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

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Paul Segall
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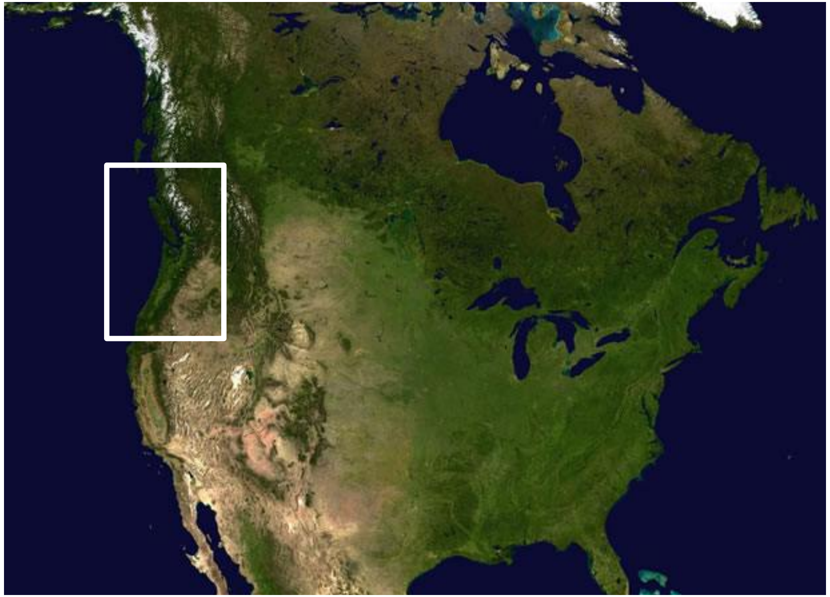
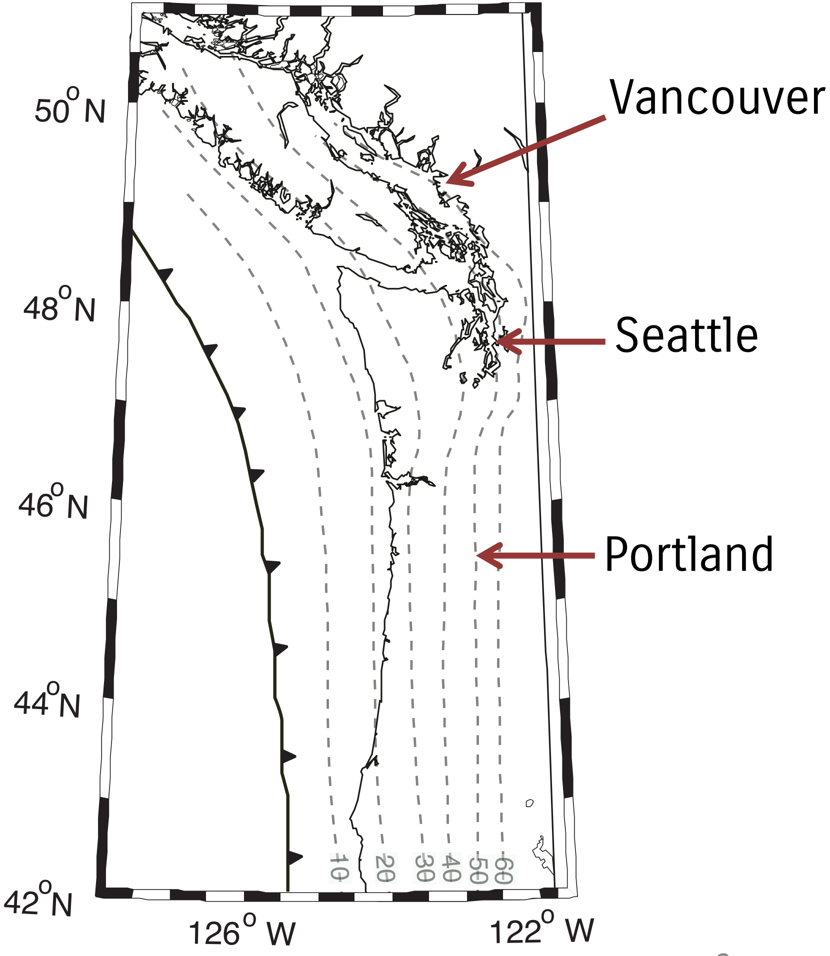
Interseismic period for the Cascadia subduction zone





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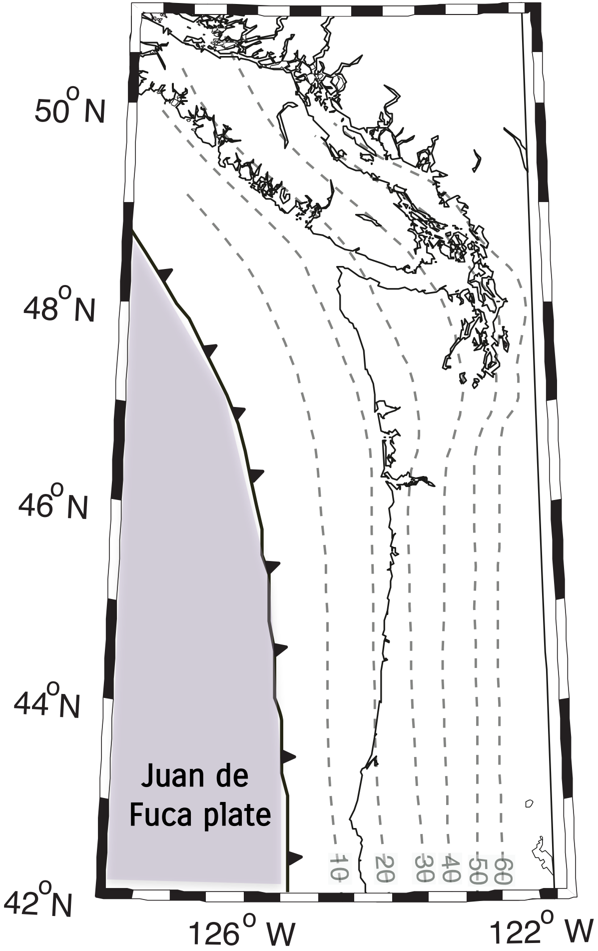

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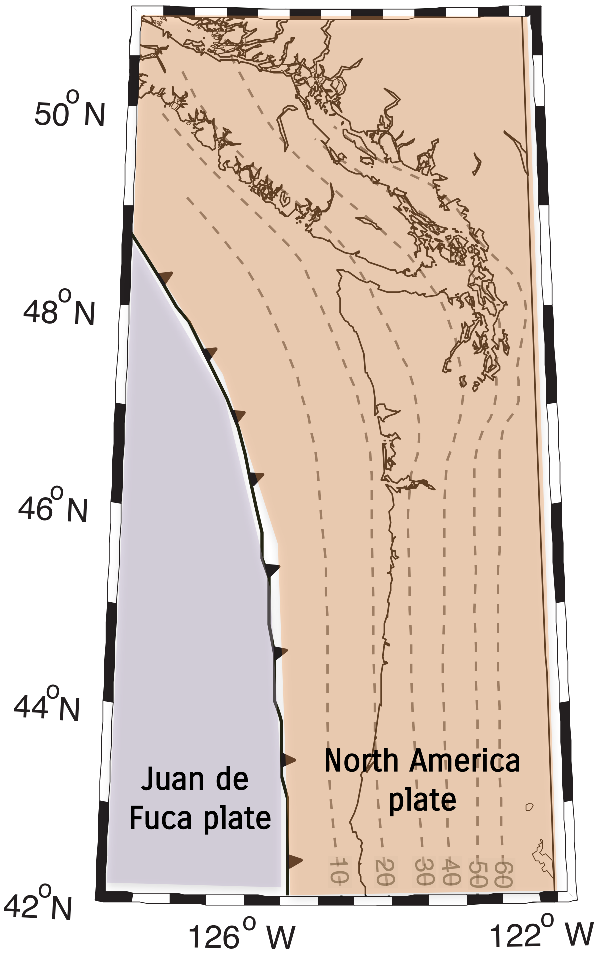

