Slow Slip and Dynamic Rupture as a Competition Between Dilatant Strengthening and Thermal Weakening

Paul Segall
Andrew Bradley
Stanford University

Also: Allan Rubin, Jim Rice, Yajing-Liu, and others

Possible Mechanisms for Slow Slip

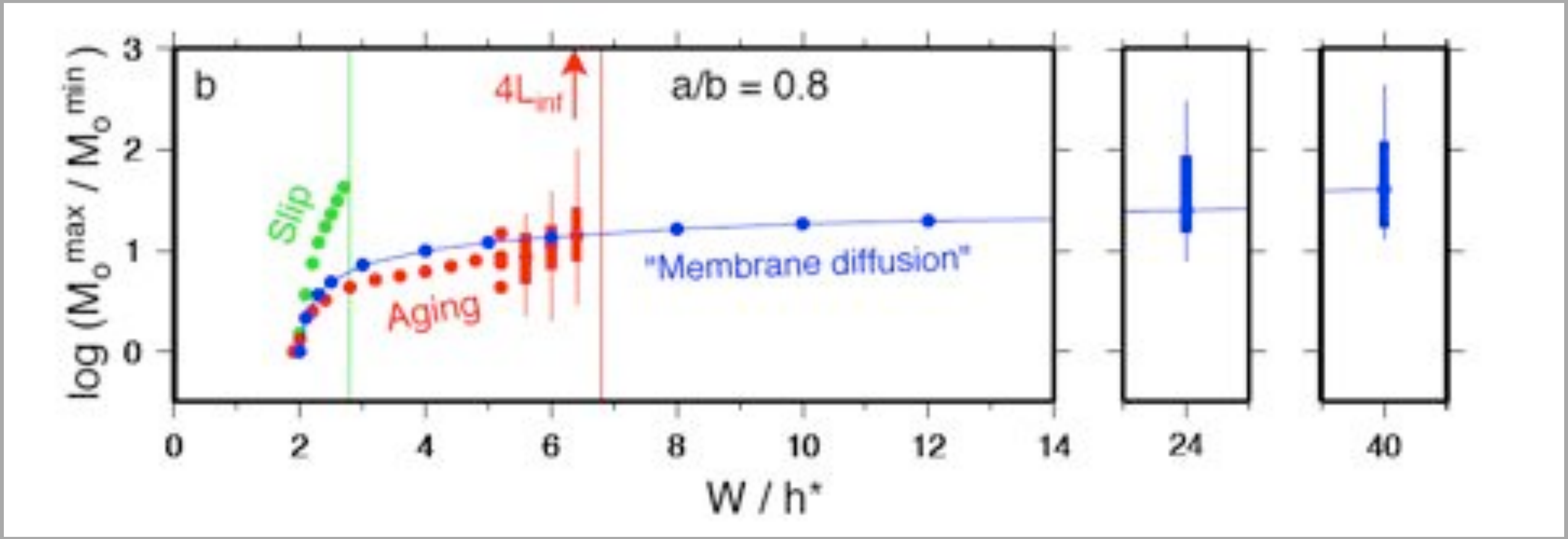
- Change in frictional behavior at high slip speed [e.g., Shibazaki and Iio, 2003; Shibazaki and Shimamoto, 2007].

- Rate-state friction near neutral stability [Yoshida and Kato, 2003; Kuroki et al, 2004; Liu and Rice, 2005; 2007; Rubin, 2008].

- Stable friction perturbed from steady-state [Perfittini and Ampuero, 2009].

- Dilatant stabilization [Rice, 1975, Rice and Simons , 1976, Rudnicki, 1979]; in rate-state friction context [Segall and Rice, 1995; Segall and Rubin, 2007-9 AGU; Segall et al, 2010 in press, Liu and Rubin, in press], also Suzuki and Yamashita [2008, AGU; JGR, 2009].

Rate-State Friction Alone: Goldilocks Problem



Segall, Rubin, Bradley, Rice,JGR in press.

- Slip-zone too small -> No transient.
- Slip-zone too large -> Dynamic slip.
- “Just right” range small for preferred slip-law.
- Dilatancy removes this problem.

Hypothesis

Velocity weakening rate-state friction nucleates localized slip.

If dilatancy stabilizes slip before thermal weakening onset → slow slip.

If dilatancy unable to limit slip speeds below thermal weakening limit → fast slip.

Previous work:

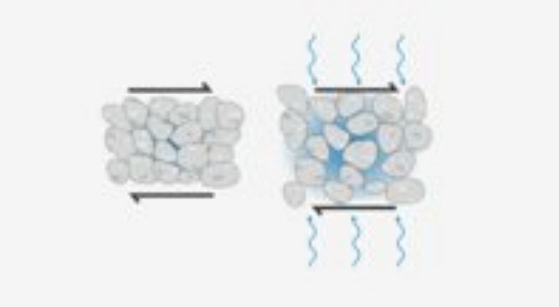
Isothermal approximate diffusion [Segall and Rubin, 2007 AGU; Liu et al 2008, AGU] building on Segall and Rice [1995] and Taylor and Rice [1998].

Slip weakening, thermo-poro dynamic, short (10 s) integration times [Suzuki and Yamashita, 2009; JGR]

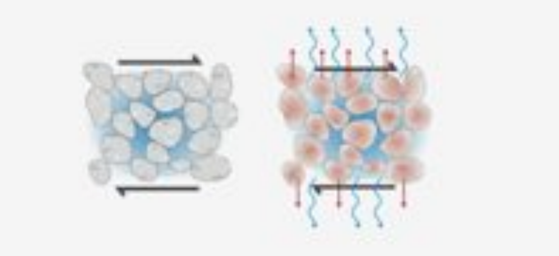
This work:

Rate-state proper thermo-poro diffusion, quasi-dynamic, integrated over many cycles (centuries).

Dilatancy: stabilizing



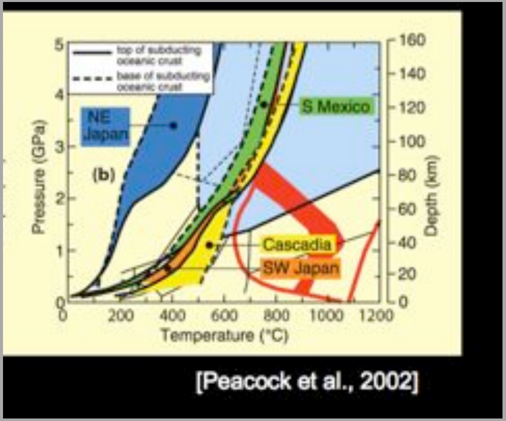
versus



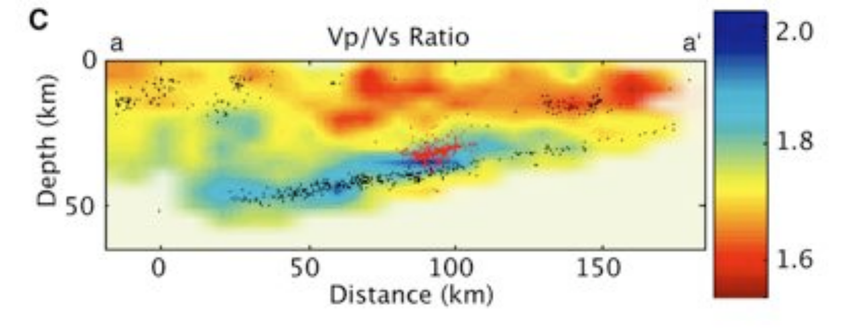
Thermal pressurization: de-stabilizing

High Pore-Pressure in ETS zones

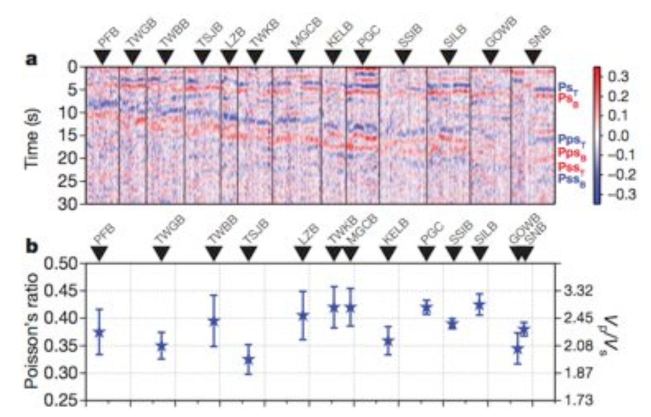
- High Vp/Vs
- Low Stress Drop
- Available Dehydration reactions

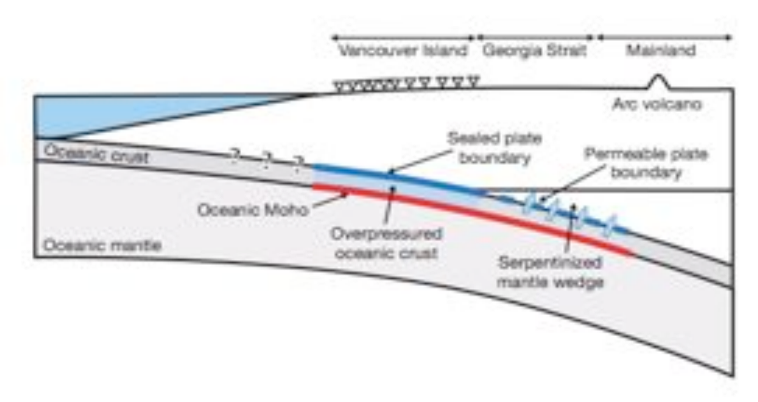


[Peacock et al., 2002]



Shelly et al, 2006





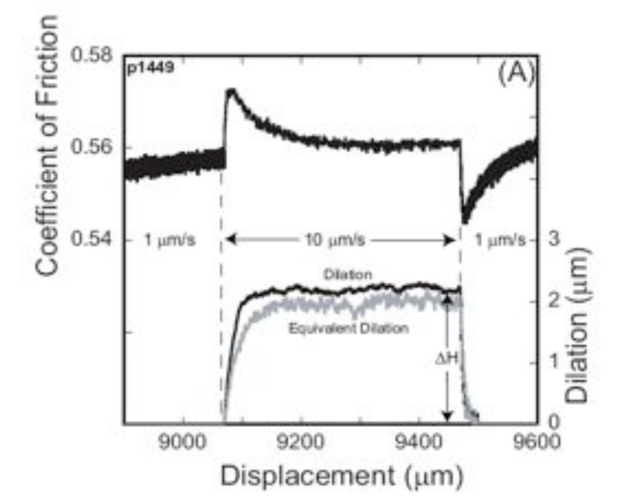
Audet et al, (Nature, 2009), conclude that near lithostatic pore-presure in slab crust.

Thermal pressurization weak at low effective stress → stable slip.

