Observing and modelling the spectrum of a slow slip event
A single fault zone process for slow earthquakes?

Jessica Hawthorne (Oxford)
Noel Bartlow (Berkeley)

Tremor migration: Peng and Rubin; VLFEs: Yabe and Ide, 2014
- How do these events contribute to moment rate variations?
- What do they imply about the underlying physical processes?
Slow slip in Cascadia

- 1 month long, M 6.5 - 6.9, about 1 per year
- Slip rates $10^{-7} – 10^{-6} \text{ m/s}$, 100 to 1000 times plate rate

So which fault zone processes control these slip rates?
What could limit slow slip slip rates?

**A limit on frictional weakening from minimum asperity size**

- **Shear-induced fluid pressure drops, via dilatancy or fracture**
  - Shibazaki and Iio, 2003; Hawthorne and Rubin, 2013

**Mix of brittle and viscous deformation**

- Lavier et al, 2013; Fagereng et al, 2014; Behr et al, 2018

**Slip rate (m/s)**

- $10^{-9}$
- $10^{-6}$
- $10^{-3}$
- $1$

**Frictional strength**

- $1.05$
- $1$
- $0.95$

Liu and Rubin, 2010; Segall et al, 2010; Moore and Piazolo, in review
<table>
<thead>
<tr>
<th>Proposed mechanism</th>
<th>Creates slow earthquakes?</th>
<th>Creates abundant events?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum asperity size</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Shibazaki and Iio, 2003; Hawthorne and Rubin, 2013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brittle and viscous deformation</td>
<td>yes</td>
<td>yes?</td>
</tr>
<tr>
<td>Lavier et al, 2013; Fagereng et al, 2014; Behr et al, 2018;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear-induced fluid pressure changes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Liu and Rubin, 2010; Segall et al, 2010; Moore and Piazolo, in rev.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Borehole strain-based observations of heterogeneity

To first order, strain rate / mean = moment rate / mean

How many physical processes have been shown to reproduce these moment rate bursts?
<table>
<thead>
<tr>
<th>Proposed mechanism</th>
<th>Creates slow earthquakes?</th>
<th>Predicts abundant events?</th>
<th>Complexity on simple faults?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimum asperity size</strong></td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Shibazaki and Iio, 2003; Hawthorne and Rubin, 2013</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Brittle and viscous deformation</strong></td>
<td>yes</td>
<td>yes?</td>
<td>no?</td>
</tr>
<tr>
<td>Lavier et al, 2013; Fagereng et al, 2014; Behr et al, 2018;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Shear-induced fluid pressure changes</strong></td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Liu and Rubin, 2010; Segall et al, 2010; Moore and Piazolo, in rev.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Models appear too stable to allow heterogeneity on simple faults
→ Fault networks are complex

**But how can we measure and assess the heterogeneity?**
A spectrum of slow earthquakes

Slow slip: a specific fault zone process
Tremor: low-stress drop earthquakes

or

A continuum of slow slip events of different sizes
Where smaller events are faster!?

After Ide et al, 2007; Gao et al, 2012
Could we reproduce this variability with a collection of subevents?

strain rate / mean = moment rate / mean

(a) steady background rate
(b) many small, short subevents
(c) some intermediate subevents
(d) few large, long subevents
(e) total event

+ 6 hours

strain rate / mean = moment rate / mean

time (days)
Could we reproduce this variability with a collection of subevents?

Need to choose
- Number of events of each moment
- Relationship: moment $\sim$ duration$^m$
Modelled moment rate spectrum

- steady background rate
- many small, short subevents
- some intermediate subevents
- few large, long subevents
- total event

coherent stack at long periods
periods close to event duration
subevents distributed in time, but all contribute flat spectra
composite of subevent sizes and spectral shapes

power \sim frequency^{-m}
where subevent moment \sim duration^m
large m
\rightarrow Short events small
\rightarrow Little high-frequency power
How would our geodetic moment rate observations reflect subevents?

