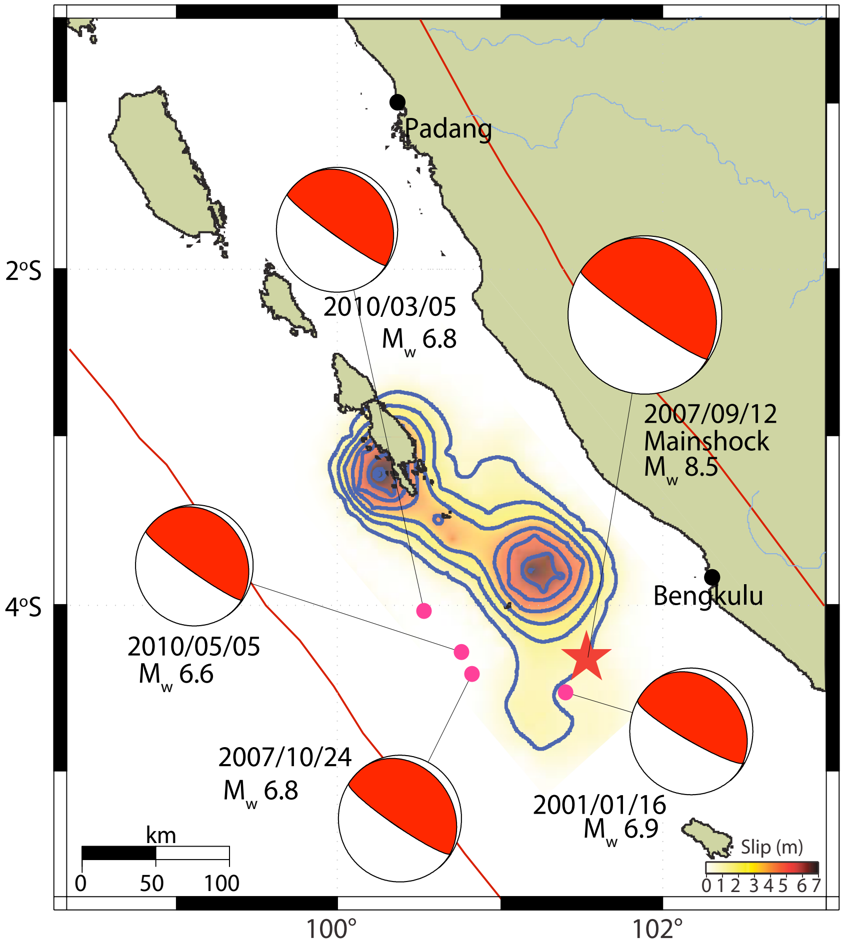
Bilateral rupture

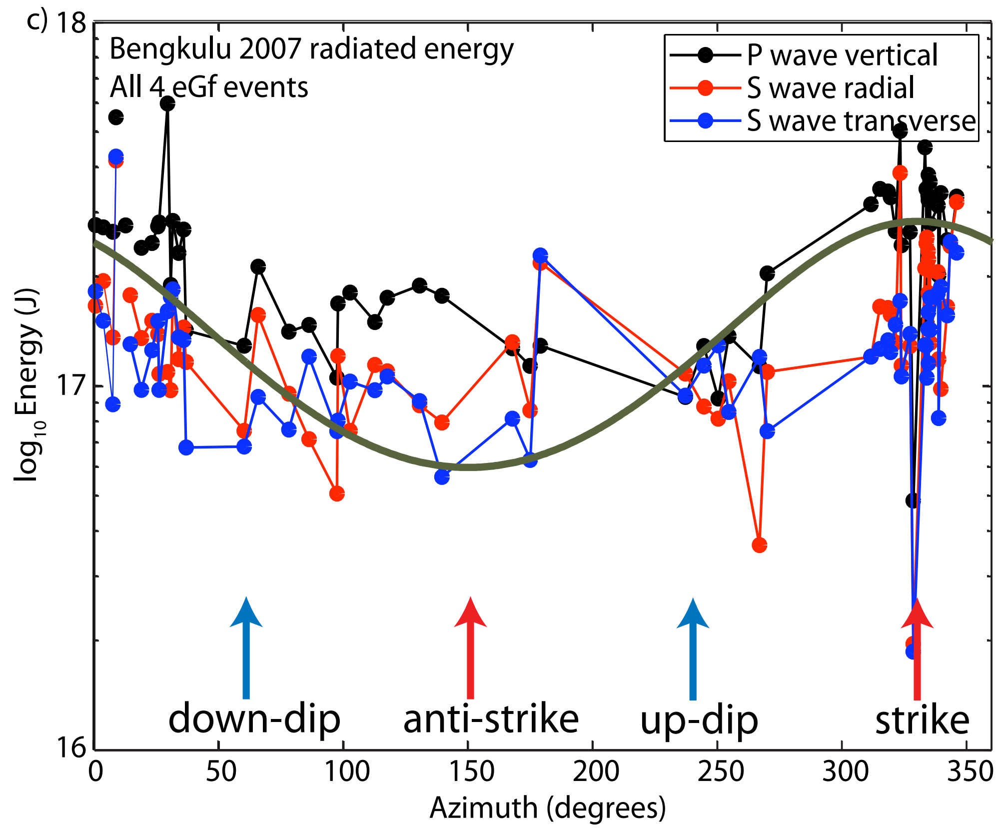
Mean from 4 egf events, 3 components, and 64 stations

E_s = 2.19 x10^{17} J E_s/M_o= 2.09 x 10^{-5} τ_a = 0.81 MPa

Slip inversion from
Konca et al. [2007]