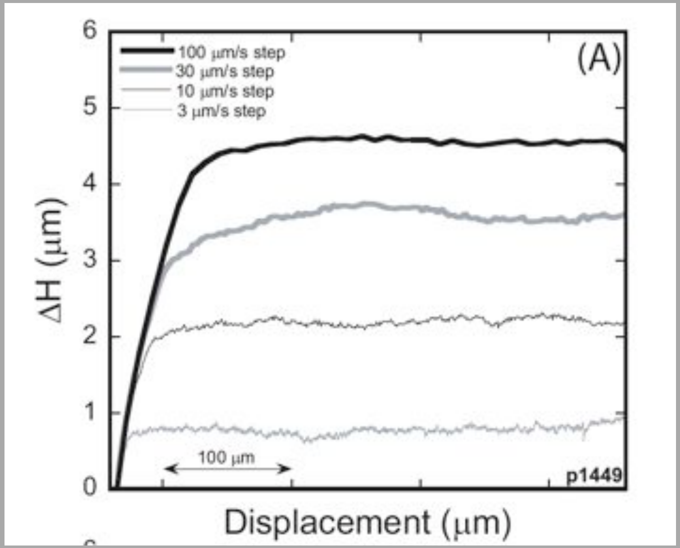
Approach

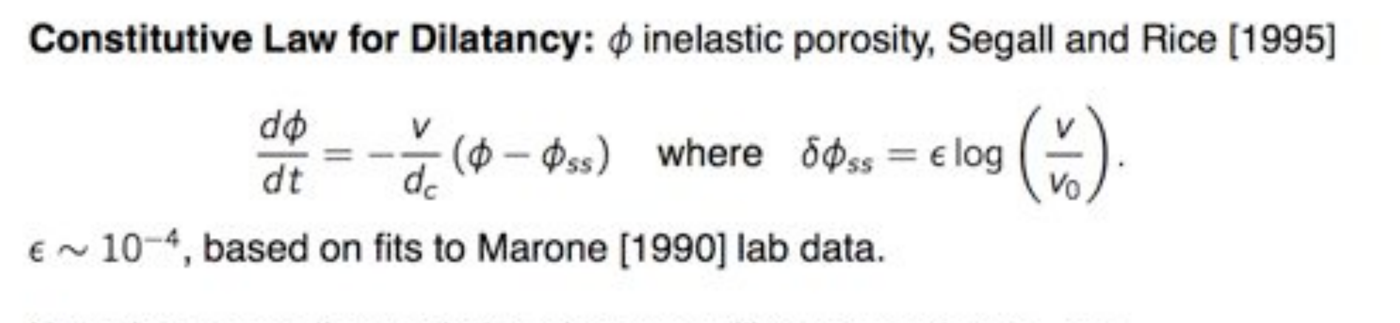
- Include only well documented (if not fully understood) fault physics.
- To the extent possible, use physical parameters based on laboratory experiments and field observations.
- Employ efficient numerical methods that permit simulation of many slow-slip and earthquake cycles. Approximations:
    - 2 dimensional elasticity, 1D fault
    - Limit of very thin shear zone
    - Approximate elastodynamics
- Compare simulations with slow-slip observables.

Dilatancy/Compaction:



Samuelson, Elsworth, Marone, (2009)

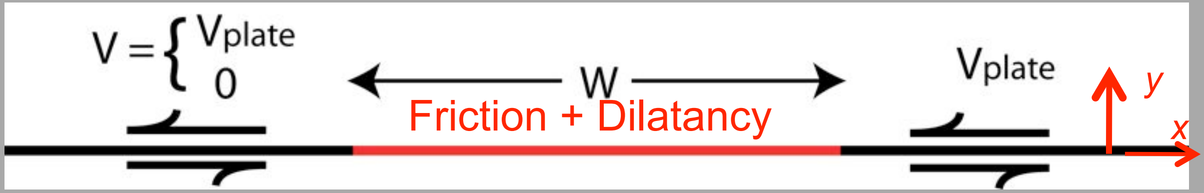




Constitutive Law for Dilatancy: ϕ inelastic porosity, Segall and Rice [1995]

$$\frac{d\phi}{dt} = -\frac{v}{d_c}(\phi - \phi_{ss}) \quad \text{where} \quad \delta\phi_{ss} = \epsilon \log\left(\frac{v}{v_0}\right).$$

$\epsilon \sim 10^{-4}$, based on fits to Marone [1990] lab data.



Momentum Balance On Fault [e.g., Rice 1993]

$$\underbrace{\frac{\mu}{2\pi(1-\nu)}\int_{-\infty}^{\infty}\frac{\partial\delta/\partial\xi}{\xi-x}d\xi}_{\text{shear stress}} - \underbrace{f(v,\theta)(\sigma-p)}_{\text{frictional resistance}} = \underbrace{\frac{\mu}{2v_s}v}_{\text{radiation damping}}$$

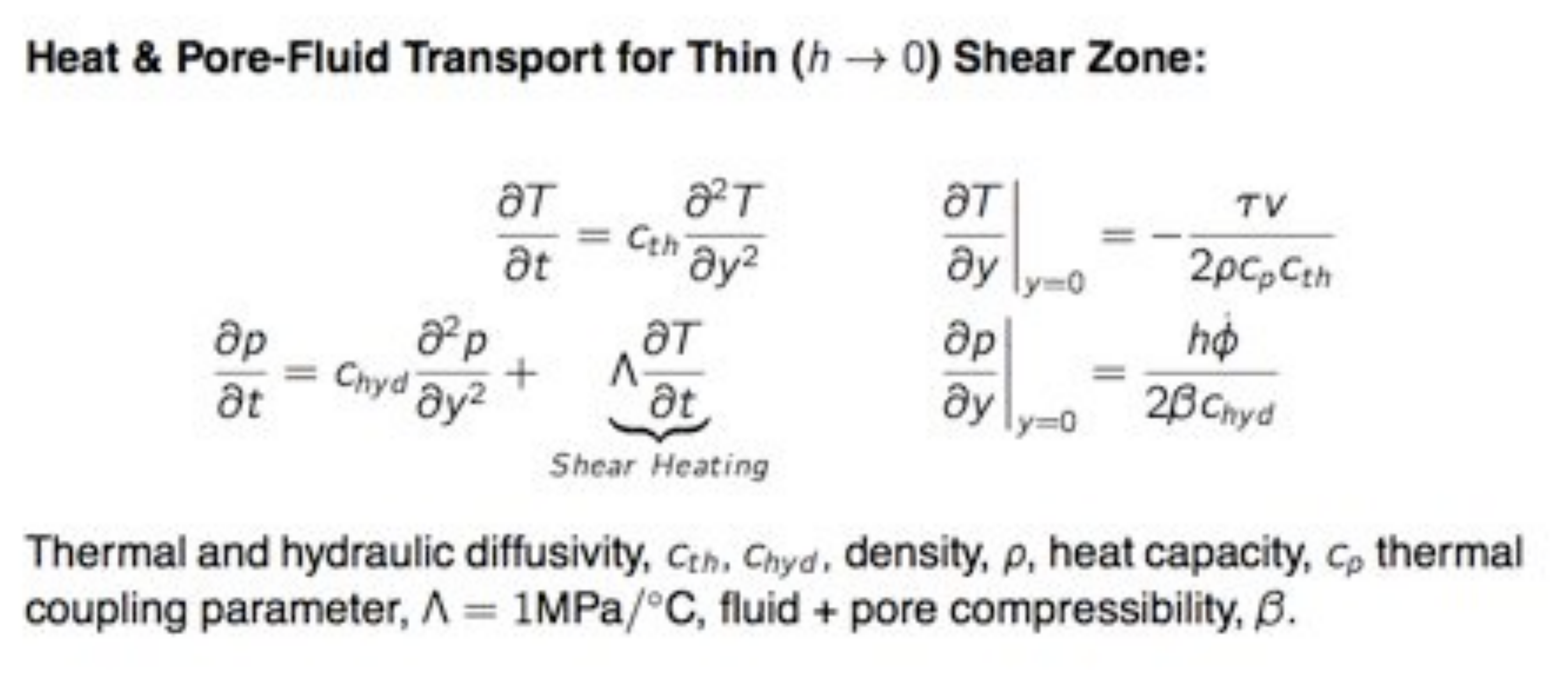
μ : Shear Modulus, δ : Slip, f : friction coefficient, v : slip speed, θ : "state"

Rate state friction: Ruina [1983]; Dieterich [1979]; Linker and Dieterich [1992].

$$\tau = \underbrace{f(v,\theta)}_{\text{fric. coeff.}}\ \underbrace{(\sigma-p)}_{\text{effec. stress}} = (\sigma-p)\left[f_0 + a\ln\left(\frac{v}{v_0}\right) + b\ln\left(\frac{\theta}{\theta_0}\right)\right]$$

$$\frac{d\theta}{dt} = \underbrace{-\frac{\theta v}{d_c}\ln\left(\frac{\theta v}{d_c}\right)}_{\text{slip law}} - \underbrace{\frac{\alpha\theta}{b(\sigma-p)}\frac{d}{dt}(\sigma-p)}_{\text{Linker Dieterich effect}}$$

Fluid & Heat Transport for Thin Shear Zone



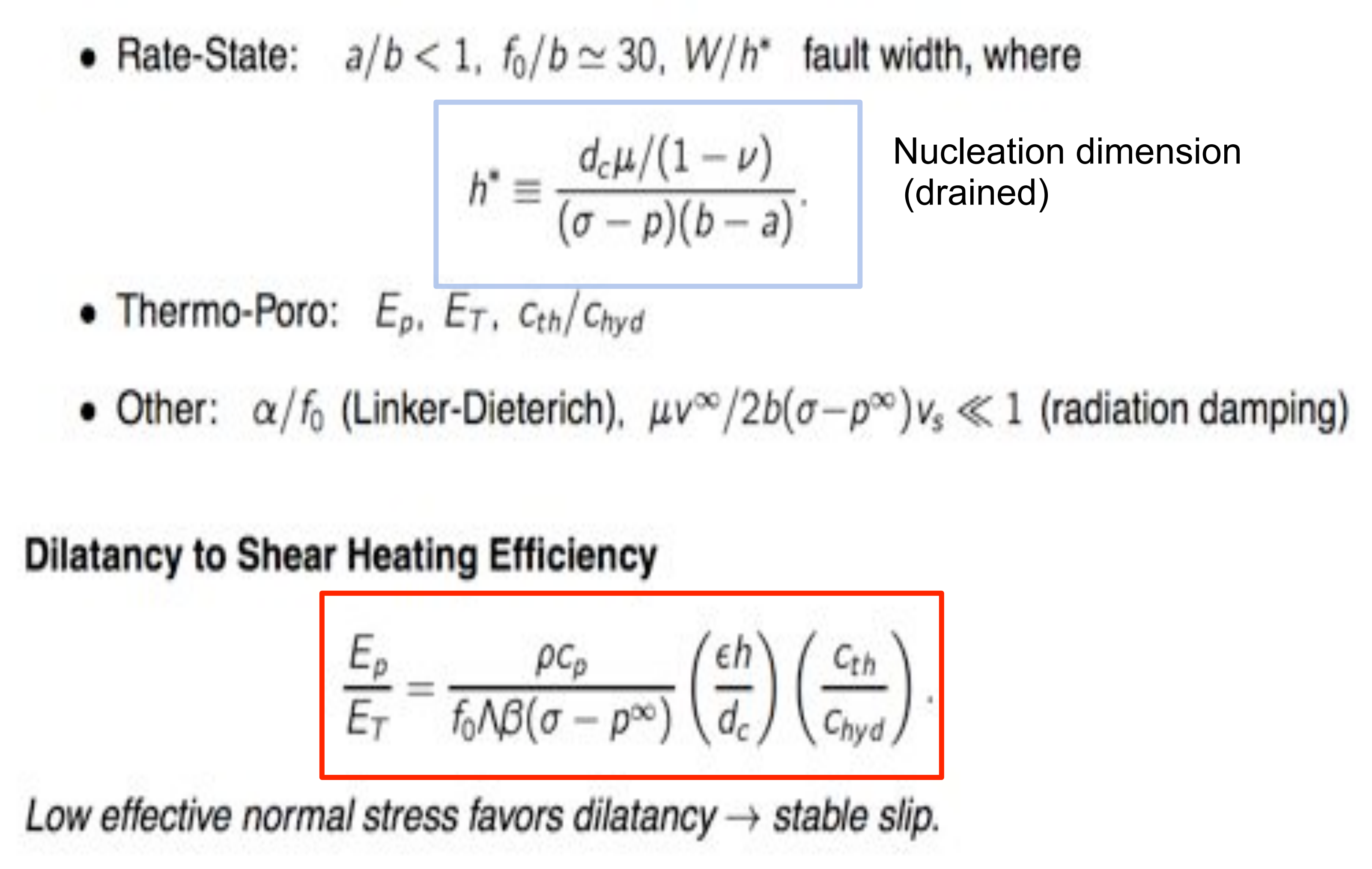
Heat & Pore-Fluid Transport for Thin ($h \to 0$) Shear Zone:

$$\frac{\partial T}{\partial t} = c_{th}\frac{\partial^2 T}{\partial y^2} \qquad \left.\frac{\partial T}{\partial y}\right|_{y=0} = -\frac{\tau v}{2\rho c_p c_{th}}$$

$$\frac{\partial p}{\partial t} = c_{hyd}\frac{\partial^2 p}{\partial y^2} + \underbrace{\Lambda\frac{\partial T}{\partial t}}_{\text{Shear Heating}} \qquad \left.\frac{\partial p}{\partial y}\right|_{y=0} = \frac{h\phi}{2\beta c_{hyd}}$$

Thermal and hydraulic diffusivity, c_{th}, c_{hyd}, density, ρ, heat capacity, c_p thermal coupling parameter, $\Lambda = 1\text{MPa}/^{\circ}\text{C}$, fluid + pore compressibility, β.