Can estimate amplitude of moment rate variability on a range of timescales.
Observed moment rate spectrum

- Decays as frequency$^{-1}$ at high frequencies
Modelled moment rate spectrum

- Data decays as frequency\(^{-1}\)

To match a frequency\(^{-1}\) decay, need \(m=1\), consistent with the proposed continuum scaling
Slow slip and tremor: 1 continuum, 1 physical process?

After Ide et al, 2007; Gao et al, 2012

Moment rate variability consistent with a single continuum of slow earthquakes with moment ∼ duration

Which processes could produce a continuum where small events are faster?
<table>
<thead>
<tr>
<th>Proposed mechanism</th>
<th>Creates slow earthquakes</th>
<th>Predicts abundant events</th>
<th>Complexity on simple faults?</th>
<th>Size-dependent slip rates?</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minimum asperity size</strong></td>
<td></td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Shibazaki and Iio, 2003; Hawthorne and Rubin, 2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Brittle and viscous deformation</strong></td>
<td></td>
<td></td>
<td>via fault viscosity</td>
<td></td>
</tr>
<tr>
<td>Lavier et al, 2013; Fagereng et al, 2014; Behr et al, 2018;</td>
<td></td>
<td></td>
<td>via fault width</td>
<td></td>
</tr>
<tr>
<td><strong>Shear-induced fluid pressure changes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liu and Rubin, 2010; Segall et al, 2010; Moore and Piazolo, in rev.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Slow earthquakes come in a range of sizes and durations.

Moment rate spectra are consistent with a single continuum of slow earthquakes.

The continuum would:
- exclude several physical processes
- could indicate size-dependent shear zone properties
GPS-based observations of slow slip heterogeneity

Bartlow et al, 2011
<table>
<thead>
<tr>
<th>Proposed mechanism</th>
<th>Creates slow earthquakes?</th>
<th>Predicts abundant events?</th>
<th>Complexity on simple faults?</th>
<th>Size-dependent slip rates?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum asperity size</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Shibazaki and Iio, 2003; Hawthorne and Rubin, 2013</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brittle and viscous deformation</td>
<td>yes</td>
<td>yes</td>
<td>no?</td>
<td>via fault viscosity</td>
</tr>
<tr>
<td>Lavier et al, 2013; Fagereng et al, 2014; Behr et al, 2018;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear-induced fluid pressure changes</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>via fault width</td>
</tr>
<tr>
<td>Liu and Rubin, 2010; Segall et al, 2010; Moore and Piazolo, in rev.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frictional weakening and strengthening patches</td>
<td>yes</td>
<td>no</td>
<td>no?</td>
<td>via v-s fraction</td>
</tr>
<tr>
<td>Skarbek et al, 2012; Luo and Ampuero, 2017; Yabe et al, 2017</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size-limited weakening areas?</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Liu and Rice, 2007; Rubin, 2008; Skarbek et al, 2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fluid addition to viscous</td>
<td>yes</td>
<td>yes</td>
<td>??</td>
<td>??</td>
</tr>
</tbody>
</table>
Slow earthquake complexity: hours-long sub-ruptures

Rupture speeds 10 to 50 times faster than main event
Option 1: Clusters of brittle failures

- Whole slipping area: small brittle fraction $\rightarrow$ low slip rate
- Upper half: moderate brittle fraction $\rightarrow$ moderate slip rate
- Smaller clusters: higher brittle fraction $\rightarrow$ higher slip rate
- Smallest clusters: highest brittle fraction $\rightarrow$ highest slip rate

Fagereng et al, 2014
Option 1: Clusters of brittle failures

Larger stress drops in smaller, faster events?
Option 1: Clusters of brittle failures

But we don’t infer high stress drops from strain observations of hours-long RTRs, even though slip rates are 5 times higher.

Peng and Rubin, 2016

Hawthorne et al, 2016
Option 2: Size-dependent fault properties

Smaller shear zones have lower viscosities?

