The transient and intermittent nature of slow slip

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Slow-slip events (SSEs)

- New mode of aseismic transient **release**
  - Lasts from several days to weeks to months
  - Can release as much built-up tectonic stress as a major earthquake
Slow slip is where big earthquakes happen

Slow slip must play some role in the earthquake cycle!

Modified from Ide, JGR, 2012
Slow slip is where big earthquakes happen

Understanding the slow slip cycle and its dynamics is essential if we are to understand the earthquake cycle!

Slow slip must play some role in the earthquake cycle!
Geodesy is our tool to directly constrain slow slip

- No direct seismic radiation
- Mainly cGPS (although also tilt- and strain-meters)
- Point observations integrate elastic response over wide area
  - Spatiotemporal resolving power dependent on network density
- Position solutions sampled daily with error of several mm
Geodetic image of a $M_w$ 7.5 slow slip event

- Six-month long rupture
- Smooth, continuous
- Long-period (>30-day) deformation well constrained
Geodetic image of a $M_w$ 7.5 slow slip event

But what about slow slip dynamics at shorter time-scales?

- Six-month long rupture
- Smooth, continuous
- Long-period (>30-day) deformation well constrained

Modified from Radiguet et al., GJI, 2011

Observed Modeled
Slow seismicity: Low-frequency earthquakes (LFEs)

- Small, impulsive, repetitive seismic events on the plate interface
- Correlated with slow slip in both time and space

Modified from Frank and Shapiro, GJI, 2014

Tectonic tremor

LFEs
Low-frequency earthquakes as a proxy for slow slip

- Bursts of LFEs occur during slow slip (Frank et al., Sci. Adv., 2016)
- LFEs are a spatio-temporally precise proxy for slow slip!

Modified from Frank et al., EPSL, 2015
Slow slip in Guerrero

- Flat slab subduction
  - Natural control on pressure
- Major M7.5 slow slip events every 4 years
- Tectonic release to the South
Low-frequency earthquakes in Guerrero

- 2.5-year catalog contains 1,849,486 LFEs
  - 1120 unique spatial sources
- Shearing focal mechanism on plate interface
- Precise locations reveal multiple LFE source regions
- **Updip** LFE activity strongly correlated with geodetically-observed slow slip
2006 M7.5 slow slip through the lens of LFEs

- Slow slip at the interface concentrated in the *updip zone*

Modified from Frank et al., Sci. Adv., 2018
Long-period displacement during a M7.5 slow slip event

- Monotonic motion towards the South
- Continuous six-month release

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Long-period displacement during a M7.5 slow slip event

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- About ~3.85 cm displacement (after correcting for data gaps)

Modified from Frank et al., Sci. Adv., 2018
Quantifying LFE activity

- Focus on updip LFE sources closest to slow slip
- Quantify on a daily time scale
  - Same time scale as GPS!
- $N_{LFEs} \times \text{median}[\text{amplitude}]$

Modified from Frank et al., Sci. Adv., 2018
Intermittent LFE activity during slow slip

**Hypothesis:** high LFE activity = slow slip transient

- Seismicity > threshold, **tectonic release**
- Seismicity < threshold, **tectonic loading**

![Graph](Modified from Frank et al., Sci. Adv., 2018)
Intermittent LFE activity during slow slip

**Hypothesis:** high LFE activity = slow slip transient

- Seismicity > threshold, **tectonic release**
- Seismicity < threshold, **tectonic loading**

Let’s decompose GPS time series based on this hypothesis…

*Modified from Frank et al., Sci. Adv., 2018*
Long-period displacement during a M7.5 slow slip event

- Monotonic motion towards the South
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![Graph showing cumulative NS surface displacement](image)

- **Six months prior to slow slip**
  - 1.9 cm/yr
  - -5.7 cm/yr

Modified from Frank et al., Sci. Adv., 2018
Displacement during intense LFE activity

**Tectonic release (>threshold):**

- 5x greater displacement rate
- Displacement happens during <60 days (three times faster!)