[e.g., w/out dilatancy, Rice, 2006]



- Rate-State: $a/b < 1$, $f_0/b \simeq 30$, W/h^* fault width, where

$$\boxed{h^* \equiv \frac{d_c\mu/(1-\nu)}{(\sigma-p)(b-a)}.}$$

Nucleation dimension
(drained)

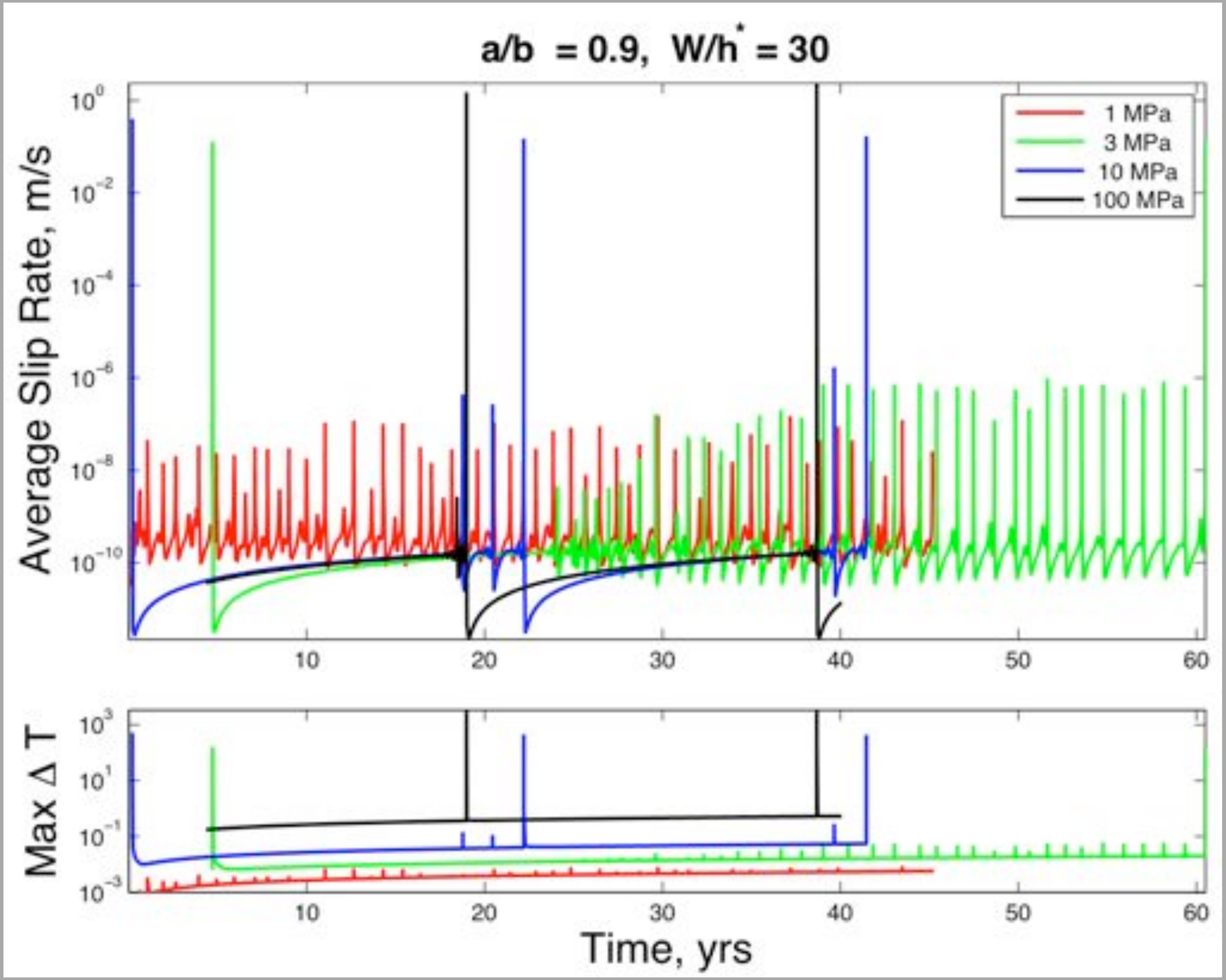
- Thermo-Poro: E_p, E_T, c_{th}/c_{hyd}
- Other: α/f_0 (Linker-Dieterich), $\mu v^\infty/2b(\sigma-p^\infty)v_s \ll 1$ (radiation damping)

Dilatancy to Shear Heating Efficiency

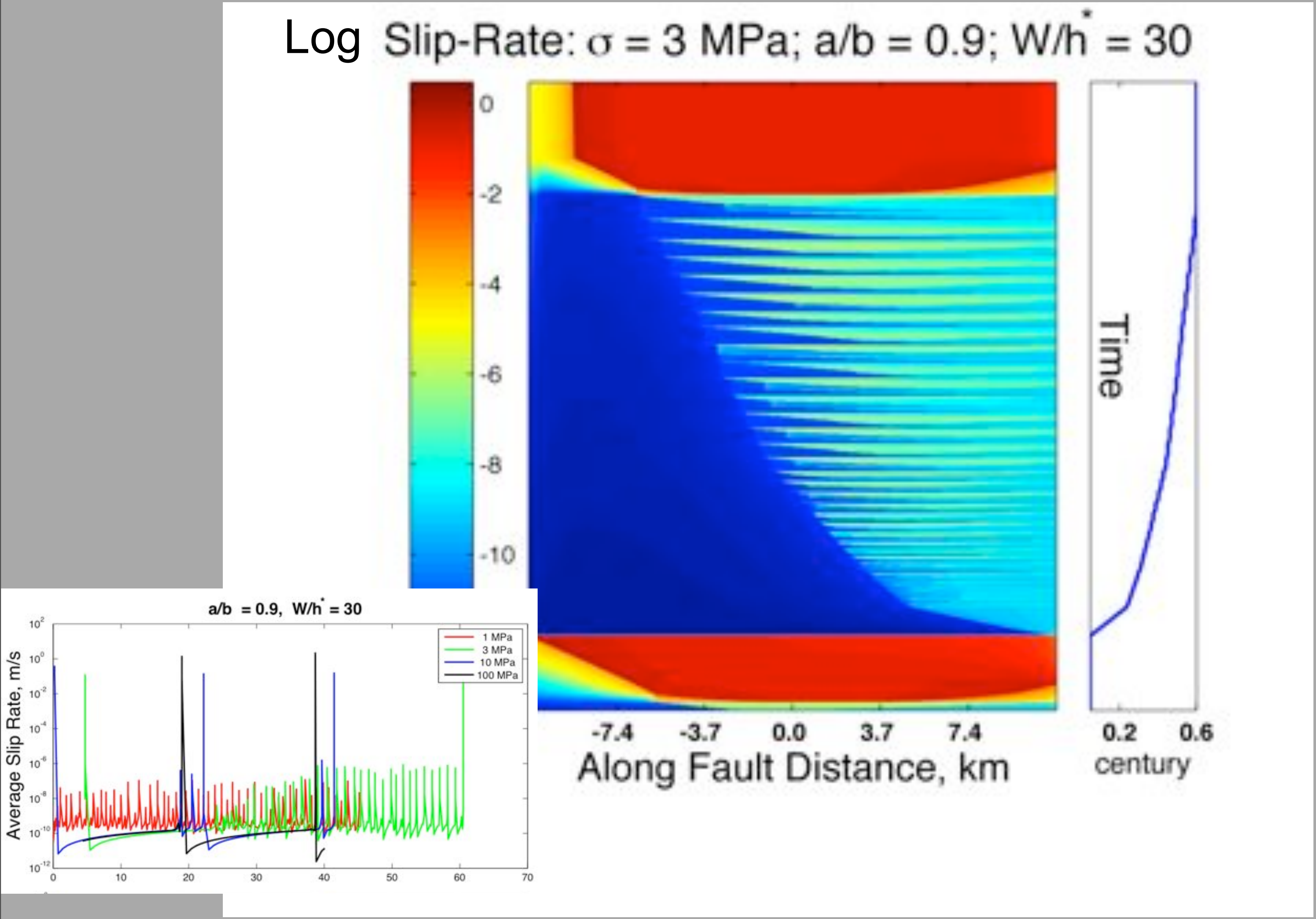
$$\boxed{\frac{E_p}{E_T} = \frac{\rho c_p}{f_0 N\beta(\sigma-p^\infty)}\left(\frac{\epsilon h}{d_c}\right)\left(\frac{c_{th}}{c_{hyd}}\right).}$$

Low effective normal stress favors dilatancy → stable slip.