Bengkulu, Sumatra, 2007 Mw 8.5



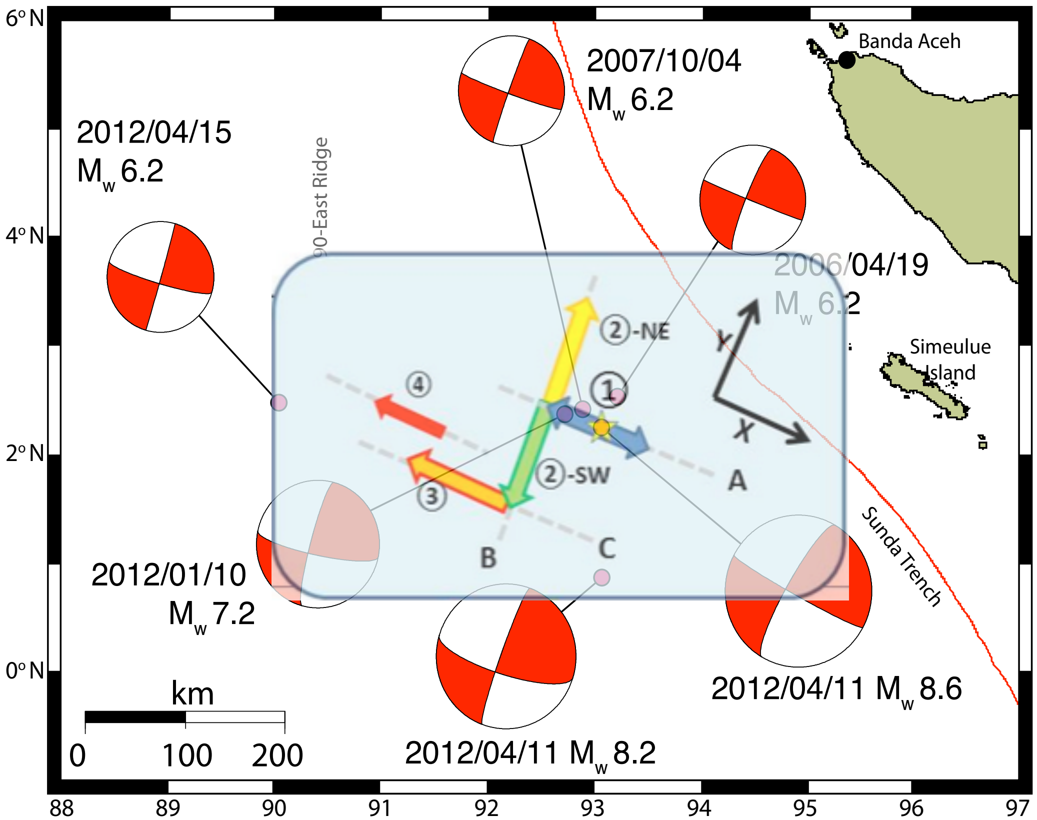


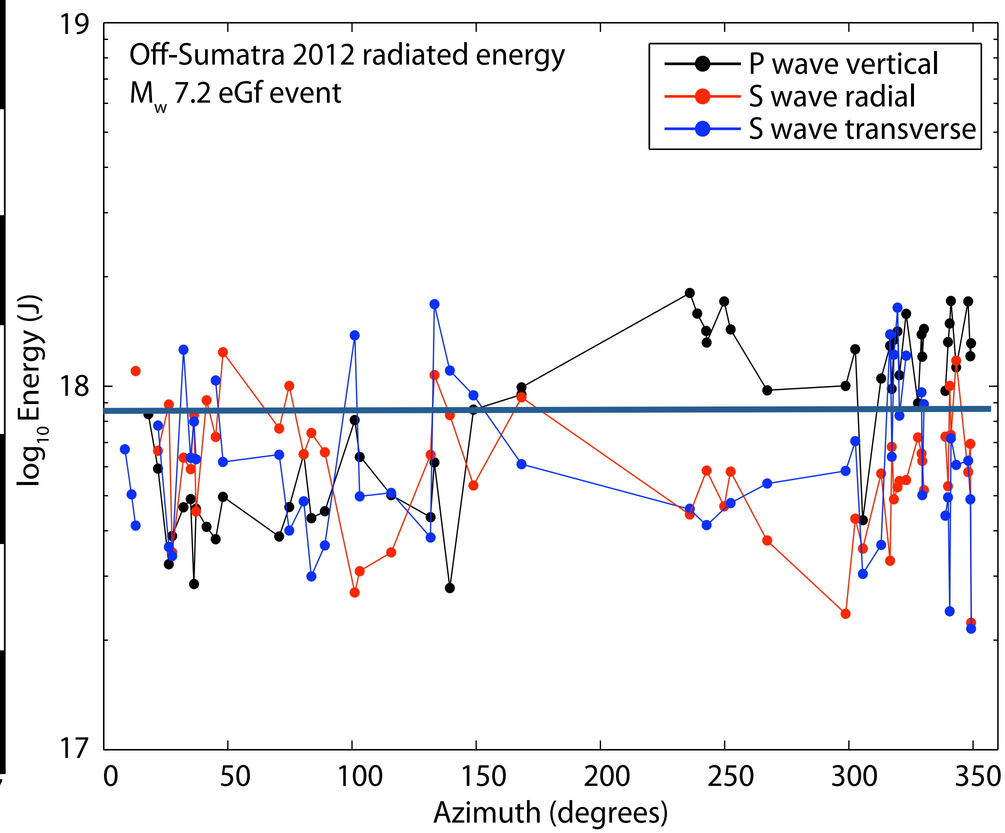
Mean from 4 egf events, 3 components, 57 stations

$E_s = 1.33 \times 10^{17}$ J; $E_s/M_o = 1.98 \times 10^{-5}$ $\tau_a = 0.77$ MPa

Slip inversion from *Konca et al.* [2008]

