Using deformation rates in Northern Cascadia to constrain time-dependent stress- and slip-rate on the megathrust

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INTERSEISMIC PERIOD FOR THE CASCADIA SUBDUCTION ZONE
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Interseismic period for the Cascadia subduction zone
1. What is the physical behavior of this “gap”?

2. How deep can the megathrust rupture go?
   Can it propagate in the gap?
   in the ETS region?

[e.g., Hyndman & Wang (1995), Flück et al. (1997),
Dragert et al. (2004), Chapman & Melbourne (2009),
Wech & Creager (2011), Hyndman (2013)]
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INTERSEISMIC PERIOD FOR THE CASCADIA SUBDUCTION ZONE

1. What is the physical behavior of this “gap”?  
2. How deep can the megathrust rupture go?  
   Can it propagate in the gap in the ETS region?  

Looking at “long-term” deformation
Horizontal GPS rates
LOOKING AT "LONG-TERM" DEFORMATION
HORIZONTAL GPS RATES + TIDE-GAUGE & LEVELING UPLIFT RATES

a) Locations of the GPS Stations

b) Locations of the tide-gauges & leveling data
FORWARD RATE–STATE FRICTION MODELS OF SSE

(a) Geometry of the dipping fault

(b) Depth distribution of effective normal stress $\bar{\sigma}$, $D_e$ and rate and state coefficient (a-b)

$\bar{\sigma}$ (MPa)

$D_e$ (mm)

Velocity strengthening

Velocity weakening
FORWARD RATE–STATE FRICTION MODELS OF SSE FIT THE GPS DATA
Averaged over many ETS cycles, stress within the slow slip zone (30-40km) is nearly constant.
SAME RATE-STATE FRICTION MODELS OF THE INTERSEISMIC SLIP RATE DO NOT FIT THE LONG-TERM RATES

Computed long-term slip rates

- Uplift rates from tide gauges & leveling
Physics-based models predict too much locking in the gap, up dip the ETS region. Why?

- Bias due to use of homogeneous half-space Green’s functions?
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Physics-based models predict too much locking in the gap, up dip the ETS region. Why?

- Bias due to use of homogeneous half-space Green’s functions? ✗
- Gap creeping due to velocity-strengthening friction behavior?
**Gap Creeping due to Velocity-Strengthening Friction Behavior?**

**a) Computed long-term slip rate profiles (mm/yr)**

- Slip rates (mm/yr)
- ETS region
- No V-S above the SSE zone
- V-S between 26 and 30km
- V-S between 22 and 30km
- V-S between 18 and 25km
- V-S between 14 and 25km

**b) Depth distribution of effective normal stress $\bar{\sigma}$ and rate and state coefficient (a-b)**

- $\bar{\sigma}$ (MPa)
- ETS region
- $D_e$ (mm)

- Velocity strengthening
- Velocity weakening
GAP CREEPING DUE TO VELOCITY-STRENGTHENING FRICTION BEHAVIOR?

b) Predicted velocities for model with creep between 14 and 30km

- Horizontal rates (Variance Reduction = 95.8%)

- Vertical rates (Variance Reduction = 27.3%)

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Which slip rate distribution is required by the data?
INVERSION OF THE RESIDUALS FROM THE STARTING PHYSICS-BASED MODELS

a) Slip rate profiles (mm/yr)

b) Map view of the slip rates for the best fitting model

c) Predicted velocities for the best fitting model (velocity-strengthening region between 26 and 30km)

- Horizontal rates (Variance Reduction = 95.6%)
- Vertical rates (Variance Reduction = 87.3%)
Physics-based models predict too much locking in the gap, up dip the ETS region. Why?

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Which slip rate distribution is required by the data?

Larger slip rates are necessary within both the gap and the ETS zone relative to the physics-based model with constant shear stress.
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Larger slip rates are necessary within both the gap and the ETS zone relative to the physics-based model with constant shear stress.
Inversions for interseismic shear stress rates find negative shear stress rates to explain the large slip rates in the gap and the ETS region [Bruhat & Segall, 2016]

Inverted shear stress rates (kPa/yr)

Corresponding slip rate profile (mm/yr)

Inversions for solutions as close as possible to constant stress
Inversions for interseismic shear stress rates find negative shear stress rates to explain the large slip rates in the gap and the ETS region [Bruhat & Segall, 2016]

Inversions for solutions as close as possible to constant stress
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Implicit assumption
Can the interseismic transition depth change with time?
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\[ \text{Slip rate} \quad \frac{ds}{dt} = f(z, t)v^\infty \]

\[ \text{Slip} \quad s(z, t) = f(z, t)v^\infty t \]
Can the interseismic transition depth change with time?