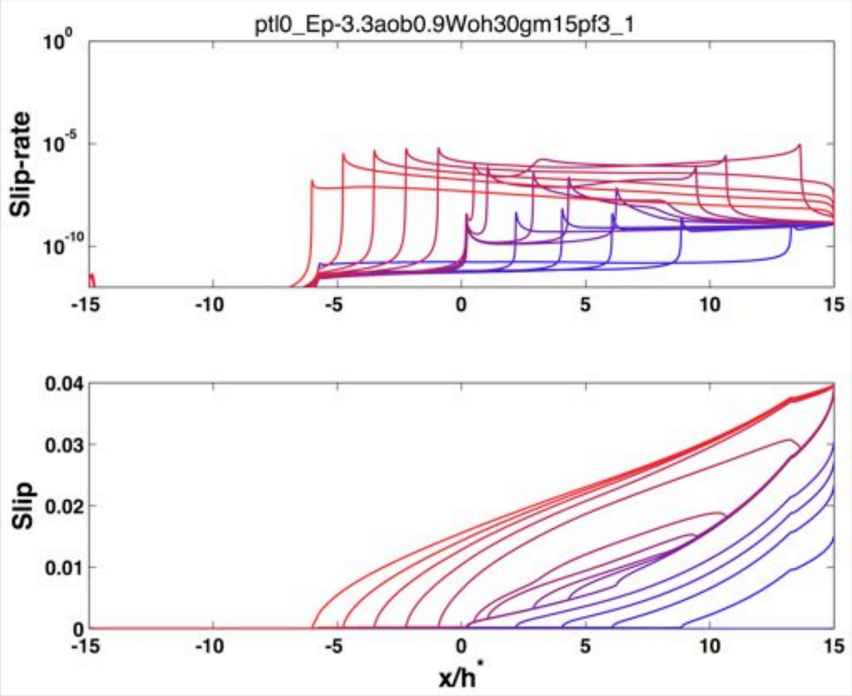
Stable at Low Effective Stress (Fixed Length)

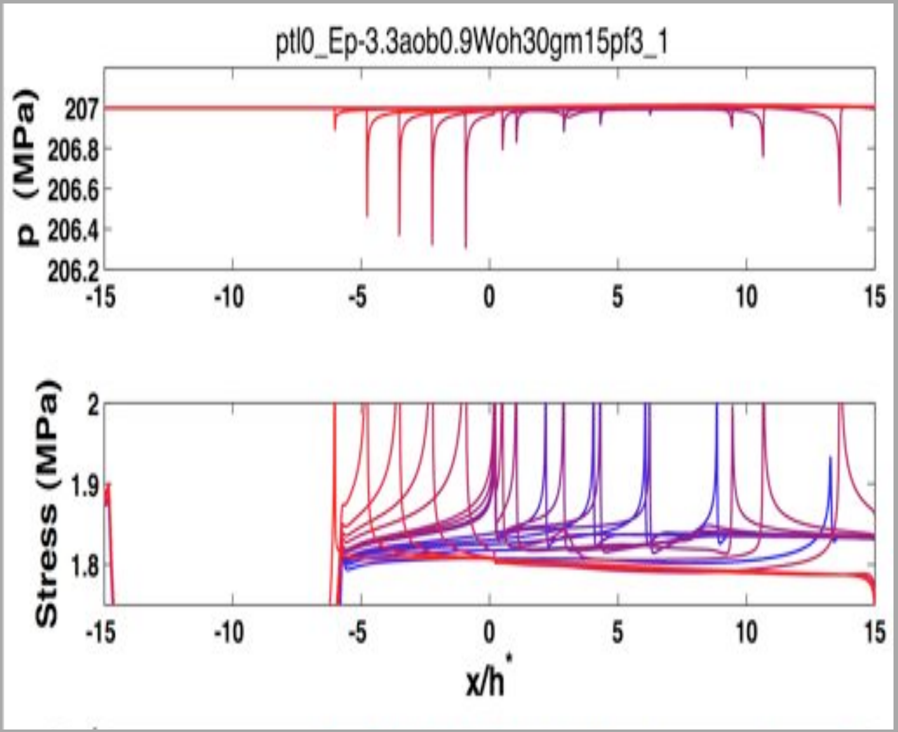


Space-Time Evolution: 3 MPa Effective Stress

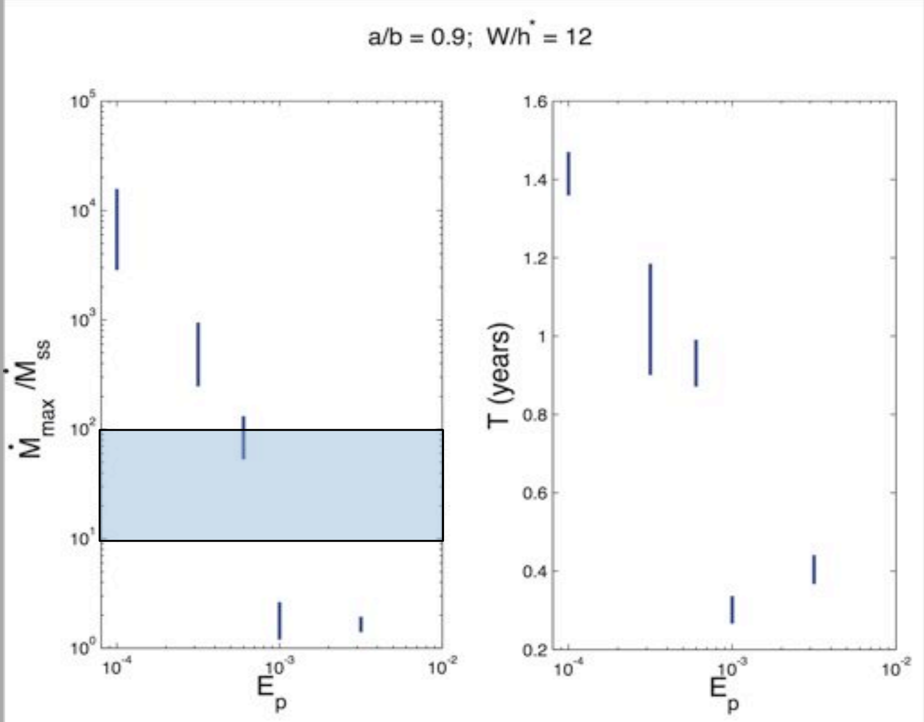


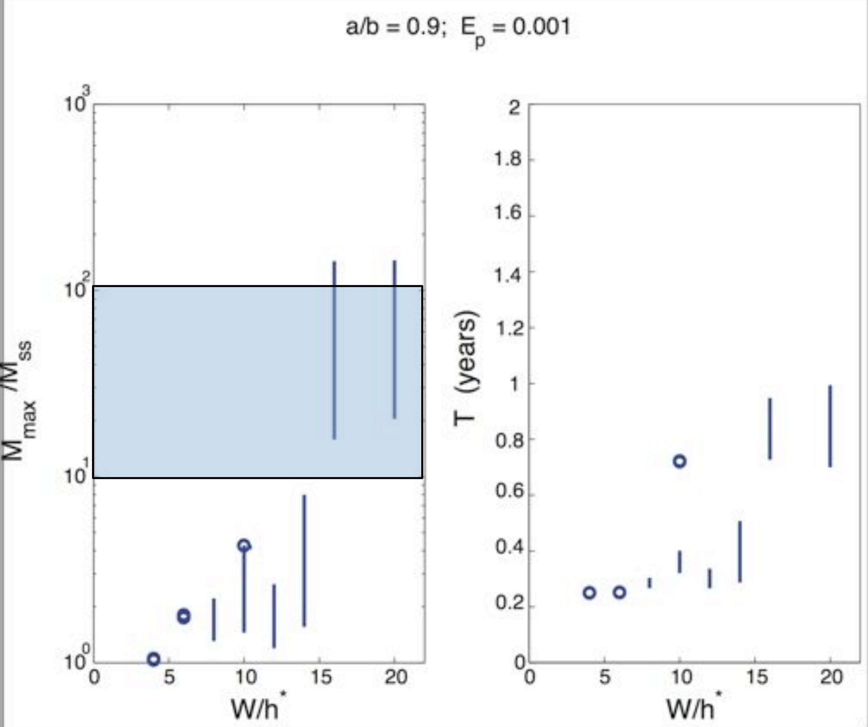
Slow Slip Phase: 3 MPa Effective Stress





Slip Rate and Period in Range of Observations





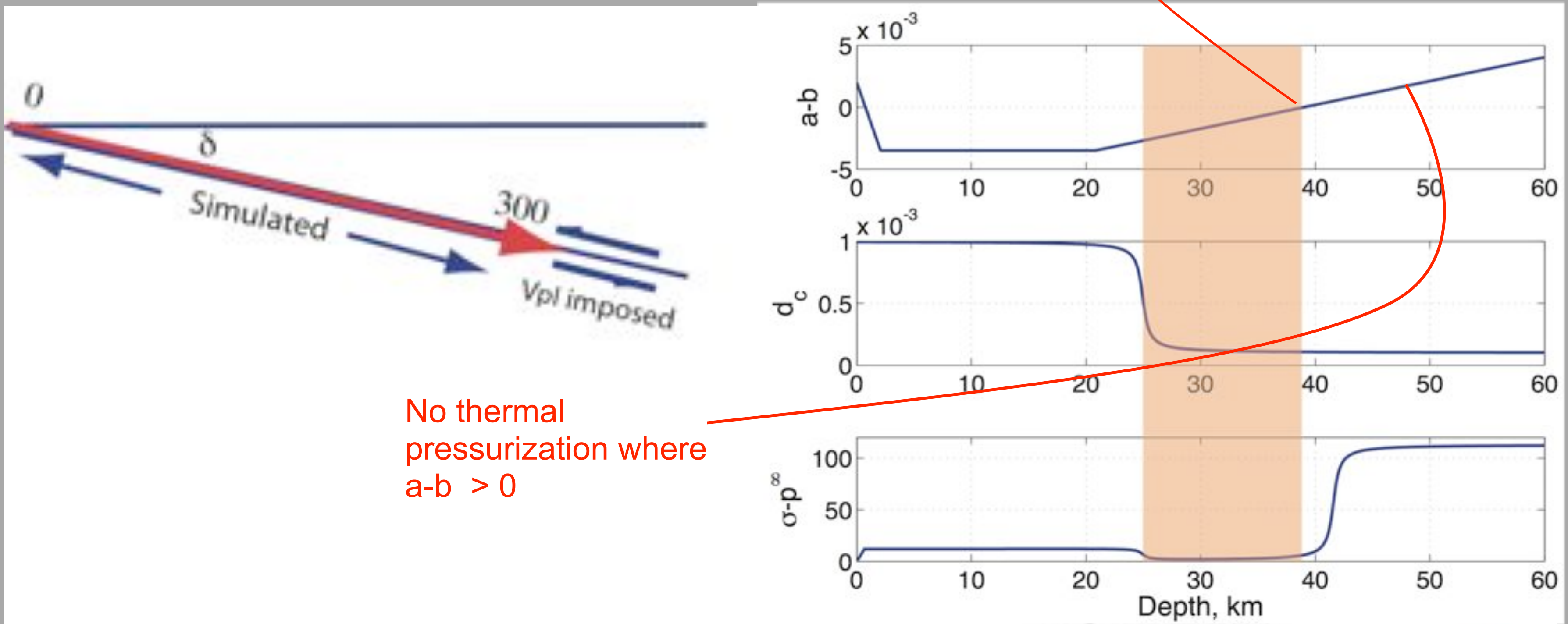
Increasing Dilatancy or
Decreasing Eff. Stress

Increasing Slip-zone Length

Slow-slip like behavior occurs for broad parameter range. (Isothermal calculations [Segall et al, 2010 in press])