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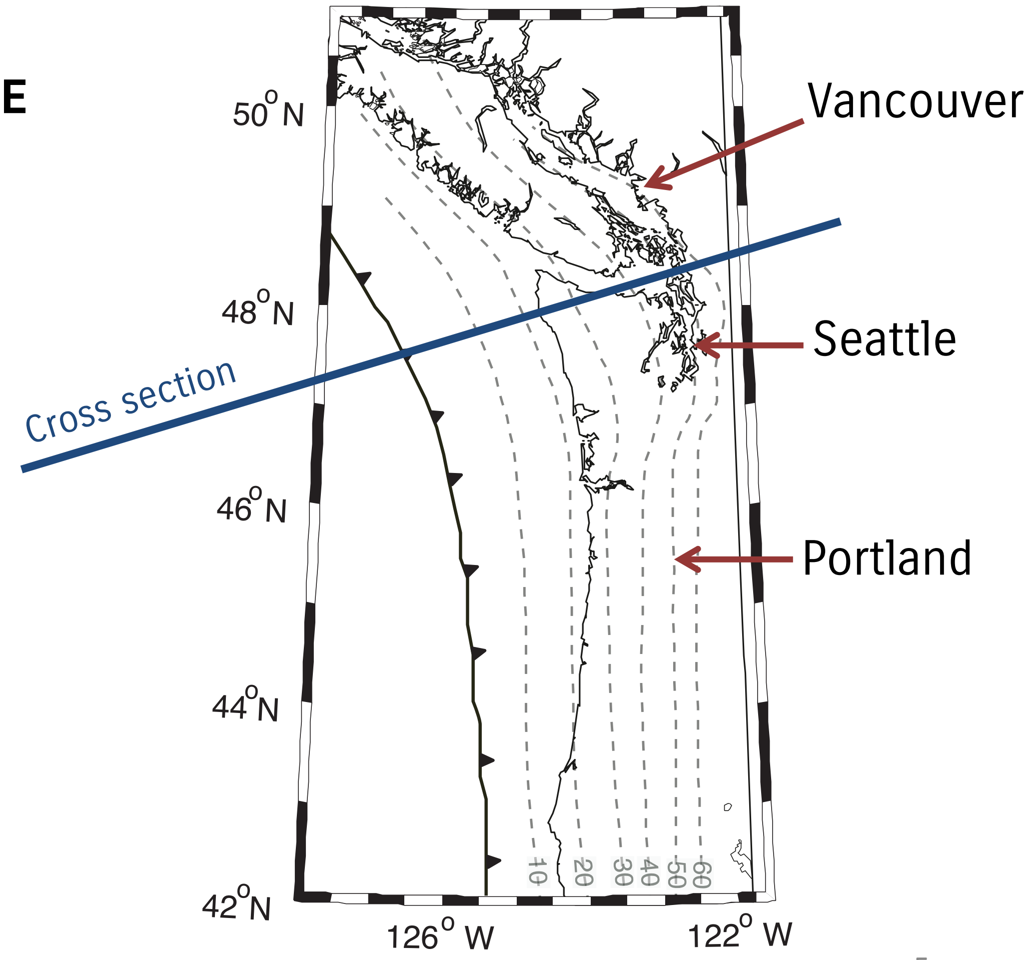

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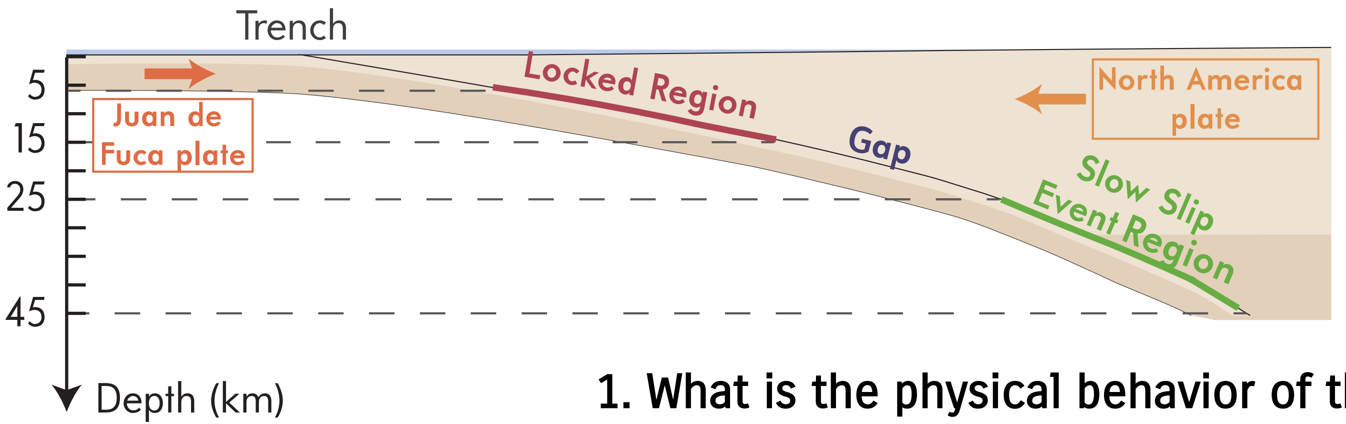

1. What is the physical behavior of this "gap"?

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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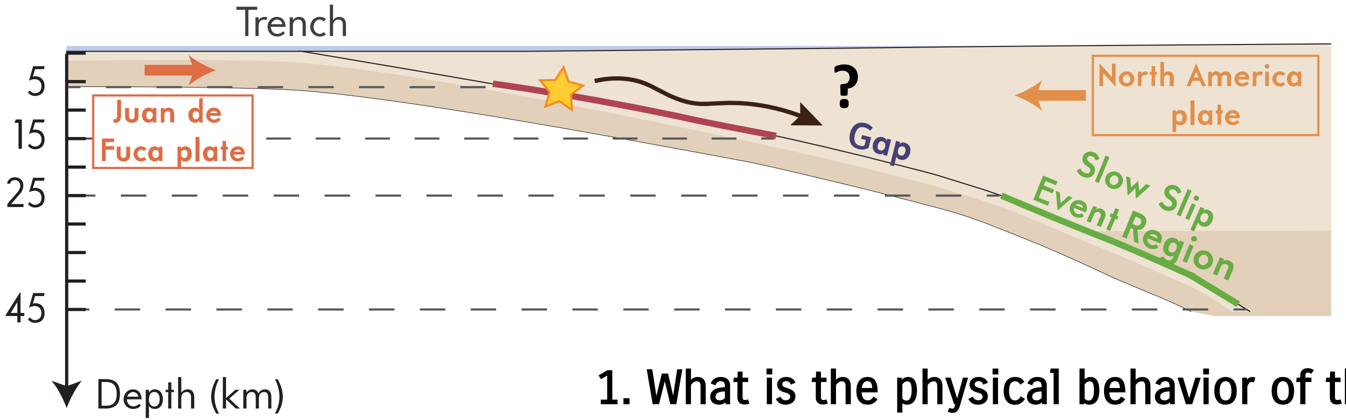

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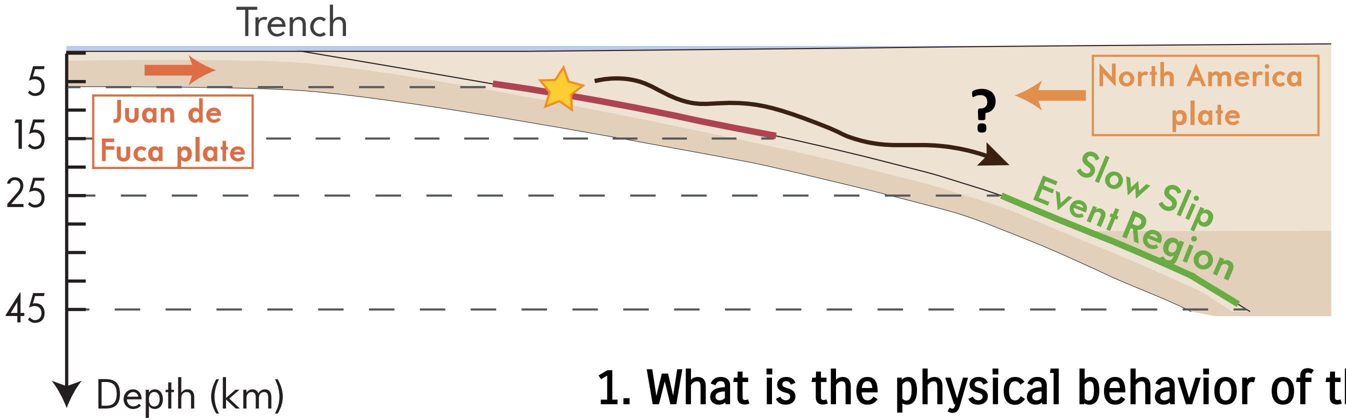