Modified from Frank et al., Sci. Adv., 2018
Displacement the rest of the time

Tectonic loading (<threshold>):

- Northward loading motion during slow slip!
- Loading rate greater than inter-SSE loading

Modified from Frank et al., Sci. Adv., 2018
Slow slip is an intermittent slip process

- 40% greater displacement *in a third of the time*
- Just as intermittent as LFE activity!
- Slow slip is faster and bigger than geodesy would suggest

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**Diagram:**

- **MEZC ±2σ:**
  - 5.7 cm/yr
  - 1.9 cm/yr
  - -30.8 cm/yr
  - 5.1 cm/yr

- **Relative SSE time (days):**
  - 0
  - 100
  - 200

- **Cumulative NS surface displacement (cm):**
  - Release Loading
  - SSE period
  - SSE release period
  - SSE loading period
  - Inter-SSE period

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Modified from Frank et al., Sci. Adv., 2018
Slow slip is an intermittent slip process

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Modified from Rousset et al., submitted

Modified from Frank et al., Sci. Adv., 2018
Slow slip is also intermittent **outside** of major slow slip events

Decomposed GPS displacements between geodetically observed slow slip events
Slow slip is also intermittent outside of major slow slip events

Intermittent slow slip is observed across many subduction zones
Slow slip is also intermittent outside of major slow slip events

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Intermittent slow slip is observed across many subduction zones
Is LFE moment rate diagnostic of slow slip?

\[ \dot{M}^{\text{seis}}_o \propto \dot{M}^{\text{geo}}_o \]
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- If the LFE moment rate was diagnostic of the geodetic moment rate...
Is LFE moment rate diagnostic of slow slip?

\[ \dot{M}_{seis} \propto \dot{M}_{geo} ? \]

- If the LFE moment rate was diagnostic of the geodetic moment rate…

We could turn this catalog of LFEs into a catalog of slow slip!
Measuring LFE (seismic) moment rate

- Seismic displacement amplitude is directly proportional to moment rate (Aki and Richards, 2002)
- Measure RMS displacement amplitude during every LFE S-wave
Spatiotemporal evolution of LFE moment rate

Modified from Frank and Brodsky, Sci. Adv., 2019
Measuring moment rates of slow slip events

Geodetic moment rate of a slow slip event

- Geodetic moment ÷ duration
- NB: intermittent slip = larger moment and shorter duration!

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So what is the duration of a slow slip event?

Modified from Frank et al., Sci. Adv., 2018
Observation: Slow slip mostly happens during LFE activity…

Assumption: slow slip ONLY happens during LFEs
  - Every LFE is driven by aseismic slip

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Slow slip duration is proportional to $N_{LFE}$
- Average aseismic slip pulse duration of $\Delta t$

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Slip duration = $N_{LFE} \times \Delta t$

Modified from Frank et al., Sci. Adv., 2018
Measuring moment rate of slow slip events

- Eight geodetically observed slow slip events
  - 2006 M7.5 slow slip
  - Seven M6.4 slow slips every 75 days (Frank et al., GRL, 2015)

**Geodetic moment rate of a slow slip event**
- Geodetic moment ÷ duration
  - Slip duration = N_{LFE} x Δt

**Seismic moment rate of LFEs during slow slip**
- Median amplitude of all LFEs within event
Average slow slip moment rate does not reflect highest moment rates

- Moment rates averaged over long time periods (weeks to months)
- Missing dynamics at high moment rates!
Sampling high moment rates

- Sample LFE amplitude on same time scale as GPS (daily)

- Bin GPS displacements by LFE amplitude

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Bin GPS displacements by LFE amplitude

Each bin represents slow transients that generate a given range of LFE amplitudes

Modified from Frank and Brodsky, Sci. Adv., 2019
Avg. slow slip dynamics suggests a constant moment rate

- **Y-axis:** Average geodetic moment rate measured over weeks or months
- **X-axis:** Median seismic moment rate of all constituent LFEs
LFE-derived slow transients sample high moment rates