Off-Sumatra, 2012 Mw 8.6





Mean from largest egf, 3 components, 32 stations

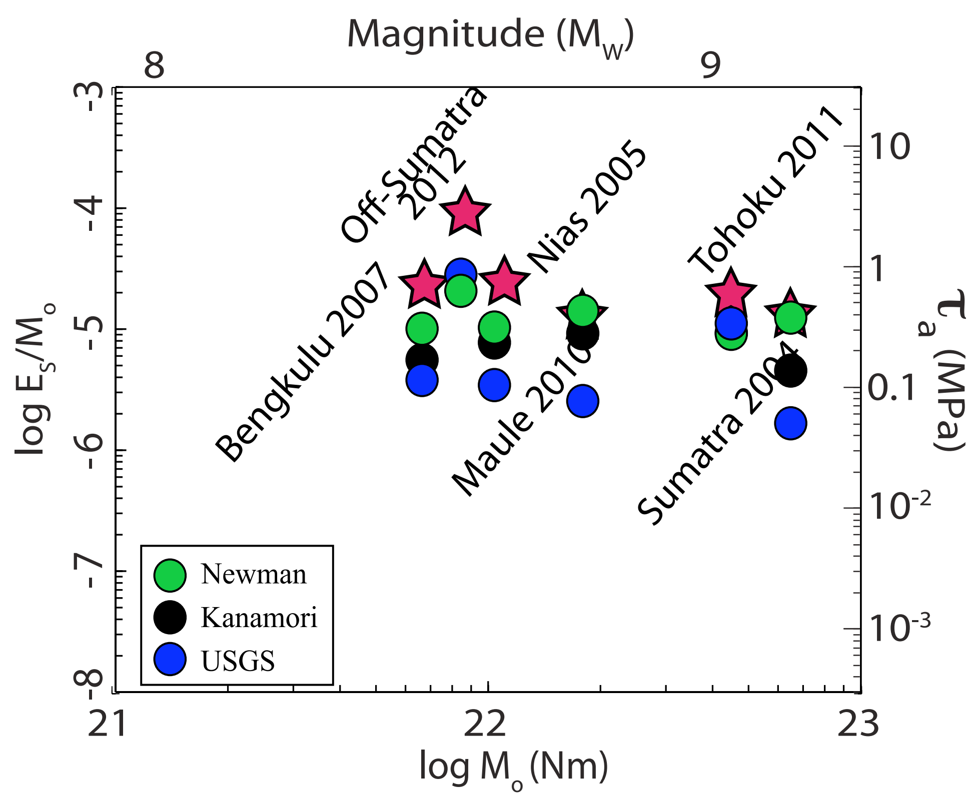
$E_s = 6.71 \times 10^{17}$ J; $E_s/M_o = 7.89 \times 10^{-5}$ $\tau_a = 3.07$ MPa

