“The Slow and the Fast Ends of the Earthquake Spectrum”

Greg Beroza (Dept. of Geophysics, Stanford University)
“The Slow and the Fast Ends of the Earthquake Spectrum”

Greg Beroza (Dept. of Geophysics, Stanford University)
Earthscope Institute on the Spectrum of Fault Slip

Hare:
  Motion is fast
  Infrequent, unpredictable activity
  Frictionally locked

Tortoise:
  Motion is slow
  Frequent, predictable activity
  Transitional frictional properties

“The Slow and the Fast Ends of the Earthquake Spectrum”

Greg Beroza (Dept. of Geophysics, Stanford University)
The recent discovery of a continuous spectrum of faulting behavior, ranging from conventional earthquakes that rupture at great speeds (including supershear velocities) to “slow earthquakes” that involve anomalously slow ruptures—some so slow that the sliding motion does not radiate detectable seismic waves or is manifested in seismic tremor—has unified seismic and geodetic monitoring of fault zones and may have fundamental importance for frictional sliding processes and earthquake hazard.
SOME CHARACTERISTICS OF “REGULAR” EARTHQUAKES

Rupture at ~70-90% of the S-wave velocity

Constant stress drop of 3-5 MPa

Self-Similar Scaling $M_0 \sim L^3$

Scaled energy $(E_S/M_0) \sim 5 \times 10^{-5}$
SOME CHARACTERISTICS OF "REGULAR" EARTHQUAKES

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12/26/2003 M 6.6 Bam, Iran, 30,000+ fatalities, ~80% of buildings destroyed

Sub-Shear Rupture at ~ Rayleigh wave velocity leads to strong directivity.

Bouchon et al. [2006]
THE FAST END OF THE EARTHQUAKE SPECTRUM

Two Kinds of “Fast”:

High Slip Rate - High Stress Drop

High Rupture Velocity - Supershear Rupture
Stress Drop

\[ f_c \sim M_0^{-1/3} \]

Allman and Shearer [2009]
Stress Drop

![Graph showing stress drop distribution with mean: 3.36 MPa, median: 3.34 MPa, and 875 events.](image)

Allman and Shearer [2009]
Stress Drop

Is there a population of high stress drop earthquakes?

Allman and Shearer [2009]
Stress Drop

Allman and Shearer [2009]
Scaled Seismic Energy ($E_s/M_0$)

No systematic variation of scaled energy with earthquake size.

*Ide and Beroza (2001)*
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Scatter in Scaled Energy

Baltay et al. [2010]
Scatter in Scaled Energy

“Low Energy” event
Chuetsu 2004
Mw 5.1

“High Energy” Earthquake
Kamaishi main event
Mw 4.7

Baltay et al. [2010]
Low Energy Earthquake

Chuetsu 2004
Mw 5.1

“Regular” Event
Mw 5.3
same station
within 10 km

Baltay et al. [2010]
Low Energy Earthquake

Chuetsu 2004
Mw 5.1

• Depleted in high frequencies

“Regular” Event
Mw 5.3
same station
within 10 km

0.05 to 0.1 Hz

0.15 to 0.5 Hz

0.5 to 1 Hz

5 to 10 Hz

Baltay et al. [2010]
High Energy Earthquake

Kamaishi main event
Mw 4.7
• Enriched in high frequencies

“Normal” Event
Mw 4.8
same distance

0.05 to 0.1 Hz

0.5 to 1 Hz

5 to 10 Hz

10 to 20 Hz

Baltay et al. [2010]
At Least some of Scatter in $E_s/M_0$ is real

Baltay et al. [2010]

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Earthquake Size-Duration Scaling

Ide et al. [2007]

Monday, November 1, 2010
Earthquake Size-Duration Scaling

Ide et al. [2007]

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SUPER-SHEAR RUPTURE

Rupture Velocity and Directivity:
Most important finite-source effect

Mode II

Mode III

\[ v_r < c_s \quad \text{and} \quad v_r > c_s \]

Rayleigh wave (surface/interface)
S wave (shear)
P wave (dilatational)

Dunham

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## Super-Shear Rupture

<table>
<thead>
<tr>
<th>Year</th>
<th>Magnitude</th>
<th>Location</th>
<th>References</th>
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<tbody>
<tr>
<td>1906</td>
<td>M 7.9</td>
<td>San Francisco</td>
<td>Song et al. [2008]</td>
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<tr>
<td>1979</td>
<td>M 6.5</td>
<td>Imperial Valley</td>
<td>Archuleta [1994]</td>
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<td></td>
<td></td>
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<td>Spudich and Cranswick [1994]</td>
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<td>1999</td>
<td>M 7.6</td>
<td>Izmit</td>
<td>Ellsworth and Celebi [1999]</td>
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<td></td>
<td></td>
<td></td>
<td>Bouchon et al. [2000]</td>
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<tr>
<td>1999</td>
<td>M 7.2</td>
<td>Duzce</td>
<td>Bouchon et al. [2001]</td>
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<tr>
<td>2001</td>
<td>M 7.8</td>
<td>Kunlun</td>
<td>Bouchon and Vallee [2003]</td>
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<td>2002</td>
<td>M 7.9</td>
<td>Denali</td>
<td>Ellsworth et al. [2004]</td>
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<td></td>
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<td></td>
<td>Dunham and Archuleta [2004]</td>
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<td></td>
<td></td>
<td></td>
<td>Aagaard and Heaton [2004]</td>
</tr>
</tbody>
</table>