Depth Dependent Properties and Effective Stress

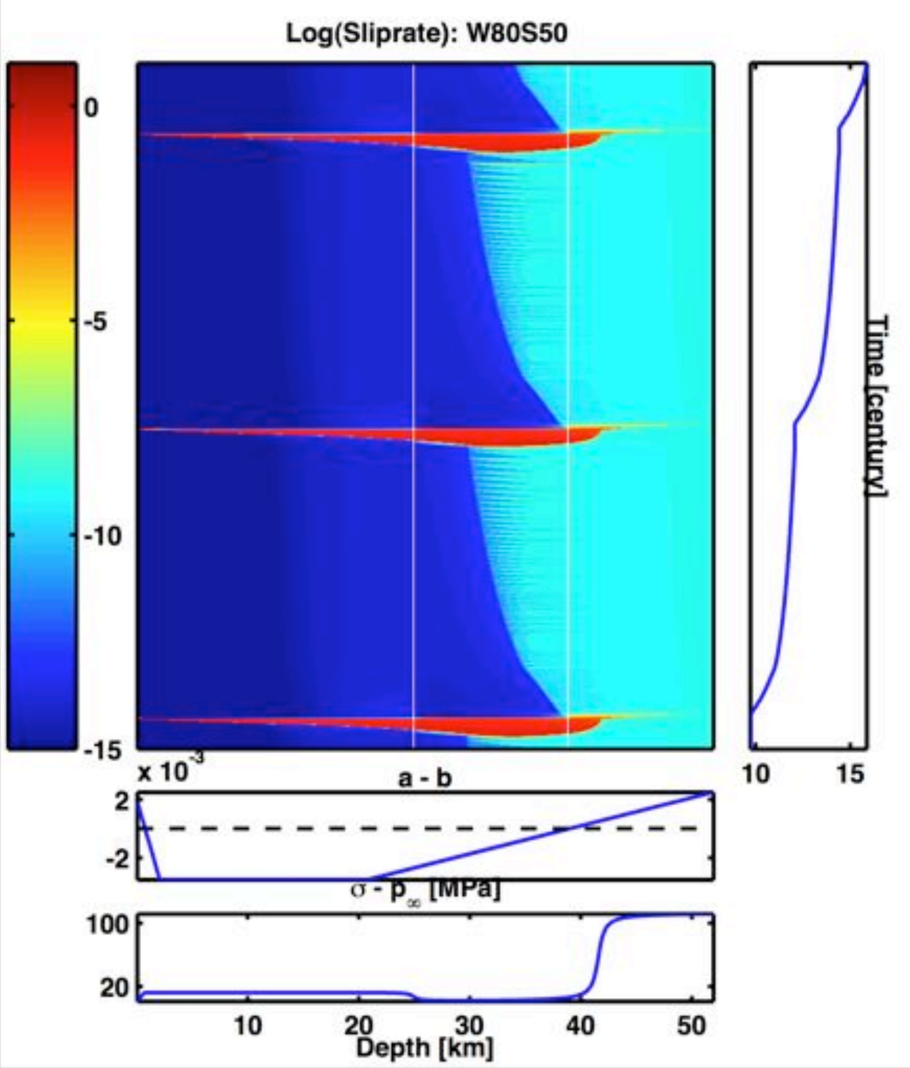
Transition at 510 C

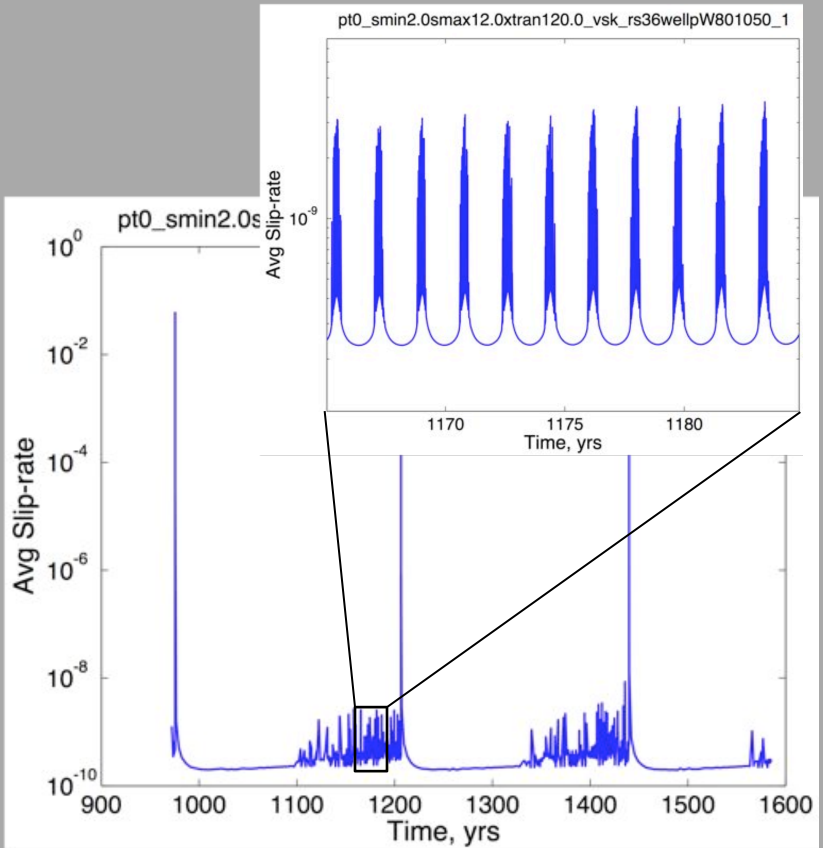


No thermal pressurization where a-b > 0

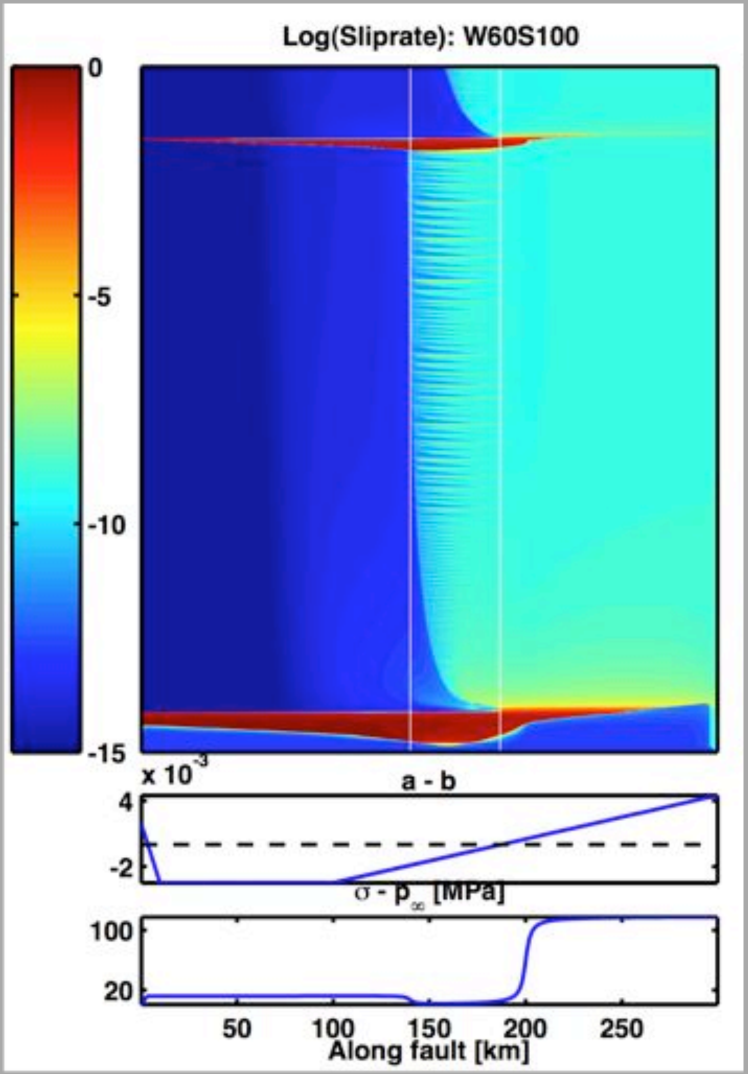
- Friction distribution loosely based on lab data for gabbro from He et al [2007], mapped to depth using Cascadia geotherm [Peacock, 2009], similar to Liu and Rice [2009].
- Very low effective stress in suggested ETS region, modest effective stress up-dip.

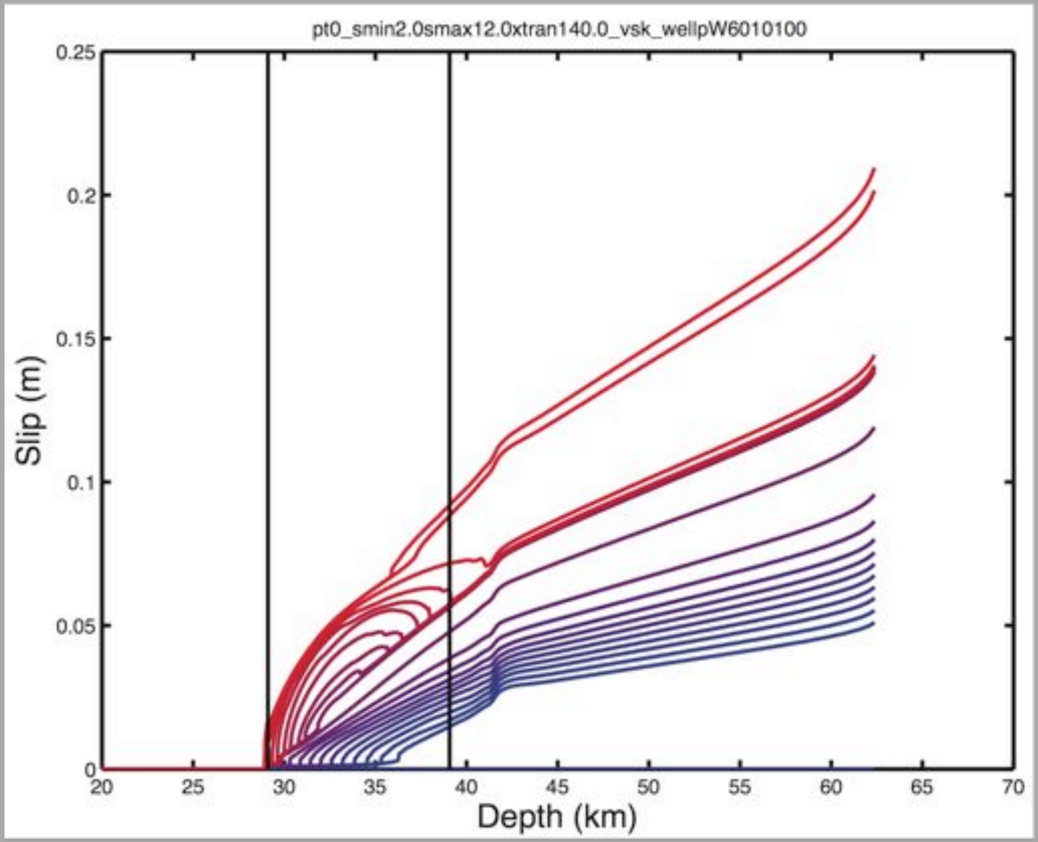
Slow slip events, occur spontaneously and may penetrate farther up-dip with time.