Greatest apparent stress of all great earthquakes

- Strike slip - Deep oceanic lithosphere

Slip inversion from
Meng, Ampuero and Luo, 2012

Great Earthquake Apparent Stress

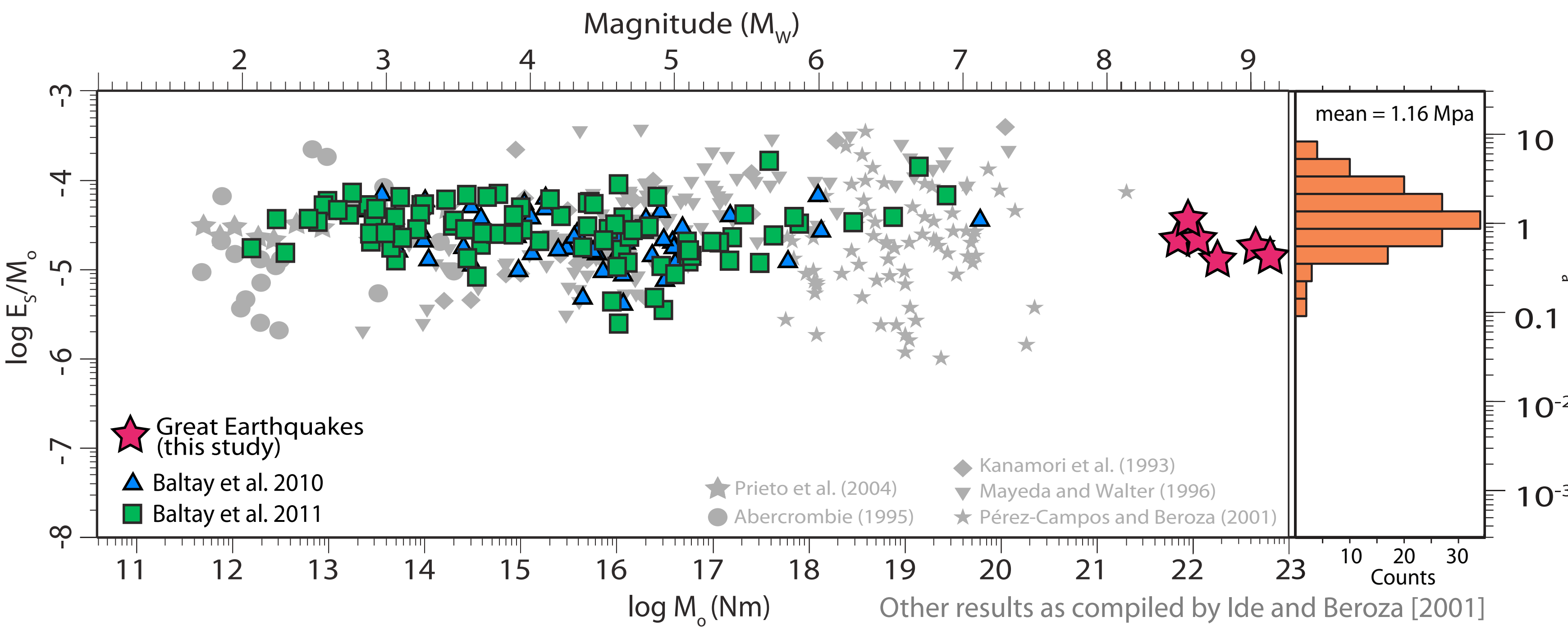


Event	Radiated Energy, E_R (Joules x10^{17})				E_R/M_o (x10^{-5})	τ_a (MPa)
	Newman	Kanamori	USGS[5]	This study		
Tohoku-Oki 2011	4.2[1]	4.3[3]	5.1	7.06	1.57	0.61
Sumatra 2004	8.2[2]	3.0[4]	1.1	7.25	1.12	0.43
Maule 2010	2.6[2]	1.7[3]	0.47	1.86	1.03	0.40
Nias 2005	1.1[2]	0.83[4]	0.37	2.19	2.09	0.81
Benkulu 2007	0.69[2]	0.38[3]	0.26	1.33	1.98	0.77
Off-Sumatra 2012	2.1[1]		2.7	6.71	7.89	3.07

Radiated Energy of Great Earthquakes

- Develop novel teleseismic eGf deconvolution method
- Can correct great earthquakes with ~ M 7 eGf events, despite complex rupture
- P and S waves give consistent results, comparable to other studies
- Overall radiated energy is a mixture of both high and low frequency radiation, and we can model some of this dependence through directivity with simple line sources and time dependent source inversions.
- Time dependent eGf source inversions would enlighten the azimuthal directivity further

Compiled Results



- EQs *M* ~2 to *M* ~9 have constant τ_α and no moment dependence
- τ_α ranges from 0.1 to 10 Mpa with mean ~ 1 Mpa, log-normal distribution

  $\Delta\sigma$ ranges from ~1 to 30 MPa, with mean ~ 6 MPa
- Considerable variability in $\Delta\sigma$ and τ_α is inherent source variability
- Supports self similar earthquake models