All are large strike-slip earthquakes.
SUPER-SHEAR RUPTURE

Particle Velocity Field Surrounding a Supershear Slip Pulse ($v_f=1.6c_s$)

(a) Data and Synthetic Seismograms

- Fp velocity (m/s)
- Fn velocity (m/s)

(b) Slip Velocity on Fault Plane

- Secondary slip pulse ($v_f<c_s$)
- Supershear rupture

Dunham and Archuleta [2004]

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Super-Shear Rupture

Vallee et al. [2008]

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SUPER-SHEAR RUPTURE

Consequences for strong ground motion

Vallee et al. [2008]

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Some Fast Earthquake Questions

Are there large, very high stress drop earthquakes?

Is super-shear rupture exceptional, or typical, for large strike-slip earthquakes?

Does super-shear rupture occur for other earthquake types?

Why isn’t super-shear rupture more obvious?
Why not stronger high-frequency ground motion?
Where are the Mach fronts?
Earthquake Size-Duration Scaling

Ike et al. [2007]

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Deep Non-Volcanic Tremor

Obara [2002]
Low Frequency Earthquakes

~1 s duration

Katsumata and Kamaya [2003]
Importance of Improved Monitoring

Beroza and Ide [2011]
Importance of Improved Monitoring

Beroza and Ide [2011]
Importance of Improved Monitoring

Beroza and Ide [2011]
Tremor matches LFEs (red)

Can locate tremor precisely

Shelly et al. [2007a]

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LFEs Allow us to Examine Tremor in Detail

Shelly [2007b]
Very Low Frequency Earthquakes (Shallow)

Obara and Ito [2005]; Ito and Obara [2006a,b]
Very Low Frequency Earthquakes (Deep)

~10 s duration

Ito et al. [2007]
Very, Very Low Frequency Earthquakes

~100 s duration

Ide et al. [2008]
Slow Slip Events

Dragert et al. [2001]

days-years duration

Miller et al. [2002]
Various slow earthquakes: LFEs, VLFs, SSEs occur in synchrony.

Beroza and Ide [2011]
Earthquake Size-Duration Scaling

LFEs/Tremor 1 s M 1.0-2.0
VLFs 10-100 s M 3.5-4.5
SSEs $10^5$-$10^8$ s M 6.0-7.5

_Ide et al. [2007]_
Earthquake Size-Duration Scaling

LFEs/Tremor 1 s M 1.0-2.0
VLFs 10-100 s M 3.5-4.5
SSEs $10^5$-$10^8$ s M 6.0-7.5

Ide et al. [2007]
Very Slow Slip Events

If moment-duration scaling of slow earthquakes is extended to $M > 8$, then duration could be decades and slow earthquakes might be expressed as partial coupling, rather than an aseismic deformation transient.

Meade and Loveless [2009]
Geography of Slow Earthquakes

Beroza and Ide [2011]
Geography of Slow Earthquakes

![Map showing the geography of slow earthquakes with labels for Tremor, SSE, and Megathrust.](Beroza_and_Ide_2011)

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Geography of Slow Earthquakes

Beroza and Ide [2011]
Geography of Slow Earthquakes

Beroza and Ide [2011]
If Tremor Limns the Edge of the Locked Zone in Cascadia, then Transition is Farther East than Thought

Chapman and Melbourne [2009]
Higher Hazard in Cascadia?
Geography of Slow Earthquakes

SSEs but no tremor

Beroza and Ide [2011]
Geography of Slow Earthquakes

SSEs and tremor disjunct

Beroza and Ide [2011]
Geography of Slow Earthquakes

Tremor and large earthquake slip intermingled

*Beroza and Ide [2011]*
Observational Gap: Much of the World is Effectively Unmonitored

Where else do slow earthquakes occur?  

*Beroza and Ide [2011]*
Observational Gap: Between Seismology and Geodesy

Also, if LFEs occur in isolation they will be difficult to detect.
Tremor Occurs on the Deep Extension of Faults

Brown et al. [2009]
Shear failure to ~25 km? If so, fault likely to slip coseismically in large events at this depth.
Almost all “deep” events (yellow) happen in 2 years after 1984 Morgan Hill earthquake.

Similar behavior after 1992 Landers earthquake

(Schaff et al., 2002)
Slow Earthquakes Occur in a “Strategic” Location

Tremor will accelerate loading of the locked zone. Is there a correlation of tremor with earthquakes?
Strong Tidal Response

Much more sensitive to stress than earthquakes: Will behavior change before a large event?

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SOME SLOW EARTHQUAKE QUESTIONS

What makes earthquakes slow? How can we get swarms of 10s of thousands of LFEs without it growing into something larger?

What is relationship between slow earthquakes and fast earthquakes? What is the relationship of tremor zone to megathrust rupture?

What is temporal relationship between slow earthquakes and fast earthquakes? Do slow earthquakes trigger fast earthquakes?
What can we learn about the base of the seismogenic zone from slow earthquakes?
Some Slow Earthquake Questions

What are conditions under which slow earthquakes occur?

Association of slow earthquakes and creep? Are slow earthquakes of various kinds happening all over the place, but going unrecognized?

What controls occurrence of spontaneous vs. triggered tremor?