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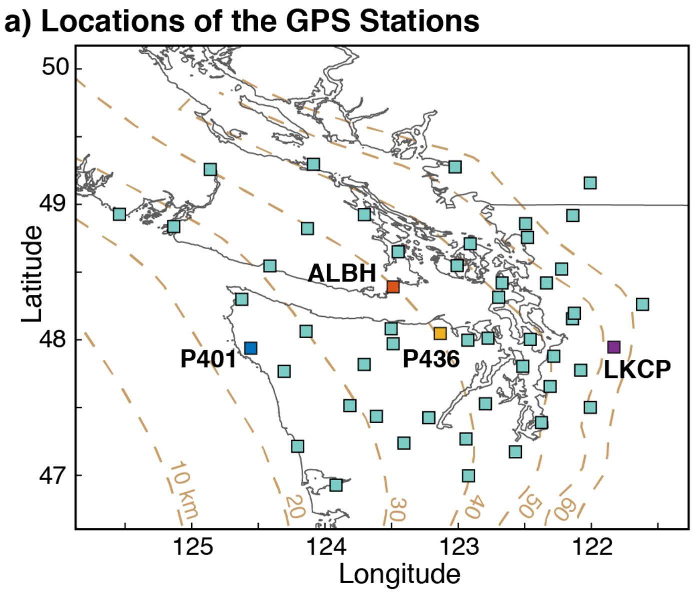
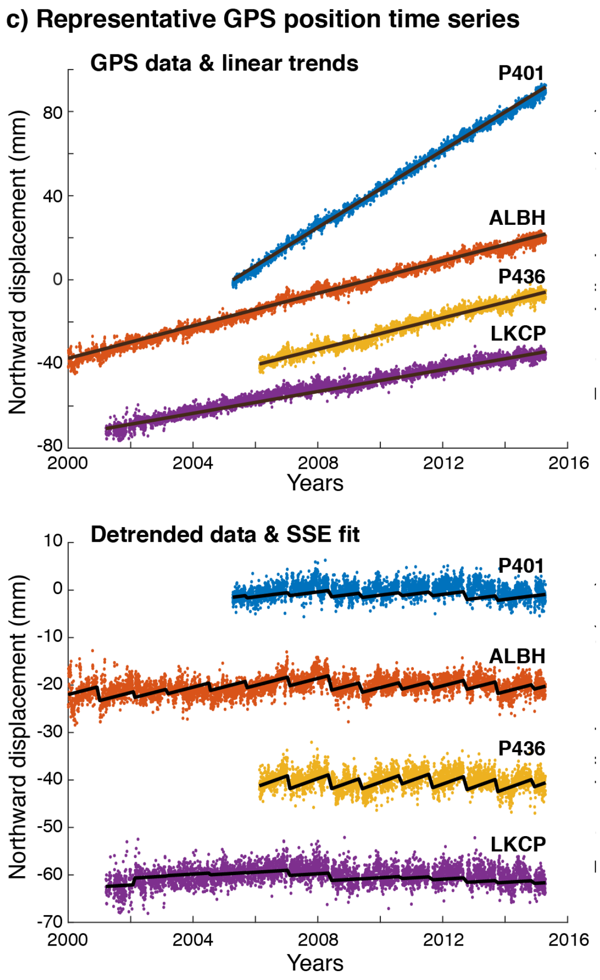
Looking at "long-term" deformation

