Temporal and spatial variations in earthquake source characteristics

Susan Bilek
Earth and Environmental Science Dept.
New Mexico Tech

w/ Heather DeShon, Bob Engdahl, Scott Phillips, Susan Schwartz, Andy Newman, Zhigang Peng, Jake Walter, and many others
Outline

• Observations of earthquake source parameter variations

• Earthquake source parameter review

• Examples in subduction zones
  – Global overview
  – Japan & Sumatra
  – Costa Rica & Nicaragua

• Connections with fault heterogeneity – can we define areas of fault that have earthquakes of similar properties?
New observations and analysis in recent ~15 years have taken us far beyond considering “normal” earthquakes.

Many scientific targets in Earth Science today relate to understanding behavior and controls on this slip spectrum.

Focus mostly here today, but also touch on transitions between groups.

Saffer et al., 2009
Depth dependence of high frequency seismic radiation

Evidence in large subduction zone ruptures – downdip part of fault has largely short-period radiation, updip part of fault has larger slip, but relatively weak short-period radiation

Lay et al, 2012, Koper et al., 2011, Ishii, 2011, and others
Subset of documented earthquakes are puzzles....

- Large tsunami generated, but not from “giant” earthquakes (M 9 2011 Tokohu event)

- Events have very long rupture durations, long-period magnitudes larger than short period magnitudes, deficient in high frequency seismic radiation

- Also tend to be very shallow slip... an important clue
**Tsunami Earthquake Slip**

Likely model for tsunami earthquakes:

- Large slip in *shallow* portion of subduction zone
- Long durations due to low rupture velocity
  - in shallow subduction zone – can easily have weaker (and heterogeneous) lithologies, heterogeneous (and low) friction, fluids to reduce $V_r$

![Diagram](https://via.placeholder.com/150)

_Satake and Tanioka, 1999_
Depth variation of rupture characteristics

Model of shallow subduction zone used to characterize several observations for earthquakes in subduction zones -- needed because of the wide variety of slip behaviors now observed

But....
Fault Zone Heterogeneity – Extends along strike

Variations in stress drop along Hayward fault, linked to strength variations (Hardebeck and Aron, 2009)

Stress drop for Japan trench earthquakes before 2011 Tohoku (Uchide et al., 2014)

Stress drop (blue high, red low) along one fault segment from 1992 Landers – variable along fault – inversely correlated with high slip (Shearer et al., 2006)
Fault Zone Heterogeneity – Extends along strike and in time

Spatial variations in stress drop along portion of San Andreas, with higher values in area of eventual 2004 M6 event

Low values of $\Delta \sigma$ in creeping section of fault

Indicative of fault variations?

Temporal variations – resolvable stress drop changes from before and after 2004 event

*Allmann and Shearer, 2007*
Variable $V_r$ within fault zone

Kiser and Ishii, 2011

Proposed segmentation and rupture velocity variations along 2010 Chile M 8.8 and 2011 Tohoku M 9 rupture zone

Kiser and Ishii, 2012
Tools for exploring source variations – using the seismic data

Far-field displacements related to time derivative of the moment tensor

In time domain, pulse width of displacement pulse related to rupture time of the earthquake, area under curve proportional to seismic moment ($M_o$)

Using displacement spectra, $f_c$ inversely proportional to $\tau$, often used to compute stress drop

Use seismic data, in time or frequency domain, to understand size and timescale of rupture, use to estimate stress drops and/or rupture velocities

Thanks Joan!
Global Survey of Earthquake Source Parameters

Focus on: Pulse width (Duration)

• Why?
  – Can be linked to rupture velocity or fault area
  – Using link to rupture velocity:
    • Long durations -- slower rupture velocity
    • Can link to fault properties that could lead to lower Vr
Source Parameter Determination

Use variety of techniques, including body wave and surface wave deconvolution; finite fault inversion results to determine source time function for all, plus slip distribution for larger events

Example Event: 2010 Sumatra
• 20 P waves, 12 SH waves
• fault plane grid of 25 km along strike, 40 km along dip
• subevent moment pulses of 5 overlapping triangles, 10 s duration

Results: concentrated slip patch near and updip of hypocenter, ~130 s long rupture (~16 s moment-normalized duration)
Earthquake Relocations

Work with Heather DeShon, Bob Engdahl, Maya El Hariri

Improved locations by using Engdahl et al. (1998) relocation techniques, including use of ak135 velocity model, first arriving P, S, PKP phases, depth phases

- Improved depth estimates using additional/revised depth phase arrivals determined using time picks based on power spectral density functions (DeShon et al., 2007)

Example of improvements:
Japan:
- 27% reduction in depth uncertainties for events
- 2x of events with depth phase arrival picks

From DeShon et al., 2007 (AGU)
Large Earthquake Results

698 events in 10 subduction zones
1989-2012
Mw 5.4-8
Normalized Duration: 0.3-16 s (median 4.25 s)
Depth: 5-61 km (median 25 km)

El Hariri et al., 2013, Bilek et al., 2011, 2012
2010 Sumatra tsunami earthquake

- Most recent tsunami earthquake (25 October 2010, mb=6.5, Ms=7.3, Mw=7.7)
- Tsunami caused peak run-ups of 2.5-9 m
- Over 400 fatalities
- Occurred in region south of 2004/2005 events, in region of past large earthquakes (1797, 1833, 2007)

Are there patches of the fault that consistently produce long-duration events?
Fault Plane: $M_o = 4.4 \times 10^{20}$ Nm $M_w = 7.7$
strike: $319^\circ$  Depth = $22$ km, Misfit = $0.39$
dip: $7^\circ$
rake: $98^\circ$

Use waveform modeling techniques to solve for moment-rate function (duration) and define high slip area for the tsunami event.
Aftershocks of 2010 event
- Majority are updip
- 2 have long normalized durations