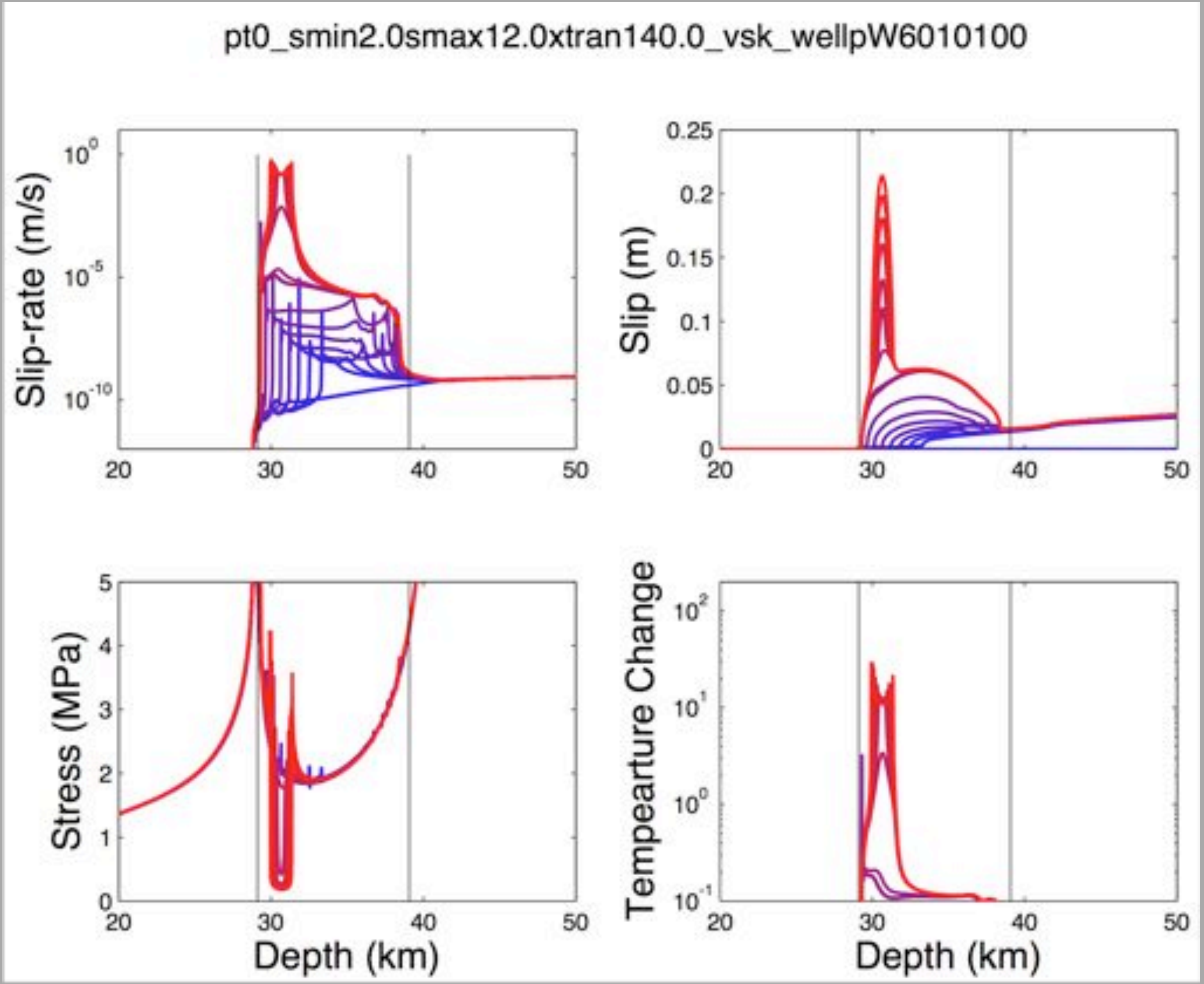
Inter-ETS propagation

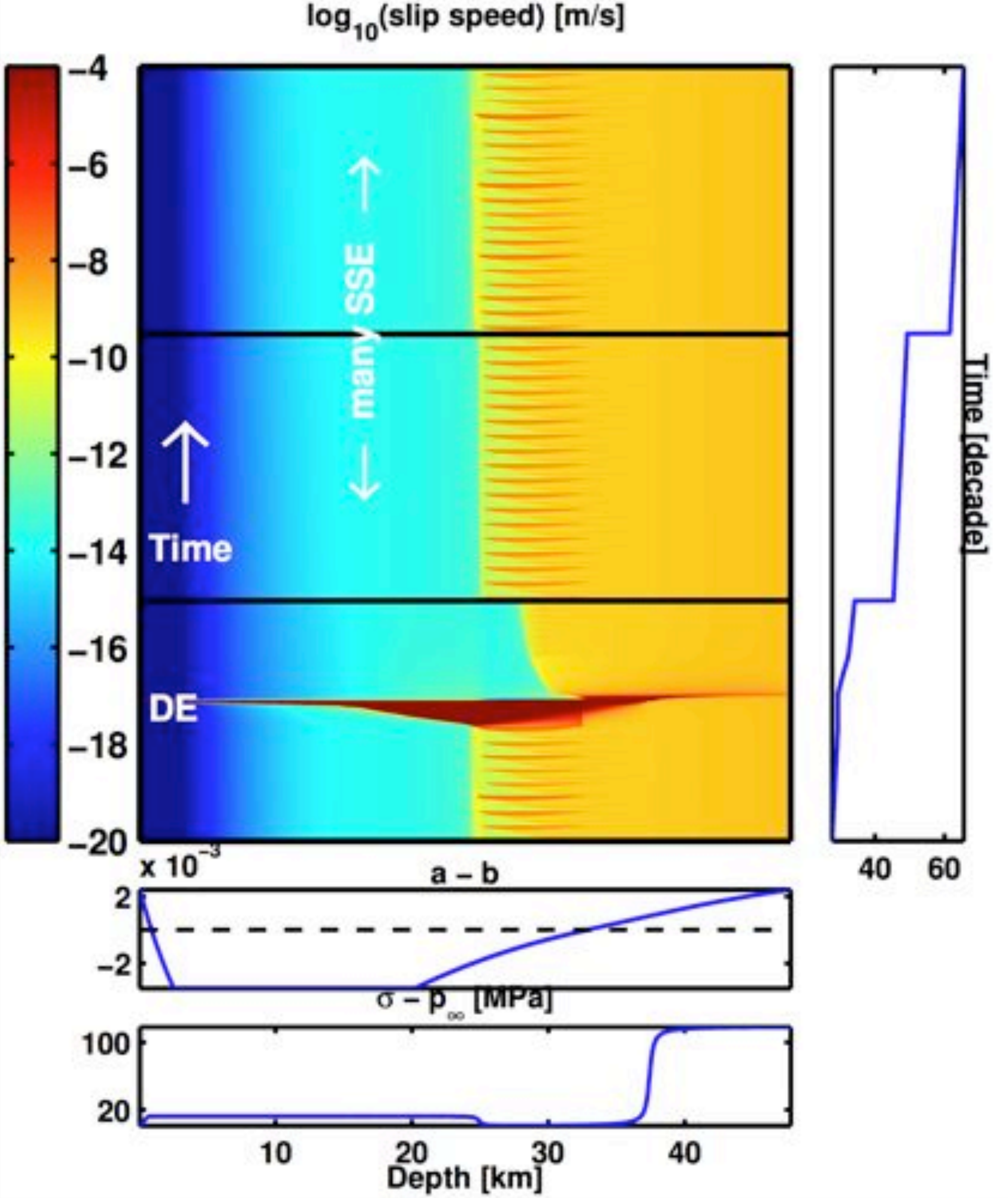




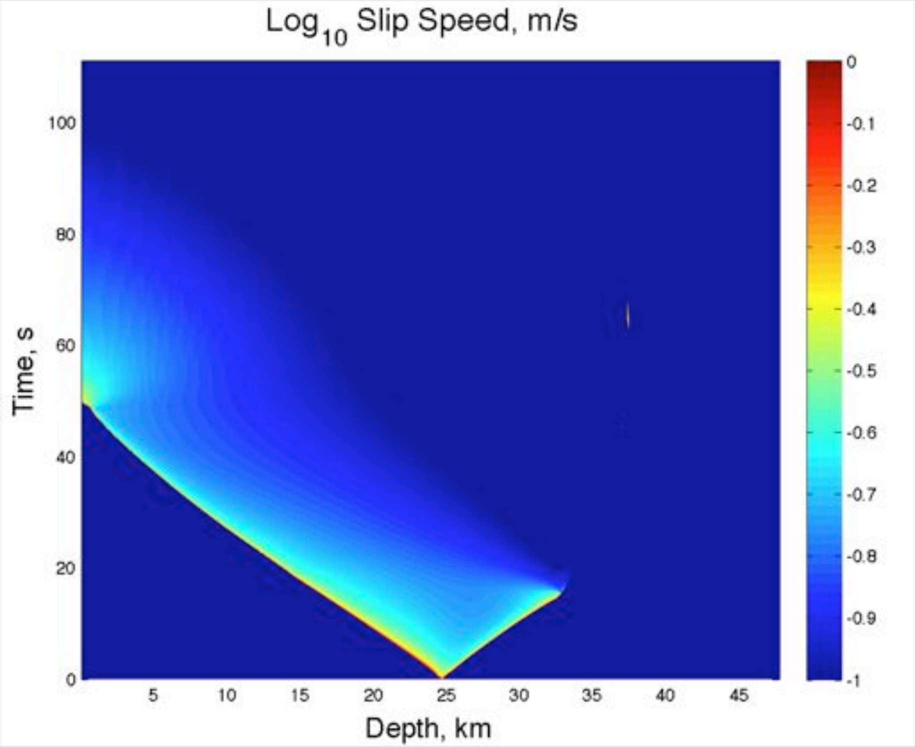
Inter-ETS phase may be reflected in tremor and may be detectable in inter-event GPS velocities

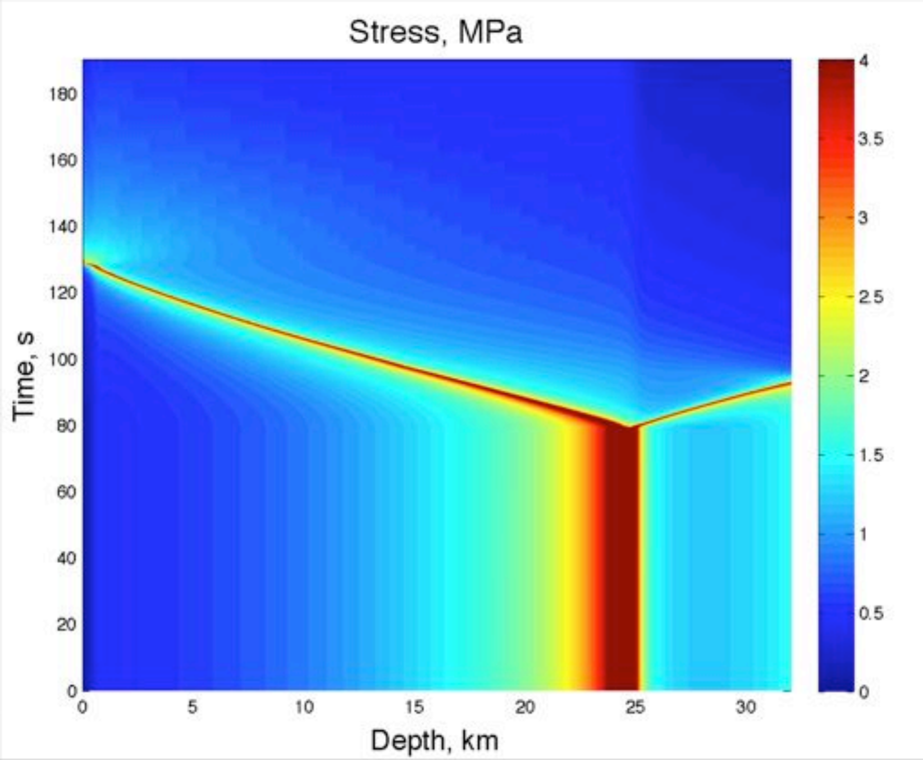
For sufficiently wide low stress zones, SSE ultimately nucleate dynamic events