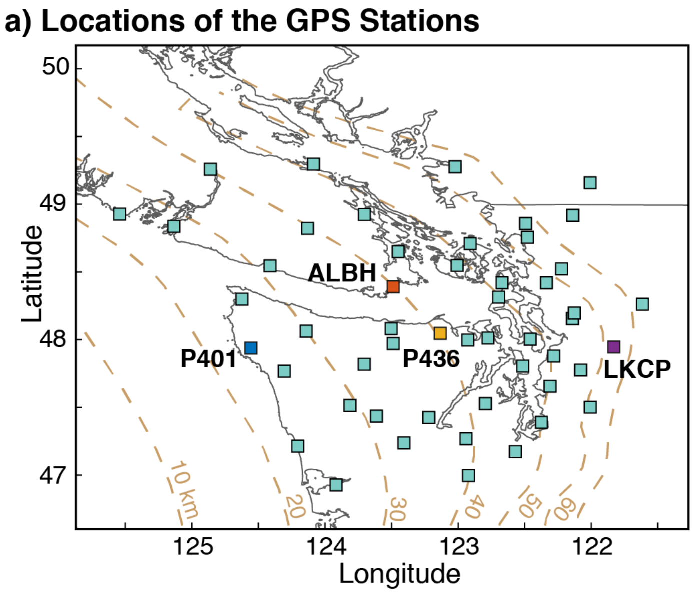
Horizontal GPS rates

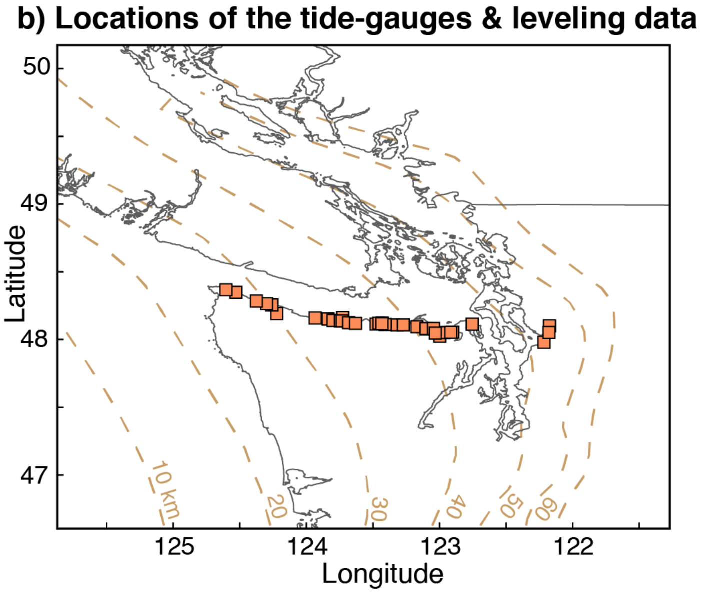




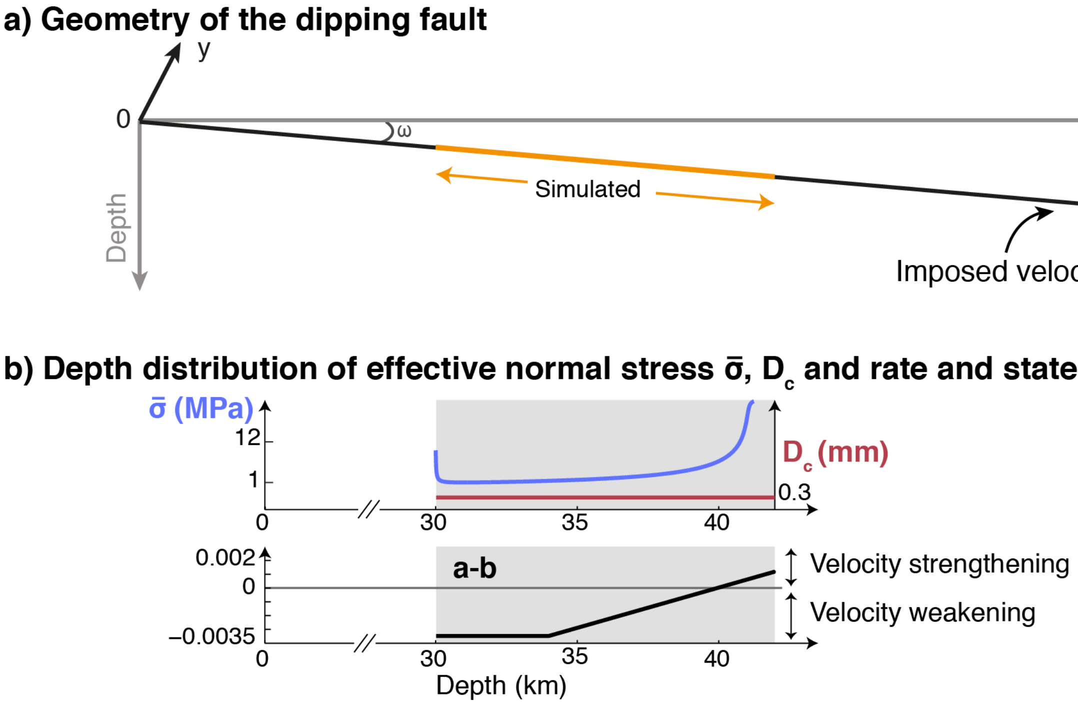
Looking at "long-term" deformation

Horizontal GPS rates + tide-gauge & leveling uplift rates



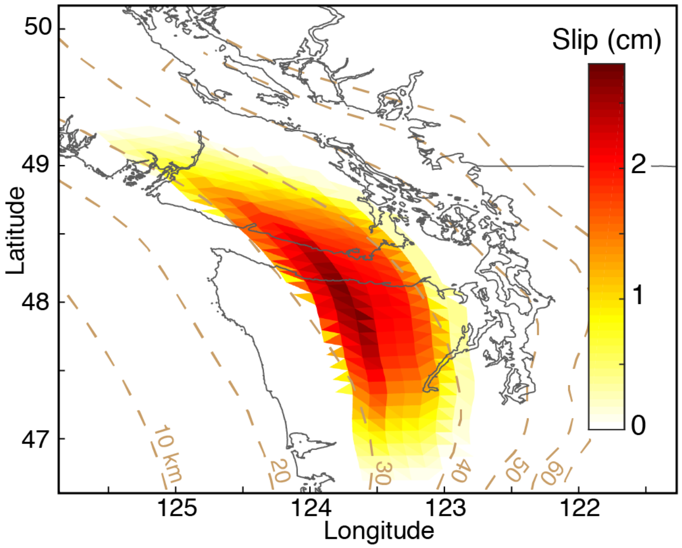


Forward rate-state friction models of SSE

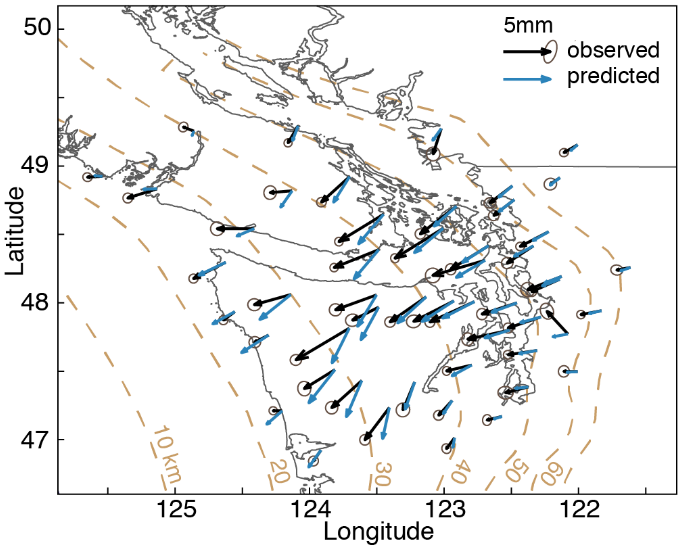


Forward rate-state friction models of SSE fit the GPS data

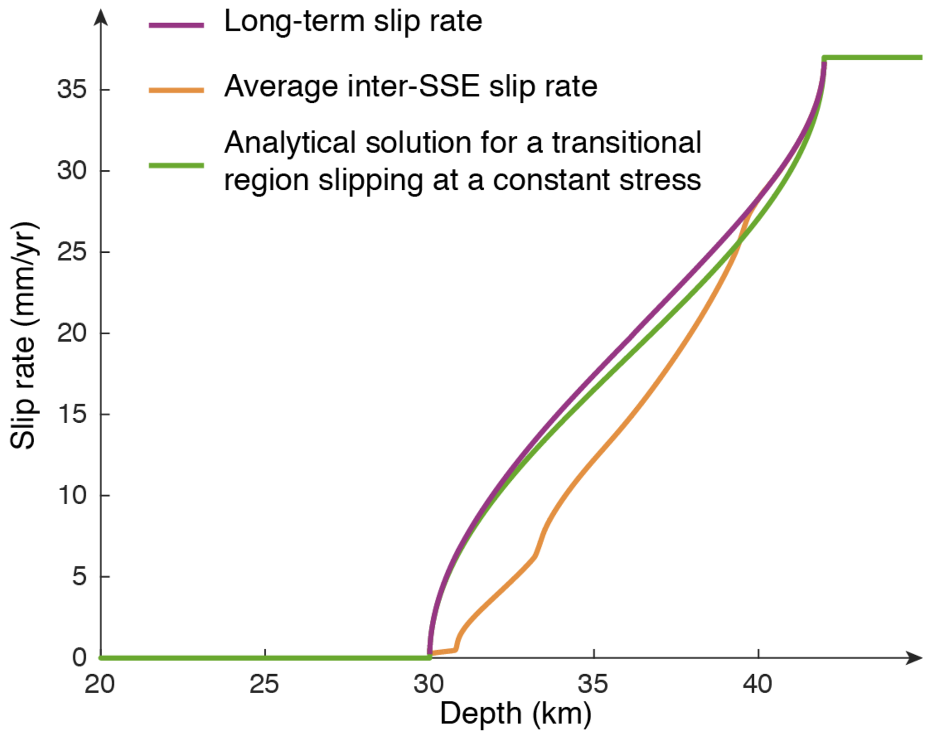
Computed average ETS slip



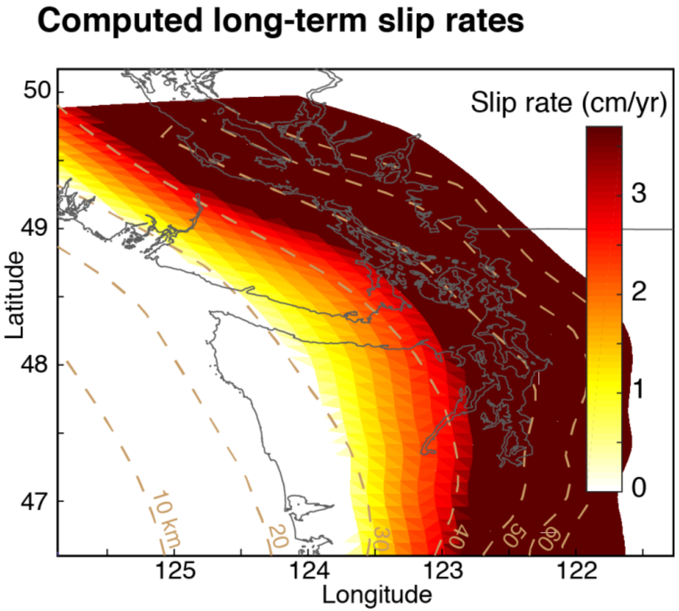
Fit to the average GPS horizontal displacements

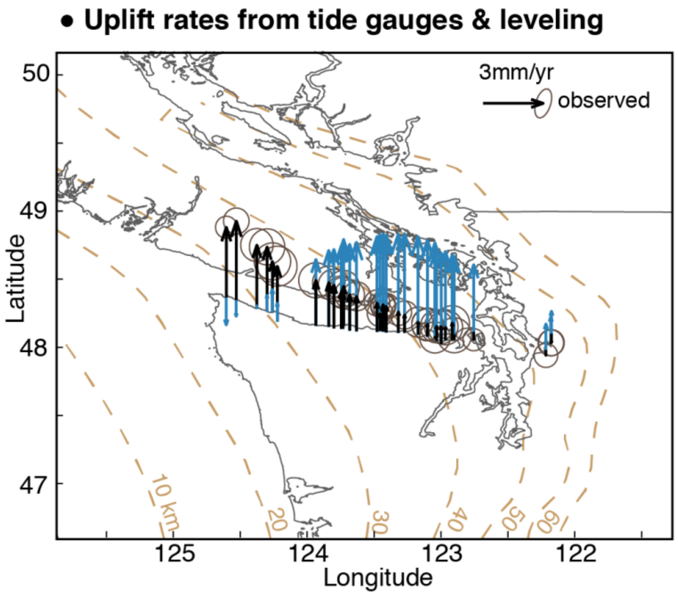


Averaged over many ETS cycles, stress within the slow slip zone (30-40km) is nearly constant



Same rate-state friction models of the interseismic slip rate do not fit the long-term rates