Graph showing the relationship between median LFE amplitude and seismic moment rate. The graph includes data points for M7.5 2006 slow slip event, M6.4 slow slip events, and slow transients. The x-axis represents seismic moment rate (N m/s) on a logarithmic scale ranging from $10^{15}$ to $10^{12}$, and the y-axis represents geodetic moment rate (N m/Δt) on a logarithmic scale ranging from $10^7$ to $10^{17}$. The median LFE amplitude A (nm) is also shown with a range from 2 to 8.
LFEs are diagnostic of the driving slow slip

- Best-fit power law scaling
- Seismic to aseismic ratio during slow slip is at least $10^{-4}$

\[ \dot{M}_o = 10^{42.4} A^{3.17} \]
LFE amplitude to slow transient moment

- LFE amplitude is converted to geodetic moment rate
- **Slow transient moment** = moment rate multiplied by slip duration \( N_{\text{LFE}} \)

From an LFE catalog to…

\[
M_c = 10^{42.4} A^{5.17}
\]
A catalog of slow transients

Modified from Frank and Brodsky, Sci. Adv., 2019
A catalog of slow transients

- **M7.5 slow slip** every 4 years
- **M6.4 slow slip** every 75 days

Modified from Frank and Brodsky, Sci. Adv., 2019
A catalog of slow transients

M7.5 slow slip every 4 years

M6.4 slow slip every 75 days

Just a cluster of M6 transients

Modified from Frank and Brodsky, Sci. Adv., 2019
A catalog of slow transients

M7.5 slow slip every 4 years
Just a cluster of M6 transients

M6.4 slow slip every 75 days
Slow slip also happens every day!

Modified from Frank and Brodsky, Sci. Adv., 2019
A catalog of slow transients

50

M7.5 slow slip every 4 years

Just a cluster of M6 transients

EQ-like scaling of slow transients!
Our evolving grasp on slow slip dynamics

Slow slip is a smooth and continuous rupture
Our evolving grasp on slow slip dynamics

LFEs are driven by surrounding slow slip
Our evolving grasp on slow slip dynamics

Smaller slow slip events occur more often than is obvious in the geodetic record
Our evolving grasp on slow slip dynamics

Major slow slip events are an intermittent cluster of small slow slips
Our evolving grasp on slow slip dynamics

Slow slip happens every day
Take away messages (and questions)

- As observational resolution increases, we observe smaller and smaller slow slip events
- Major slow slip events are made up of smaller events
  - No reason to not expect the same for the small slow slips themselves…
  - Is a single LFE symptomatic of a unit slow slip?
- Slow slip is an intermittent rupture process, made up of a cluster of earthquake-like slip transients
  - Slow slip is faster and bigger than we thought
  - Does a faster slip rate have implications for triggering EQs?
- Blending seismology and geodesy together is essential to constrain a phenomenon that spans the bandwidth of multiple geophysical instruments
Moment-duration scaling of slow earthquakes

Scaling of fundamental parameters reflects underlying physics

- Moment $M_o$ of a simple fault dislocation scales with $T^3$
- Proposed slow earthquake scaling suggests fundamentally different physics

Parent Image
Moment-duration scaling of slow earthquakes

Scaling of fundamental parameters reflects underlying physics

- Moment $M_o$ of a simple fault dislocation scales with $T^3$
- Proposed slow earthquake scaling suggests fundamentally different physics
  - Constrained by observations on extreme ends of spectrum
Earthquake-like moment-duration scaling

Slow transient moment scales with the cube of its duration

- Low-resolution GPS captures sum of the intermittent slow slip process
  - Slip during slow transients
  - Interrupted by relocking

Modified from Frank and Brodsky, Sci. Adv., 2019
Earthquake-like moment-duration scaling

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- Strip away the intermittent loading to focus on slip…

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Slow slip scales like fast slip

Slow transient magnitude ($M_{LFE}$)

Slip duration $T (\Delta t \cdot N_{LFE})$

$M_o \propto T^{3.1}$

Modified from Frank and Brodsky, Sci. Adv., 2019