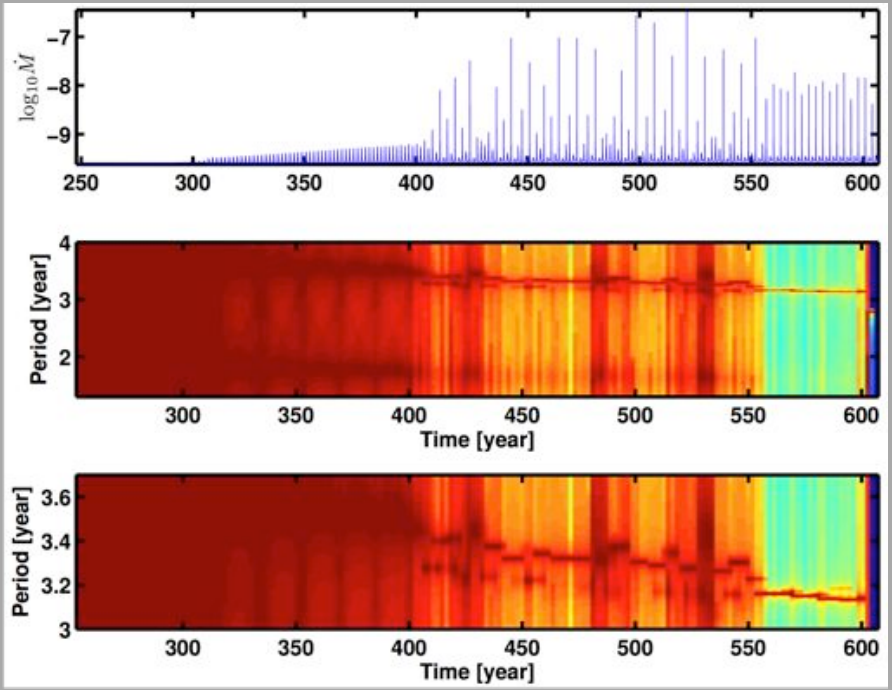

log10(slip speed) [m/s]
-4
-6
-8
-10
-12
-14
-16
-18
-20
many SSE
Time
DE
Time [decade]
40
60
x 10^-3
a – b
2
−2
σ – p∞ [MPa]
100
20
10
20
30
40
Depth [km]

Dynamic Event Nucleates at Edge of ETS zone

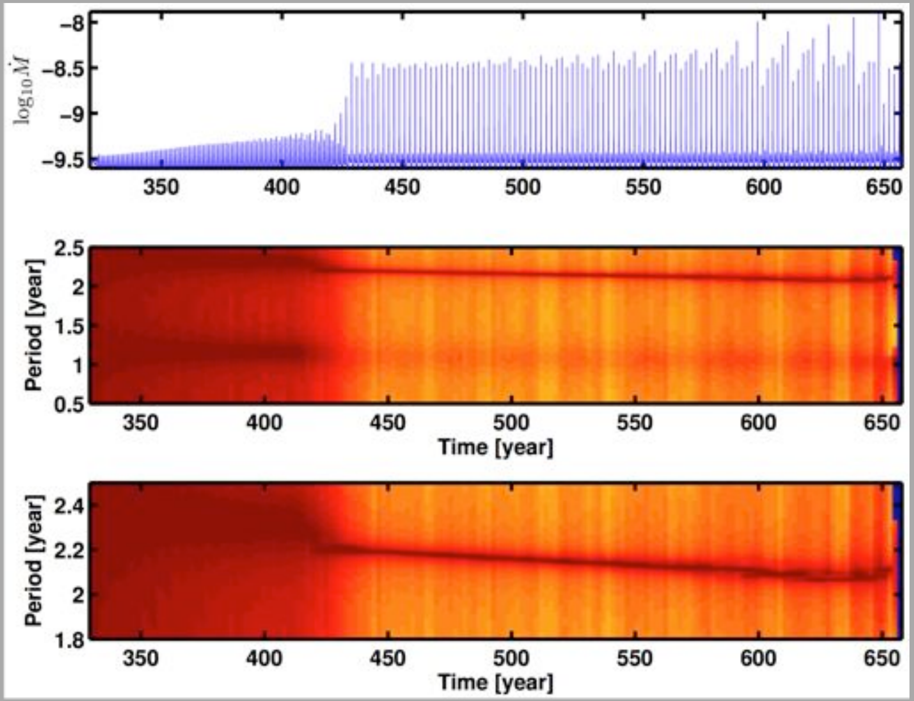




SSE Repeat Period



Nominal Case

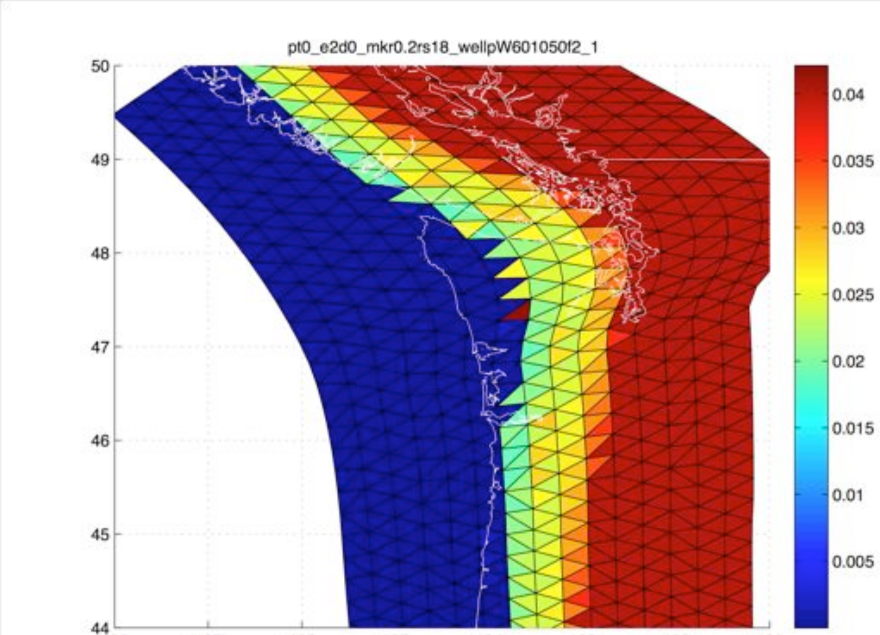


Decrease d_c by 2x

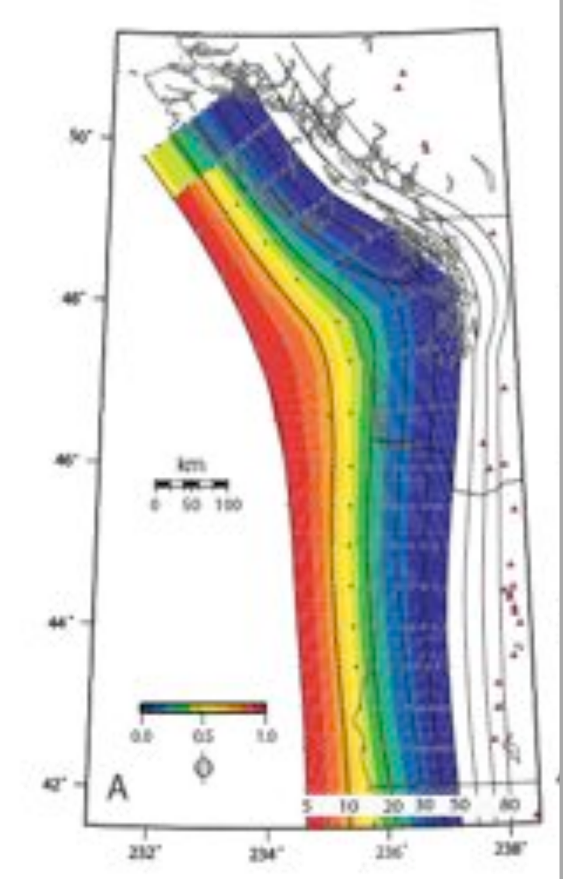
From linearized analysis of single-degree of freedom system:

$$T \approx 2\pi \left(\frac{d_c}{v^\infty}\right) \sqrt{\frac{a}{b-a}} \left[1 + \frac{f_0 E_p}{2\sqrt{2}b} F(a/b)\right] G(W/h^*)$$

Psedo 3D Deformation Model: Inter-ETS sliprate

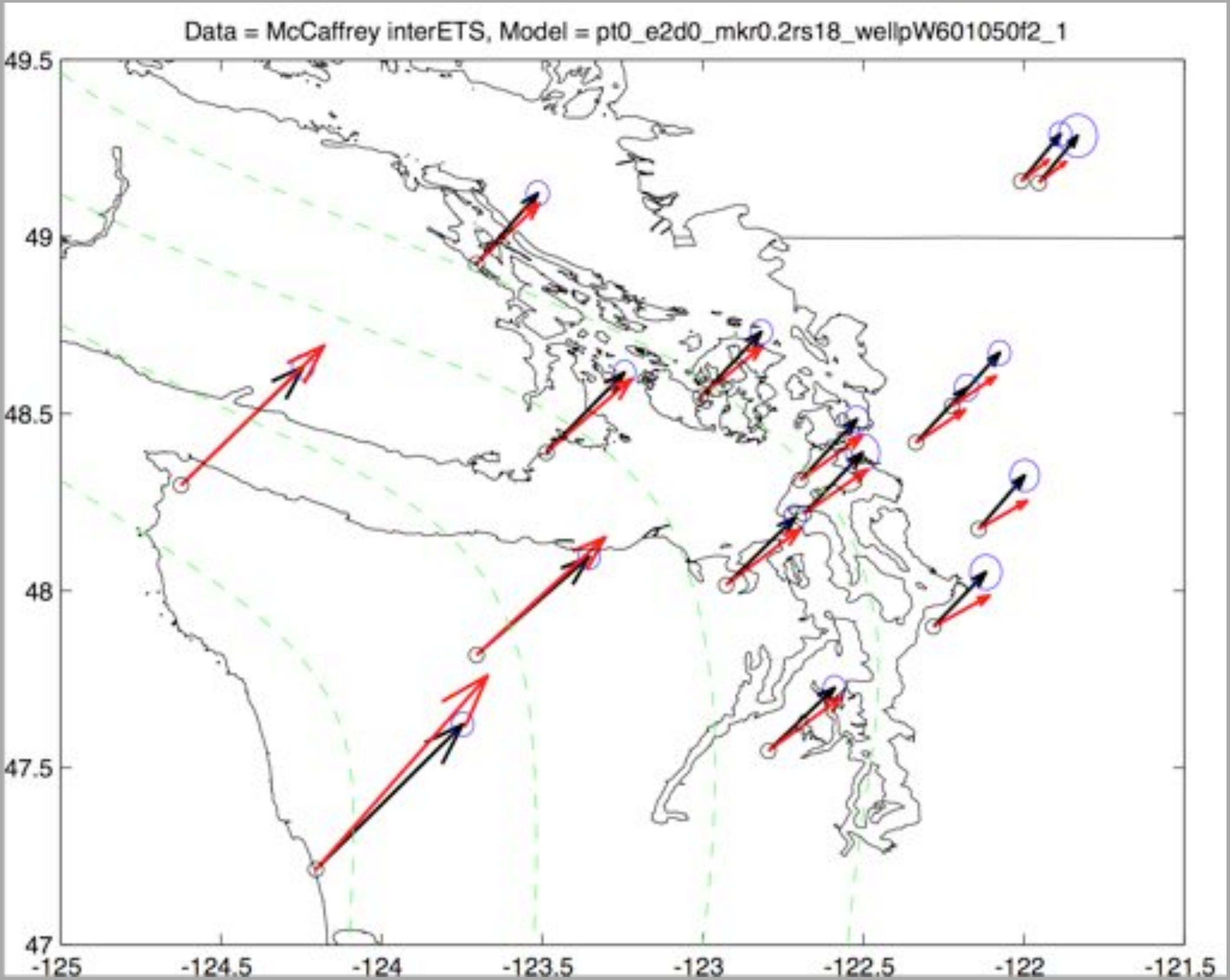


Slip speed a function of depth only, as determined by 2D physical model.