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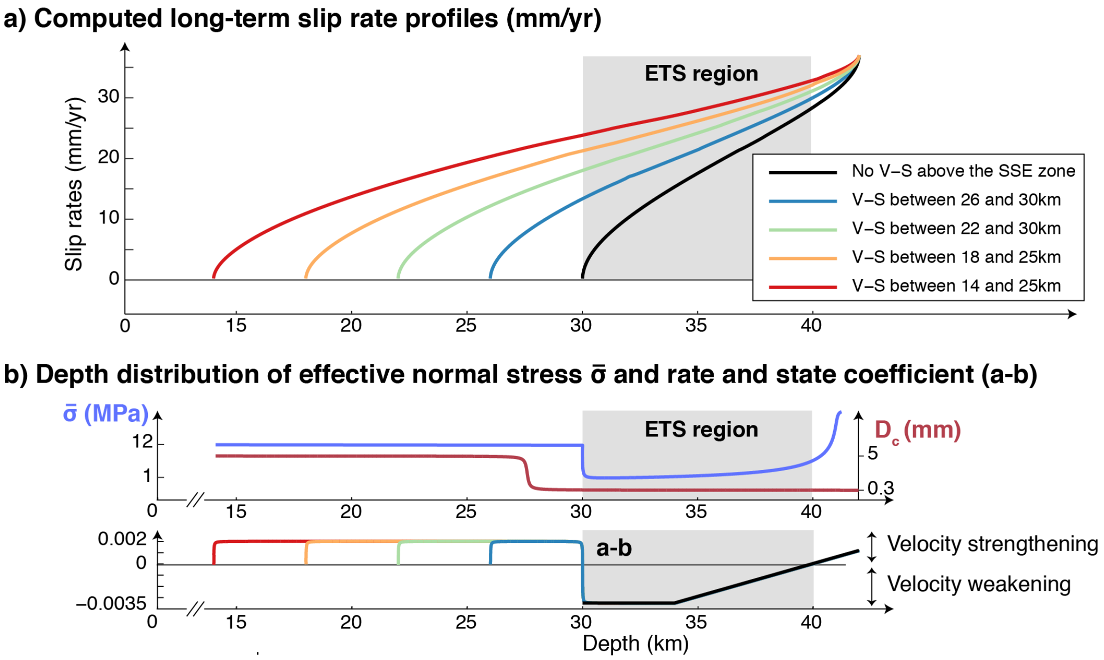
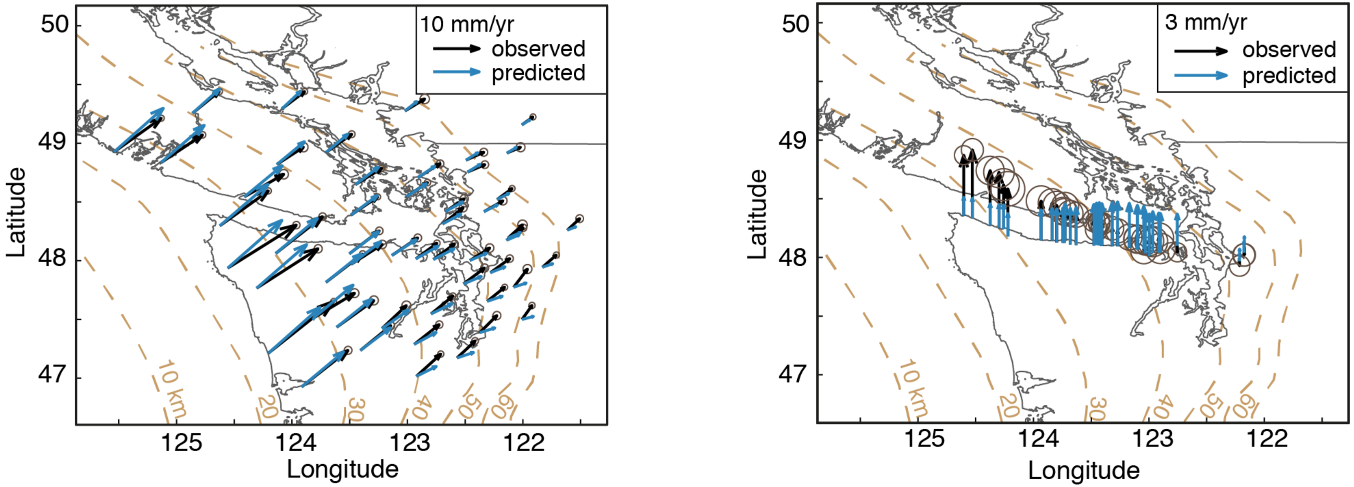


Gap creeping due to velocity-strengthening friction behavior ?

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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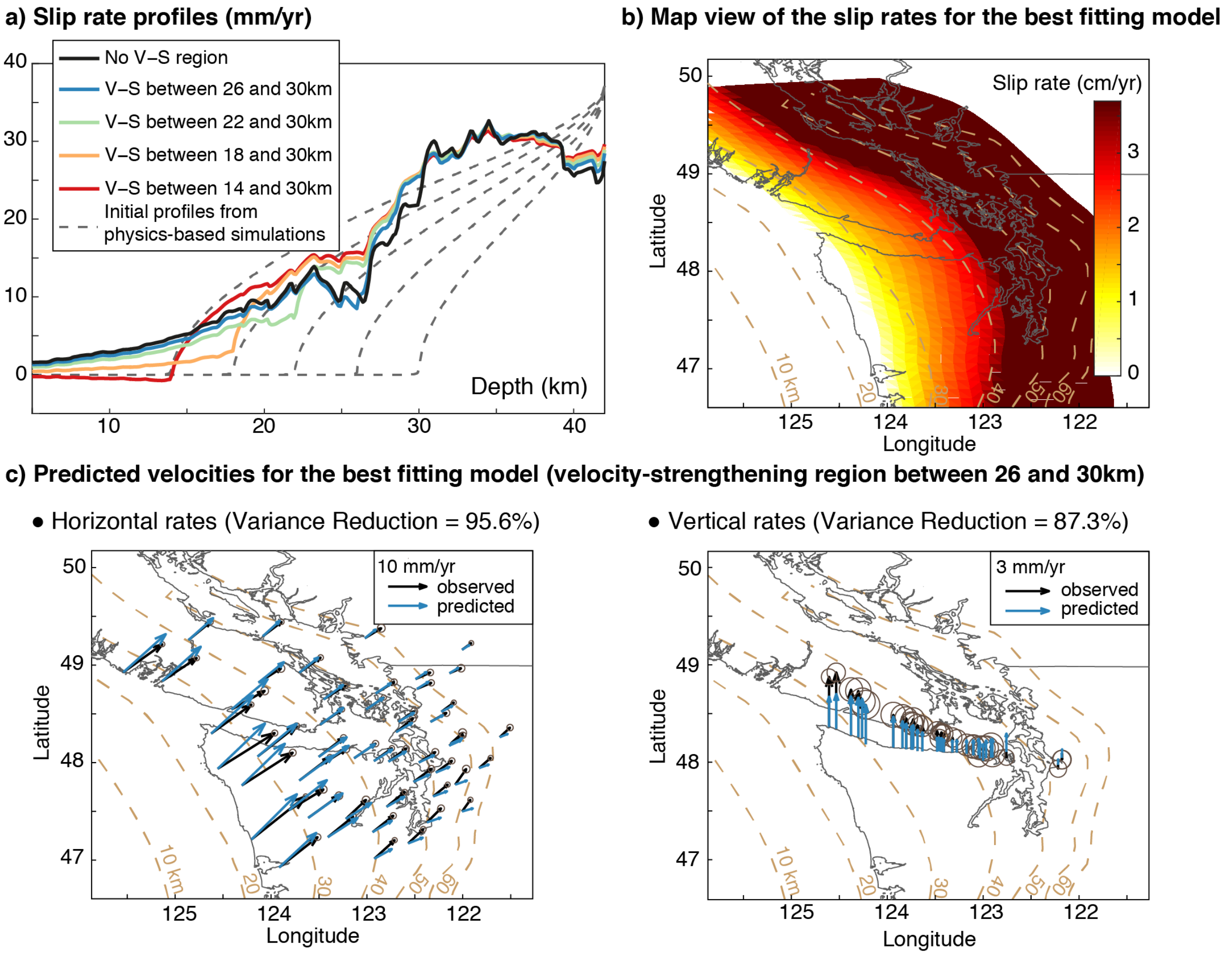
Which slip rate distribution is required by the data?

Inversion of the residuals from the starting physics-based models



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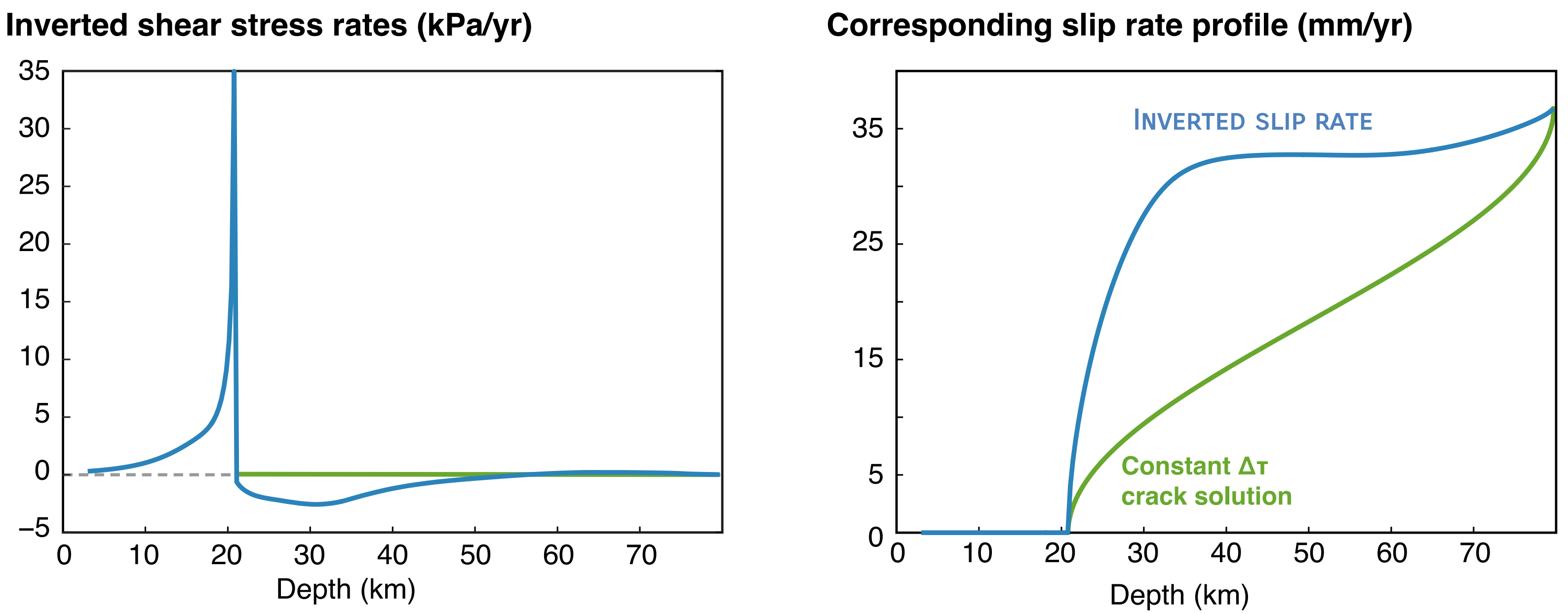
Inversions for interseismic shear stress rates find <u>negative shear stress rates</u> to explain the <u>large slip rates</u> in the gap and the ETS region [Bruhat & Segall, 2016]