Previous seismicity
- 2 events (2005, 2007) have long durations, occur at northern edge of 2010 rupture zone

Region of 1907 tsunami earthquake
- 2 events with long durations
- Boundary between 2004 and 2005 great earthquakes where Dean et al. (2010) suggest change in decollement and lowermost sediment properties

Results have implications for possible spatial distribution of slow slip, temporal stability of fault zone conditions

Bilek et al., 2011
• Concentration of long duration events in 1896 tsunami earthquake zone
Comparison with 2011 Tohoku slip distribution:

- Longest duration event occurred 1 day prior to mainshock in area of moderately high slip

- Aftershocks scattered throughout without much overlap in high slip zone

- No clear trend of short duration events only at downdip end of slip zone (as might be expected in downdip source of high-frequency radiation)
Source duration is highly variable along the Central America margin, with several regions of significantly long duration events.
Geologic conditions – complex
How does this heterogeneity affect earthquakes/slip?
Costa Rica – Nicoya Peninsula

Complex tremor and slow slip patterns – both updip and downdip tremor and SSE

Ide (2012) suggests tremor patches linked to subducted structures – spatial heterogeneity of incoming plate important for tremor processes

Zhang et al. (2011) suggests tremor have very low stress drops (few kPa)
Complex tremor and slow slip patterns – both updip and downdip tremor and SSE

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Time periods:
Osa: 1999 (3 months, 114 events)
Nicoya: 2012 (Sept 5-Oct 2, 1054 events)
1999-2001 (73 events)

Total Events: 1241
Magnitude range: 1.5-5
Stations: Mix of 3 component BB and SP land, OBS
Source Parameter Methods – Event Clustering and Envelopes

Determine event clusters within narrow depth bins with at least 3 events per cluster

For each event within a cluster, combine horizontal components and compute envelopes at specific narrow frequency bands
Methods – Envelope Measurements and Spectral Ratios

For event pairs, difference log of envelope amplitudes where amplitudes are greater than noise level

Fit an $\omega^2$ Brune source model to the ratios, finding $M_o$ and $f_c$ for each event pair

Compute stress drop ($\Delta\sigma$) using $M_o$ and $f_c$, and

$$f_c = cv\left(\frac{\Delta\sigma}{M_0}\right)^{\frac{1}{3}}$$

$c$ constant related to phase type, geometry
$v$ source medium velocity

Method modified from *Fisk and Phillips*, BSSA, 2013
Variations along-strike, with generally higher (and more heterogeneous values) along the Nicoya Peninsula relative to Quepos Plateau region.

No obvious depth trends.
• Majority of events in coseismic area fall within expected range of $\Delta\sigma$ (0.1-1 MPa)
  • median 0.32 MPa, mean 0.97 MPa

• Overall mean and median $\Delta\sigma$ in seamount region (rough plate) similar to those in 2012 coseismic region (smoother plate)
  • median 0.35 MPa, mean 1.06 MPa

• $\Delta\sigma$ higher for older events than 2012 aftershocks
  • median 0.66 MPa, mean 1.4 MPa
  • Possible temporal variations? (caveat – small numbers of previous events 73 vs 1000+)
"Regular" earthquake stress drops - co-located with tremor

Costa Rica (preliminary):
Tremor not occurring in area solely marked by very low stress drop "regular" earthquakes (Zhang et al. (2011) suggested Cascadia comprised of v. low stress drop events)

• but need to explore the other tremor areas in Costa Rica
Comparisons with Plate Coupling and Coseismic Slip

Are there any differences linked to plate coupling or seismic slip?

Dense GPS network led to maps of seismic coupling prior to 2012 earthquake

Feng et al., 2012
Within 2012 $M_w$ 7.6 event region, detailed geodetic models suggest significant variation in geodetic coupling that links partially to area of coseismic slip during the 2012 event, prompts questions/concerns about updip locked patch that did not slip in 2012.
Comparisons with Plate Coupling and Coseismic Slip

Are there any differences possibly linked to plate coupling or seismic slip?

Focus on observations within 3 key subsets in/near the 2012 rupture zone along Nicoya Peninsula.
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Comparisons with Plate Coupling and Coseismic Slip

Are there any differences linked to plate coupling or seismic slip?

- Within high slip, strongly coupled zone, higher median $\Delta \sigma$ relative to adjacent areas
- Stress drop is similar in the no-slip sections of fault, regardless of geodetic coupling

From Bilek et al., 2014 (SSA)

From Protti et al., 2014
Comparisons with Plate Coupling and Coseismic Slip

Are there any differences linked to plate coupling or seismic slip?

- Implications/Questions:
  - What is difference between strong and weak coupled areas?
  - Is area highlighted as region of concern (strong coupling, no slip) more similar to downdip or adjacent region?

$\log_{10} \Delta \sigma$ (MPa)

Median: 0.4 MPa
Mean: 1.1 MPa,

Median: 0.2 MPa
Mean: 0.8 MPa,

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From Protti et al., 2014

Bilek et al, 2014 (SSA)
Concentration of long duration events (M 5.5-7) in area of 1992 tsunami earthquake, although at the downdip end of the 1992 rupture zone.
• Δσ significantly lower to north, within rupture area of the 1992 tsunami earthquake
• Implications/Questions:
  – Is tsunami earthquake zone distinctly different from other parts of the megathrust?
  – Can these small earthquakes map out these anomalous regions?
Some Complexity Required!

- Earthquake source parameter variations can be used as probes for the fault heterogeneity
- Source parameters can map out areas of variable fault conditions
  - important for tsunami and shaking hazards
- Variety of earthquake magnitudes useful for probing at different scales
  - Important for understanding transitions between different slip behaviors
Thank You!