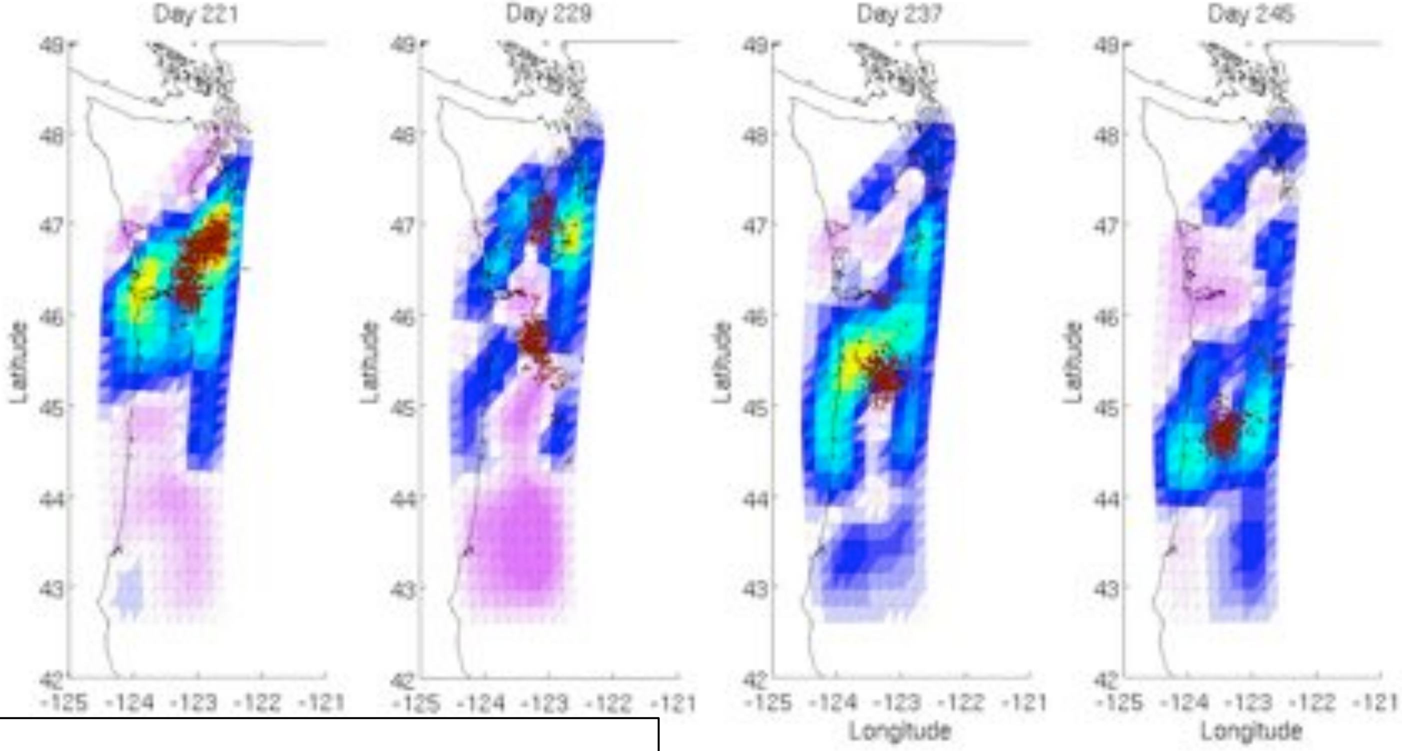
McCaffrey et al, 2007, inversion

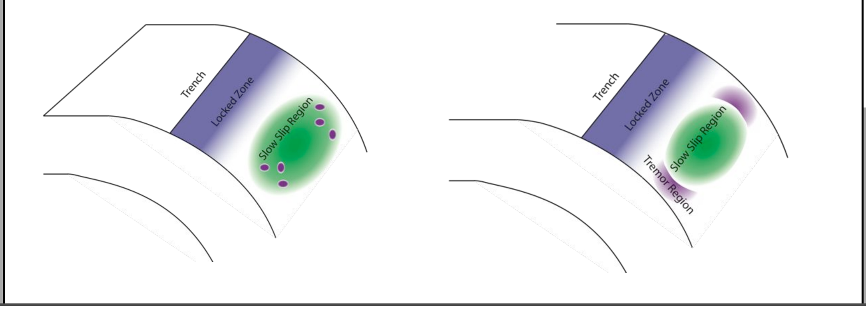
Pseudo-3D Fit to Inter-ETS Deformation



'Data' courtesy R. McCaffery

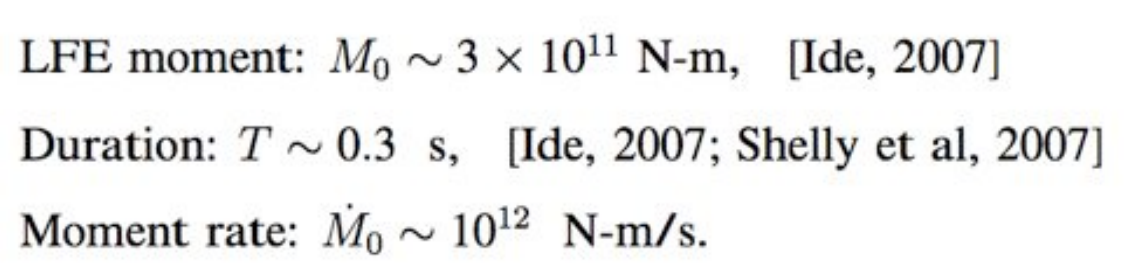
Space-Time Relationship between Slow-Slip and Tremor





Bartlow, Miyazaki, and Segall, this meeting.

Low Frequency Earthquakes



LFE moment: $M_0 \sim 3 \times 10^{11}$ N-m, [Ide, 2007]

Duration: $T \sim 0.3$ s, [Ide, 2007; Shelly et al, 2007]

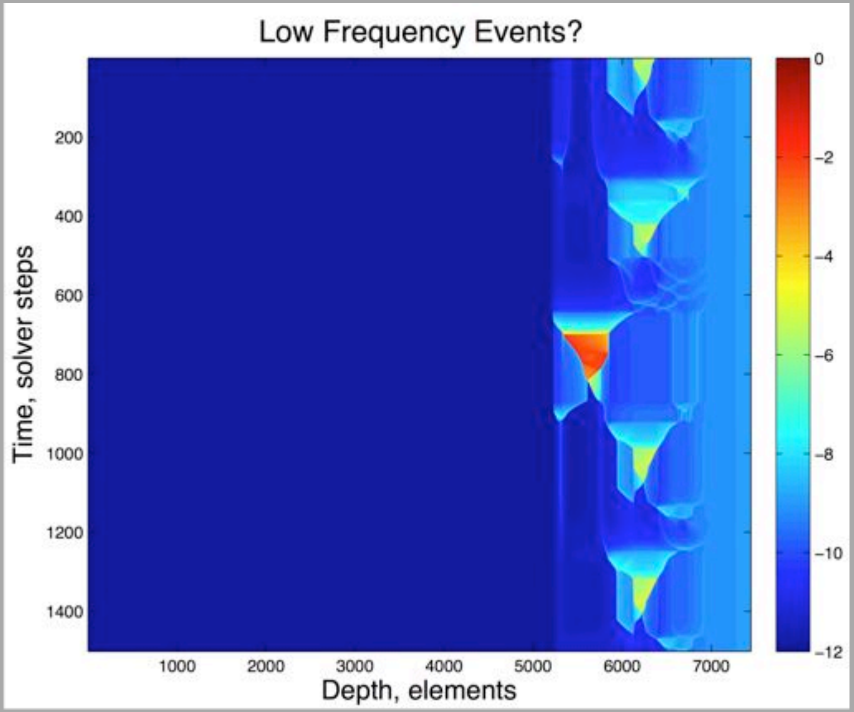
Moment rate: $\dot{M}_0 \sim 10^{12}$ N-m/s.

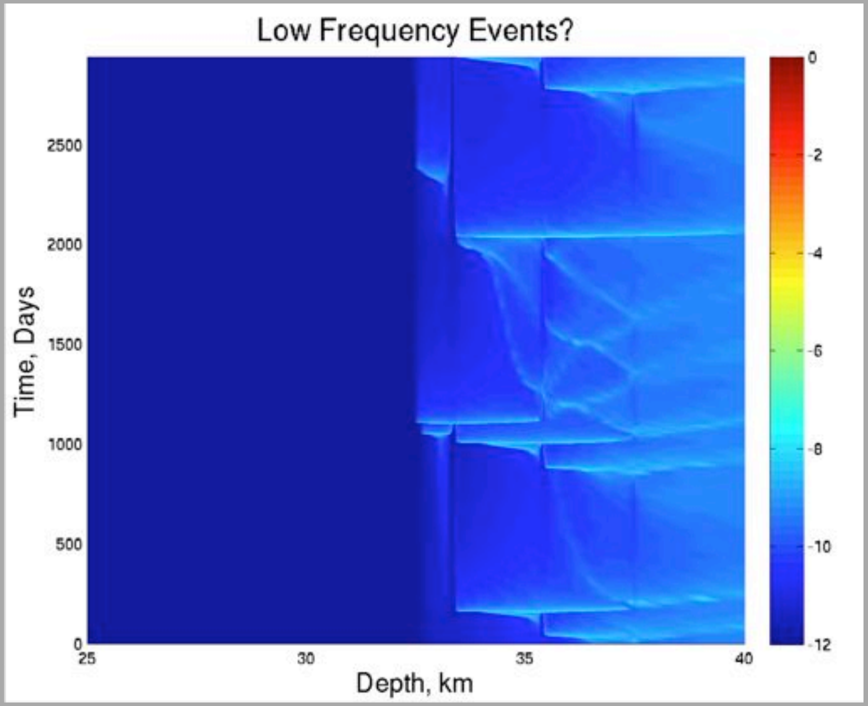
Challenge: Small areas of the plate interface must accelerate to slip-speeds sufficient to radiate seismic waves, without dynamic rupture continuing outside the LFE source region.

Hypothesis: Local regions of high permeability, perhaps due to fractures, allow rapid drainage and fast slip. Stressed by slow-slip in the surrounding regions.

Question: Is dilatancy sufficient to quench the instability, when ruptures reach the low-permeability, low effective stress surroundings? Or does thermal pressurization promote runaway dynamic rupture?

Test: Local regions w/ infinite diffusivity





Chen, Bradley, Segall

Local areas of high slip-speed decelerate after encountering low permeability background.

Conclusions

- Dilatancy allows slip to nucleate a low speeds but can limit fast slip.
- High pore-pressure mitigates against frictional and thermal weakening, thus favoring slow slip (consistent with seismological observations).
- For plausible material parameters, the predicted depth range, moment-rate, and repeat period are comparable to observations.
- Slow-slip behavior occurs for a broad range of parameters.
- Behavior highly dependent on depth dependent effective stress, as well as frictional properties.

Implications/Future Work

- For large part of parameter space, a slower phase is observed: Implication for inter-ETS tremor/slip? Need 3D models.
- For simple parameter distributions, transition between locked and steady slip at plate-velocity changes through seismic cycle: Implications for geodetic observations.
- Simple models exhibit variable behavior throughout seismic cycle. Slow-slip events penetrate into locked zone?

Implications/Future Work

- Slow slip may evolve into dynamic rupture. Diagnostic behavior prior to dynamic event?
- For simple distributions of material properties, slip in the ETS zone lags plate-rate. Consistent with geodetic observations?
- Coseismic (or rapid postseismic?) rupture into ETS zone? Implications for seismic hazard. Models with finite thickness shear zones (coming) will reduce the coseismic stress drop.
- Fractures within the ETS zone allow rapid drainage and may provide a mechanisms for LFEs.