Inversions for solutions as close as possible to constant stress

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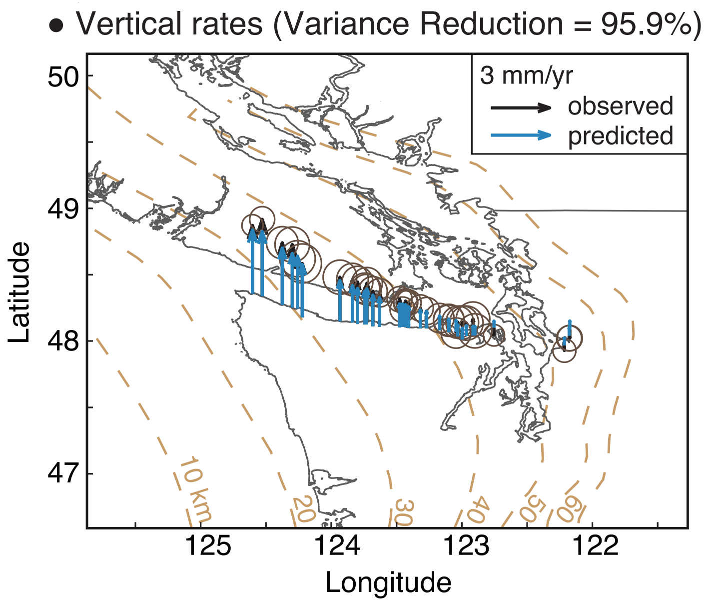

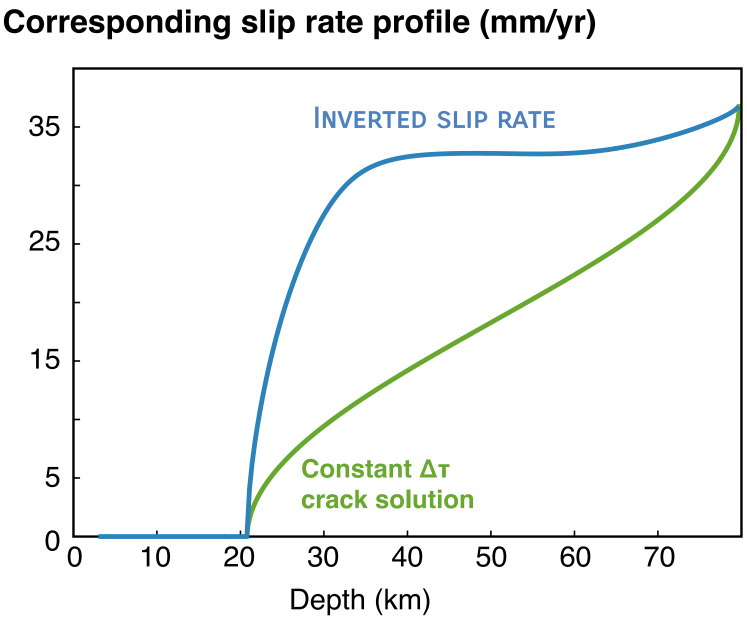

Inversions for solutions as close as possible to constant stress

Rate & State friction numerical models	Inversions for shear stress rates
Fit the average ETS displacements	Fit the long-term rates
No change in shear stress in the ETS region	Require negative shear stress rates within the gap & ETS region
	Change with time in effective stress? Fault strength?

Implicit assumption

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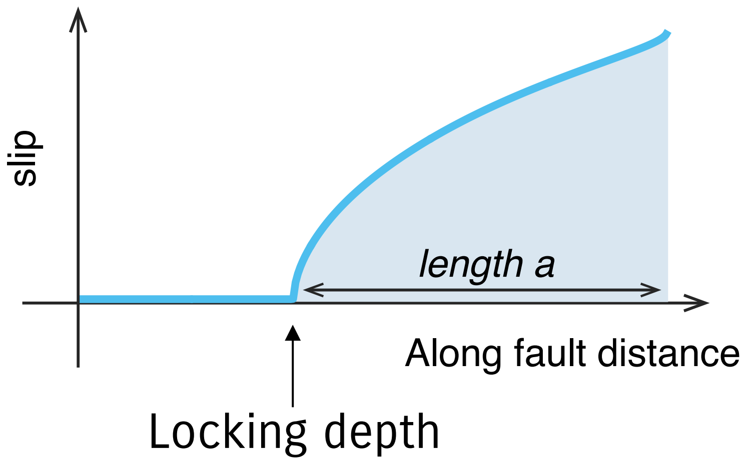
Can the interseismic transition depth change with time?



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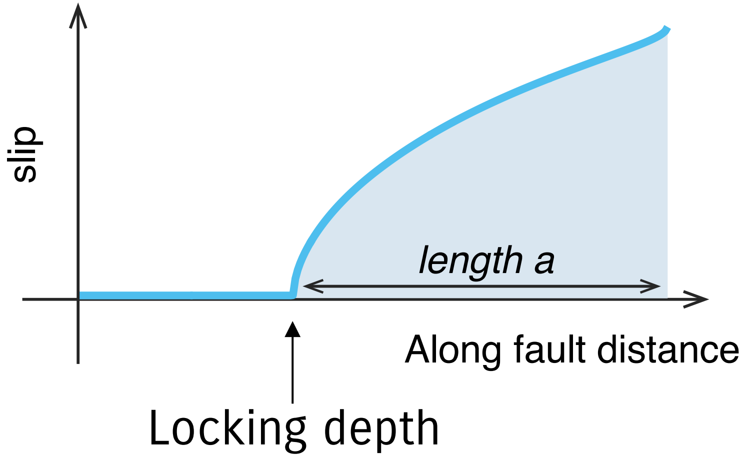

Slip $s(z,t) = f(z,t)v^{\infty}t$

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

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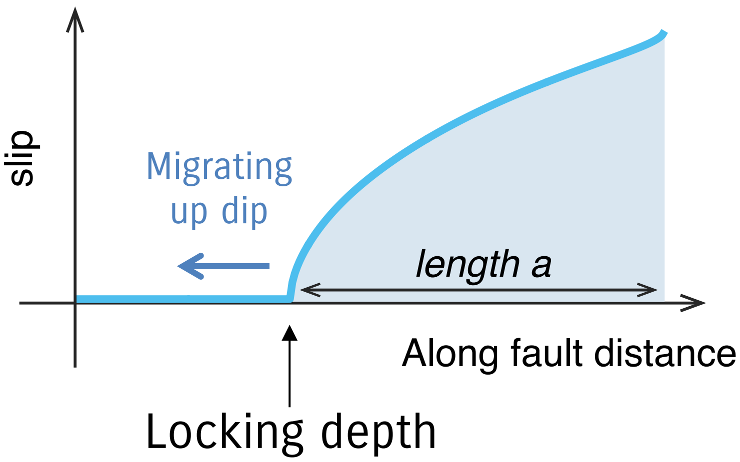

Slip $$s(z,t) = f(z,t)v^{\infty}t$$

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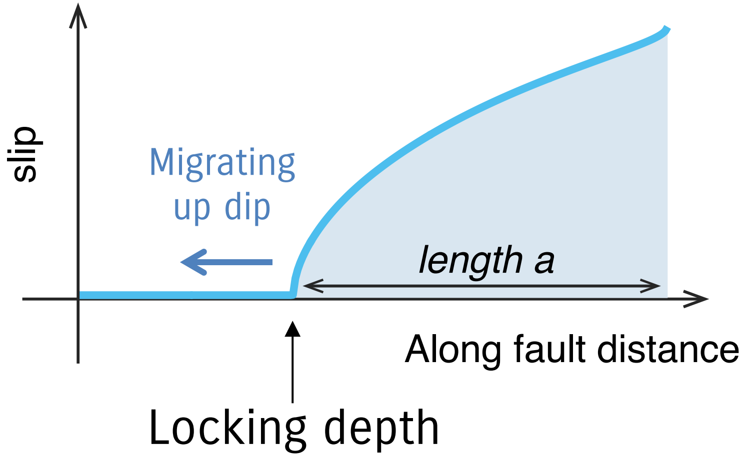

