In situ conditions and the mechanics of slow earthquakes along subduction megathrusts: Insights from laboratory experiments

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Spectrum of Fault Slip & Slow Earthquake Phenomena:

- Longer source duration for given magnitude than “normal” earthquakes
- Tend to occur at upper and lower edges of rupture/locking regions, though not exclusively
- Slip more slowly than “normal” earthquakes ($\mu$m-mm s$^{-1}$)
- Radiate less/no high frequency energy (VLFE)
- Detected mainly by geodetic approaches – or BBS (VLFE)

![Graph showing distance from trench observed or anticipated (km) vs. log characteristic duration (s)]

Obara & Ito, 2005
Ide et al., 2007
Slow earthquakes are thought to be a manifestation of *conditional stability* (transition between stable and unstable states).

Simple 1-D spring-slider system analog:

Unstable if the rate of slip weakening exceeds rate of elastic unloading:

\[ K < K_c = \frac{\sigma_n' (b-a)}{D_c} \]

Key parameters:

1. \( \sigma' \): effective stress, pore pressure
2. \( (a-b) \): rate weakening of friction
3. \( D_c \): slip weakening distance
4. \( K \): effective stiffness of slip patch

*after Scholz (2003)*
2-D numerical models of deep subduction interface support this idea; yield emergent slow slip when $K \approx K_c$. 

$Liu \ & Rice, \ 2007$
1. Merging lab rock physics and data from regional geophysical surveys: Estimation of in situ conditions

- Example from the Nankai Trough where materials relevant to shallow VLFE are accessible to high-resolution imaging and sampling by drilling
- Comparison to inferences from Hikurangi margin where similar work has been conducted

**Nankai**

**Hikurangi**
Lab Data to Define Constitutive Behavior

- Drillcore samples of subduction “inputs”
- Varied stress paths, including failure at critical state
- P- and S-wavespeed measurements (ultrasonic)

\[ \text{Shimanto Complex} \]

\[ \text{Lab Tests LSB} \]

\[ \text{IODP Site C0011} \]

Kitajima & Saffer, 2012
Lab Data to Define Constitutive Behavior

- Drillcore samples of subduction “inputs”
- Varied stress paths, including failure at critical state
- P- and S-wavespeed measurements (ultrasonic)
“Map” from seismic velocities defined by field data to in situ conditions using lab-derived constitutive models.
Nankai VLF events correlate with quantitatively identified region of overpressure; $\lambda = \sim 0.75-0.9$

[Sugioka et al., 2012]
The same seems to be true for North Hikurangi SSE, though rock properties and pressure are less well constrained.

Approximate region of repeating SSE 2002-2012

(Wallace et al., 2012)

Bassett et al., 2014

Mean effective stress (MPa)

Depth (km)
2. Laboratory Shearing Experiments: Investigation of fault stability states and spectrum of slip under geophysical conditions
• Repetitive Slow Stick-Slip Events
• $K/K_c$ controlled near transition, modulated by effective normal stress
• Slip speed, recurrence, stress all decrease systematically – and duration increases - as $K/K_c$ approaches unity

Leeman, Saffer, Marone & Scuderi, submitted
Laboratory shearing study further illustrates conditions that lead to repetitive slow slip and a spectrum of failure modes:

- Systematic variations in stick-slip duration and speed near the threshold suggest an explanation for spectrum of fault slip modes rooted transitional friction and low stress.

Leeman, Saffer, Marone, & Scuderi, submitted
Additional complexities in frictional behavior relevant to repetitive and slow fault slip

- Rate parameter \((a-b)\) increases with sliding velocity \(\rightarrow\) suppress fast rupture. Minimum at velocities comparable to SSE slip rates.
- \(Dc\) is large \(\rightarrow\) rise time?
- Increasingly rate weakening with more qtz \(\rightarrow\) role of mineralogy, diagenesis?

Saffer & Wallace, 2015
Transitionai frictional behavior and elevated pore pressure have been hypothesized as mechanisms. They indeed seem to be important.

Pore pressure is elevated in well-characterized slow EQ source regions. This is generally consistent with other – but more ambiguous – observations in areas of deep SSE, ETS, and VLFE.

Frictional properties point toward conditional stability, quenching behavior, and importance of fault mineralogy (silica). But more to be done here (e.g., elevated $T$, intact fabric, drill core from SSE).

Friction properties and low $\sigma'$ are also consistent with long rise times and low stress drops.

Does not rule out other potentially important processes: dilatancy-hardening, role of heterogeneity or roughness.
• Repetitive Slow Stick-Slip Events
• K/Kc modulated by effective normal stress in these experiments
• Slip speed, recurrence, stress all decrease systematically – and duration increases - as K/Kc approaches unity
Evidence for elevated pore pressure in source areas of tremor along the SAF

Thomas et al., 2009