**Slip**

\[ s(z, t) = f(z, t)v^\infty t \]

**Slip rate**

\[ \frac{ds}{dt} = f(z, t)v^\infty + v^\infty t \frac{\partial f}{\partial t} \]
Implicit assumption

Can the interseismic transition depth change with time?

Slip

$$s(z, t) = f(z, t)v^\infty t$$

Slip rate

$$\frac{ds}{dt} = f(z, t)v^\infty + v^\infty t \frac{\partial f}{\partial t}$$

$$= f(z, t)v^\infty + v^\infty t \frac{\partial f}{\partial a} \frac{\partial a}{\partial t}$$
TEMPORAL EVOLUTION OF THE LOCKING DEPTH
Numerical simulations from Jiang & Lapusta (2016)

The locking depth migrates up dip $\Rightarrow$ the size of the locked region reduces with time
Crack model for the interseismic slip profile

Spatial variable \( \xi = 1 - \frac{2z}{a} \)

Expand stress drop in Chebyshev polynomials:

\[
\Delta \tau = \sum_{i=0}^{\infty} c_i(t) T_i(\xi(t))
\]
Crack model for the interseismic slip profile

Spatial variable \( \xi = 1 - \frac{2z}{a} \)

For a crack with finite stress at the crack tip and driven by steady displacement:

\[
\Delta \tau = \mu \frac{v(t)}{a(t)\pi} \xi(t) + \mu \sum_{i=2}^{\infty} c_i(t) T_i(\xi(t))
\]

Slip \( s = tg(\xi(t)) + a(t) \sum_{i=2}^{\infty} c_i(t) f_i(\xi(t)) \)

Slip rate \( \frac{ds}{dt} = g(\xi(t)) + a(t) \sum_{i=2}^{\infty} \frac{\partial c_i(t)}{\partial t} f_i(\xi(t)) + \frac{\partial a}{\partial t} \left[ t \frac{u(\xi(t))}{a(t)} + \sum_{i=2}^{\infty} c_i(t) v(\xi(t)) \right] \)
**EFFECT OF THE PROPAGATION**

![Graphs showing the effect of propagation on slip rate and cumulative slip over time.](image)
New method to derive expressions for stress drop, slip and slip rate

- Allows for the up dip propagation of the creeping region
- Massively underdetermined (as most geodetic inversions)
- Can be used to invert deformation rates using MCMC methods under specific assumptions ($c_i = 0$, stress characteristics in the ETS region, etc.) to look for extremal models (e.g., bounds on propagation speed)
- Examples for Cascadia
APPLICATION TO CASCADIA
Non propagating crack, invert for \( c_i \) (N=6)

Best fitting model (MCMC inversion)
Locking depth: 20.5km
APPLICATION TO CASCADIA

Propagating crack

Best fitting model (MCMC inversion)
Locking depth: 21km
Up-dip propagation velocity: 33.4m/year
APPLICATION TO CASCADIA

Posterior distributions
APPLICATION TO CASCADEIA
Models w/ no change in shear stress in the ETS region

Minimizing \( ||\Sigma^{-1/2}(d - \hat{d})|| \) subject to \( \frac{\partial \Delta \tau}{\partial t}(\xi = ETS) = 0 \)

Stress rates do take into account the free surface effects
Assuming \( \partial c_i / \partial t = 0 \)
APPLICATION TO CASCADE

Models w/ no change in shear stress in the ETS region

Best fitting model (MCMC inversion)
Locking depth: 21.9km
Up-dip propagation velocity: 41m/year
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Bruhat & Segall, JGR, 2016

Bruhat & Segall, in review
Conclusions:

- New method to estimate interseismic slip rates
  - Include the possibility for the creeping zone to propagate up dip
  - Between purely kinematic inversions and fully physics-based models

- Possible mechanical explanations
  - Gap “locked” after deep rupture propagation, interseismic transition propagating up due to reloading by deep creep [Jiang & Lapusta, 2016]

- For Cascadia: current (?) locking depth (20-22km), steep slip rate gradient at bottom of the locked region, and important slip deficit in gap & ETS region

Questions? lbruhat@stanford.edu

Funding from: USGS