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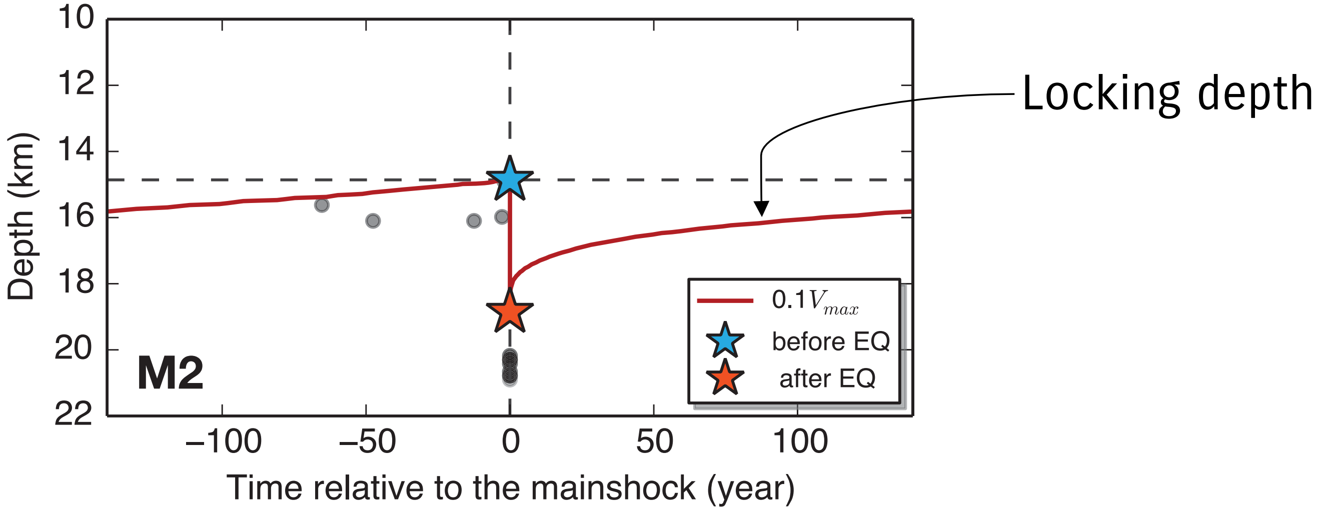
$$= f(z,t)v^{\infty} + v^{\infty}t\frac{\partial f}{\partial a}\boxed{\frac{\partial a}{\partial t}}$$

Propagation rate

Temporal evolution of the locking depth

Numerical simulations from Jiang & Lapusta (2016)



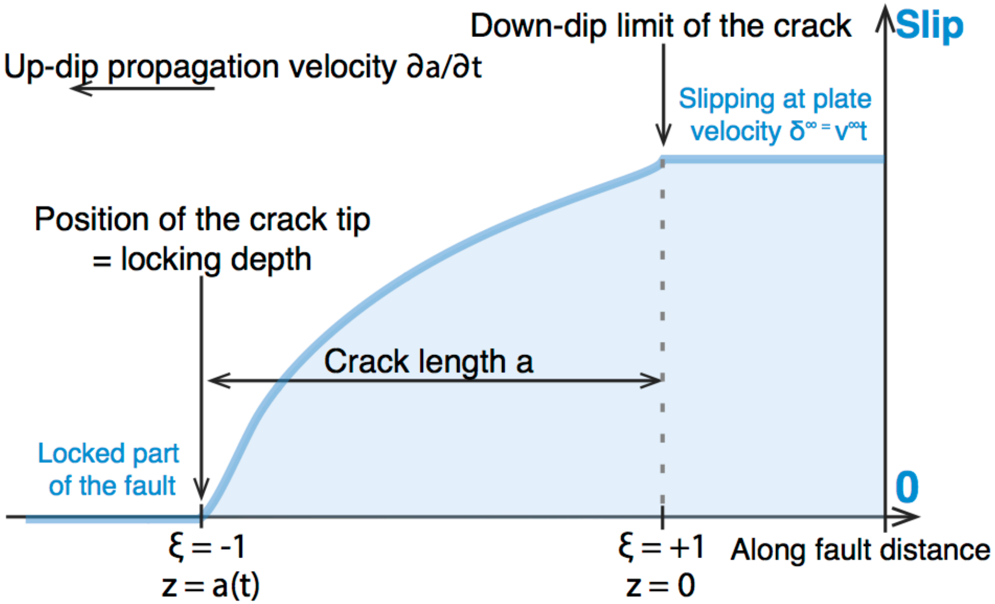
The locking depth migrates up dip → the size of the locked region reduces w/ time

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 $$\xi = 1 - \frac{2z}{a}$$

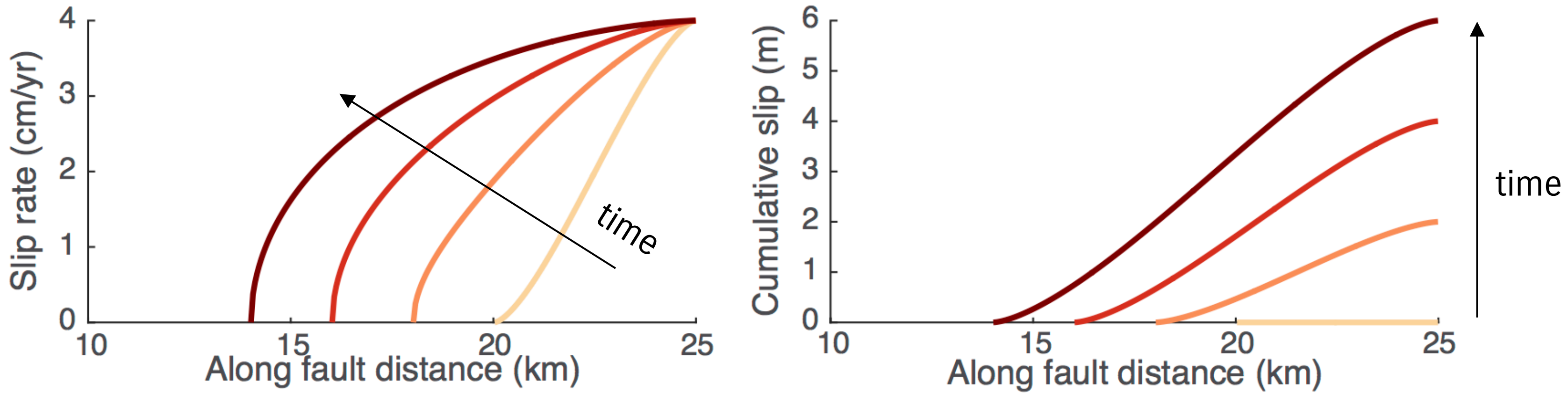
For a crack with finite stress at the crack tip and driven by steady displacement:

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

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

Slip rate $$\frac{ds}{dt} = g(\xi(t)) + a(t) \sum_{i=2}^{\infty} \frac{\partial c_i(t)}{\partial t} f_i(\xi(t)) + \underbrace{\frac{\partial a}{\partial t} \left[t \frac{u(\xi(t))}{a(t)} + \sum_{i=2}^{\infty} c_i(t) v(\xi(t)) \right]}_{\text{Propagation effect}}$$

Effect of the propagation



Crack model for the interseismic slip profile

New method to derive expressions for stress drop, slip and slip rate

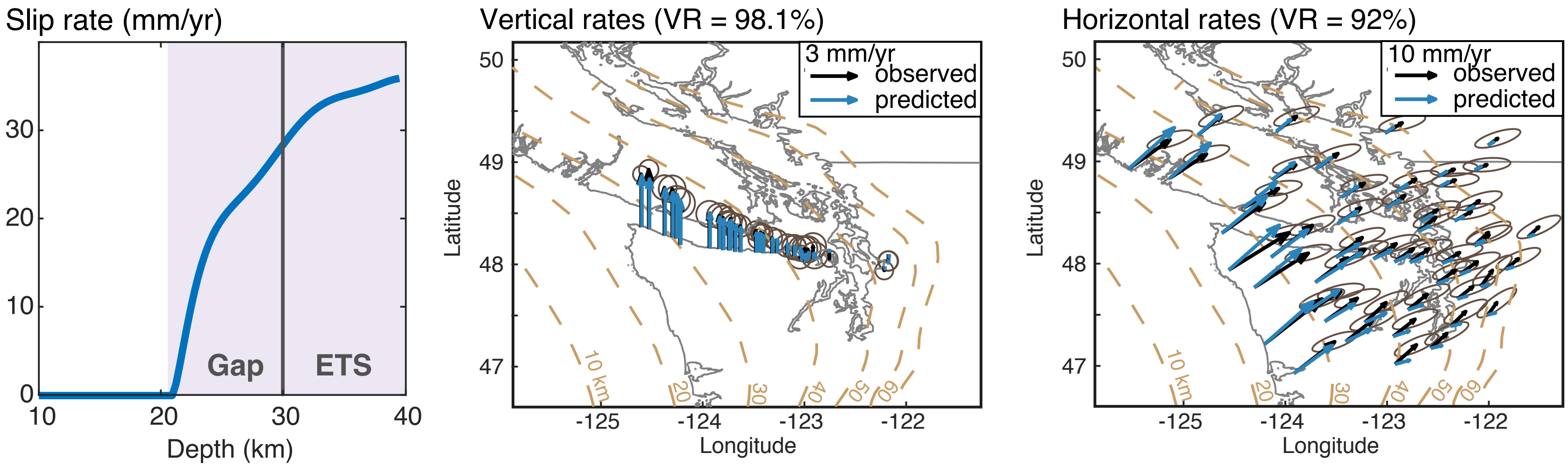
- Allows for the up dip propagation of the creeping region
- Massively underdetermined (as most geodetic inversions)
- Can be used to invert deformation rates using MCMC methods under specific assumptions ($c_i = 0$, stress characteristics in the ETS region, etc.) to look for extremal models (e.g., bounds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