Fagereng et al, 2014

![Image showing shear zones and viscosity-slip rate relationship](image.png)

- tremor
- slow slip

**Graph:**
- Slip rate (m/s) vs. viscosity (Pa s)
- Log-log scale
- Data points and trend line indicate a correlation between shear zone size and viscosity.
Option 2: Size-dependent fault properties

- Smaller faults are narrower?

→ Faster fluid diffusion?
Slow slip and tremor in Cascadia

Slow slip: transient aseismic slip
- 1 month long, M 6.5 - 6.9
- Slip rates $10^{-7} - 10^{-6}$ m/s,
  100 to 1000 times plate rate

Tremor: many small but slow earthquakes
- Mostly 0.5 seconds long, $M$ 1 – 2.5
- Slip rates probably $10^{-4}$ to $10^{-3}$ m/s
- 10 to 1000 times slower than most seismic wave-limited earthquakes

So which fault zone processes control these slip rates?
What about tremor’s characteristic durations?

Within in the tremor band, duration appears independent of moment

→ Tremor is different from slow slip?
→ Slow earthquakes occur on asperities, and we’ve only identified some of them?

Bostock et al, 2015

Stacks of LFEs with

- $M < 1.5$
- $M > 2$
What about tremor’s characteristic durations?

Within in the tremor band, duration appears independent of moment  (Bostock et al, 2015)

→ Tremor is different from slow slip?  
→ Slow earthquakes occur on asperities?

identified 0.5-s long tremor LFEs

unidentified 1-s long slip events
Is tremor really fast enough to be an earthquake?

Does it rupture at near-shear wave speeds?

LFE durations in Parkfield: 0.2 S (Thomas et al, 2016)

To estimate rupture extent, look for seismic waves generated at a range of locations

- Inter-station differences visible only at high frequencies, at seismic wavelengths shorter than D
Inter-station coherence

seismic wavelength (m)

frequency (Hz)

inter-station coherence

$P_d/P_c$: directly coherent

$P_d/P_c$: inter-station coherent
Allowable diameters and rupture speed

Matches LFE durations

Matches coherence for one LFE family

Matches coherence for both LFE families

\[ \text{rupture speed / shear wave speed} \]

→ LFEs are probably slow
Option 1: Clusters of brittle failures

- Stress drops okay, but hard to tune

The diagram illustrates the relationship between stress in the strengthening region and slip rate weakening fraction, highlighting the transition from slow slip to tremor as subevents begin and end.
Mixed frictional weakening and strengthening: too hard to tune?

Yabe and Ide, 2017
Mixed frictional weakening and strengthening: too hard to tune?

Yabe and Ide, 2017

Skarbek et al, 2012
Characteristically sized velocity-weakening segment: too hard to tune?

Large enough for acceleration, too small for instability?  
Liu and Rice, 2005, 2007

Rubin, 2008

slow slip region size / $h^*$

slip rate / plate rate

velocity-weakening slow slip region
Slow slip and tremor: 2 processes or 1 continuum?

Moment rate variability consistent with a single continuum of slow earthquakes with moment $\sim$ duration.

After Ide et al, 2007; Gao et al, 2012
Slow slip and tremor in Cascadia

Tremor: numerous small but slow earthquakes
• Mostly 0.5 seconds long, 10 to 100 times longer than normal $M 1–2.5$ earthquakes
• Slip rates probably $10^{-4}$ to $10^{-3}$ m/s

So which physical processes control these slip rates?

Boyarko et al, 2015
What limits earthquake slip rates?

Seismic waves

Seismic waves

3 km/s

1 m/s

before during after
Do seismic waves limit slow slip speeds?

frictional weakening = elastodynamic stress?
stress drop = $G \frac{V_{\text{slip}}}{V_{\text{shear}}}$?

<table>
<thead>
<tr>
<th>slip rate (m/s)</th>
<th>slow earthquake stress drops</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-9}$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^{-6}$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>1</td>
<td>$10^9$</td>
</tr>
</tbody>
</table>

No, slow slip is too slow.
But tremor *might* be fast enough.
Abundant slow earthquakes