Application to Cascadia

Non propagating crack, invert for c_i (N=6)

Best fitting model (MCMC inversion)

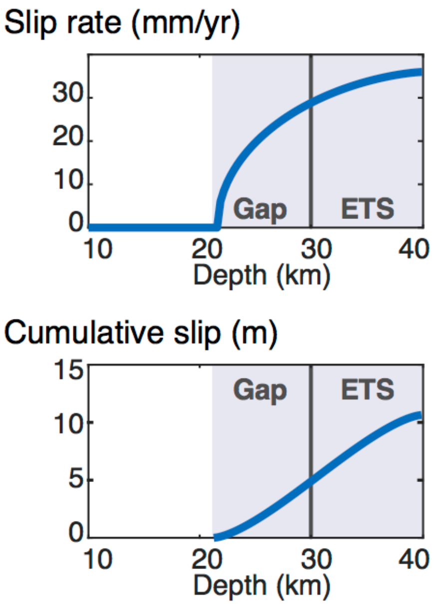
Locking depth: 20.5km

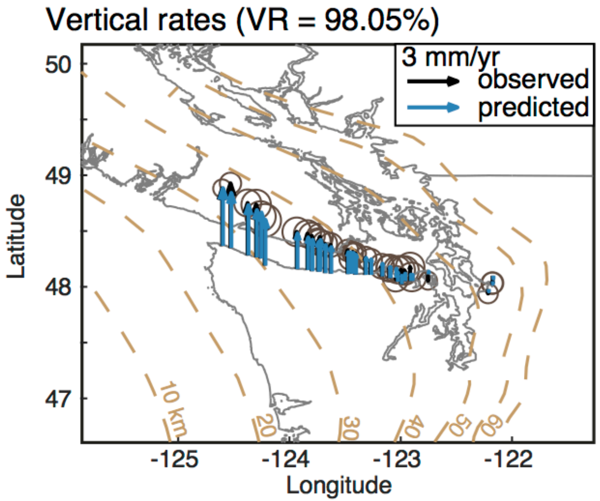


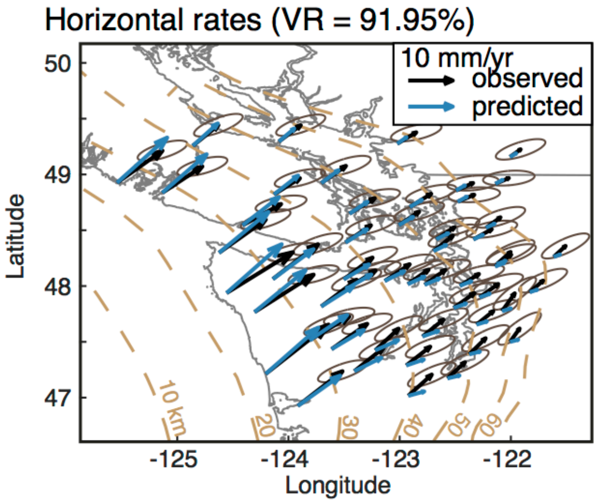
Application to Cascadia

Propagating crack

<u>Best fitting model (MCMC inversion)</u>
Locking depth: 21km
Up-dip propagation velocity: 33.4m/year

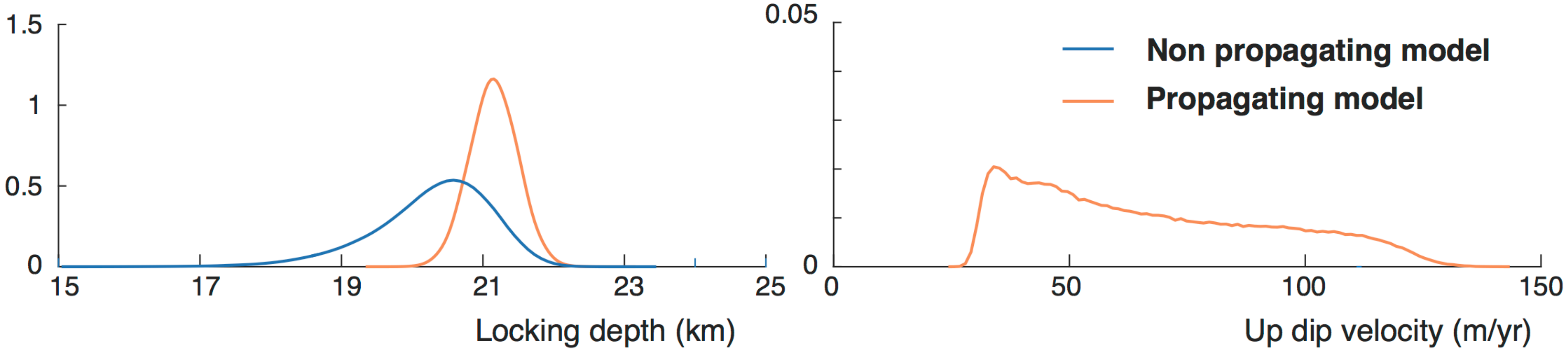






Application to Cascadia

Posterior distributions



Application to Cascadia

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 $\boldsymbol{\partial c_i / \partial t} = 0$

Application to Cascadia

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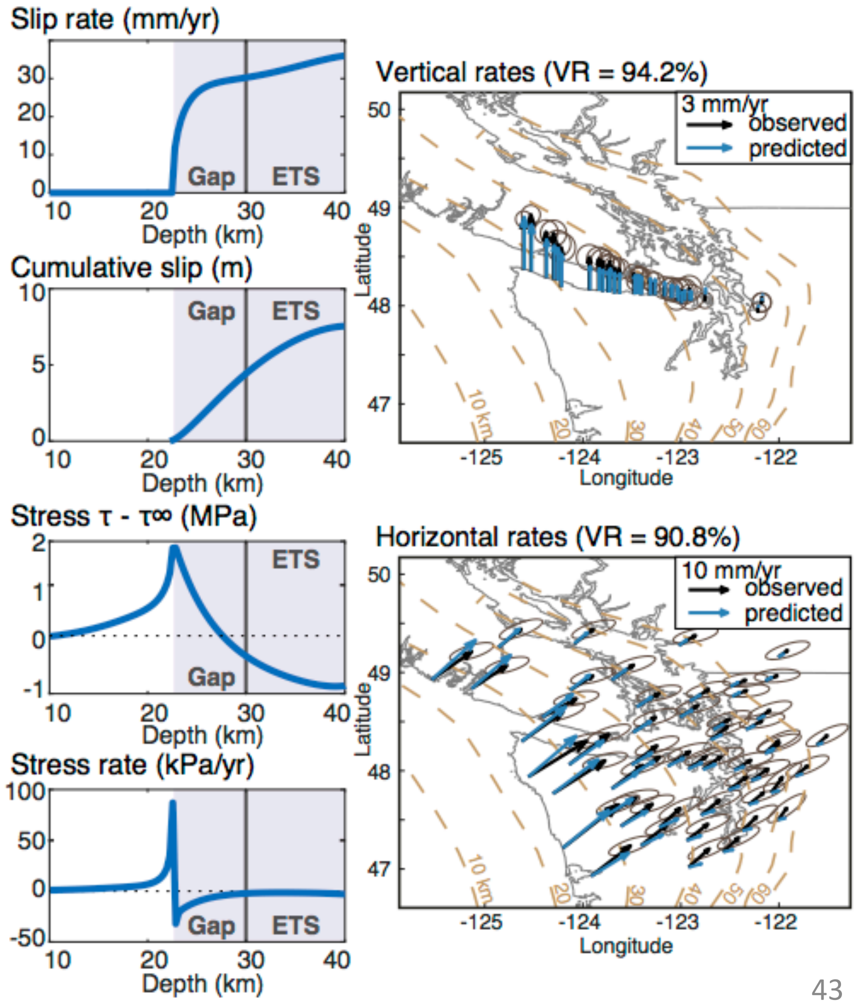

<u>Best fitting model (MCMC inversion)</u>

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

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Thanks!

Questions? lbruhat@stanford.edu