# Fault-Valve Instability: A Mechanism for Slow Slip Events

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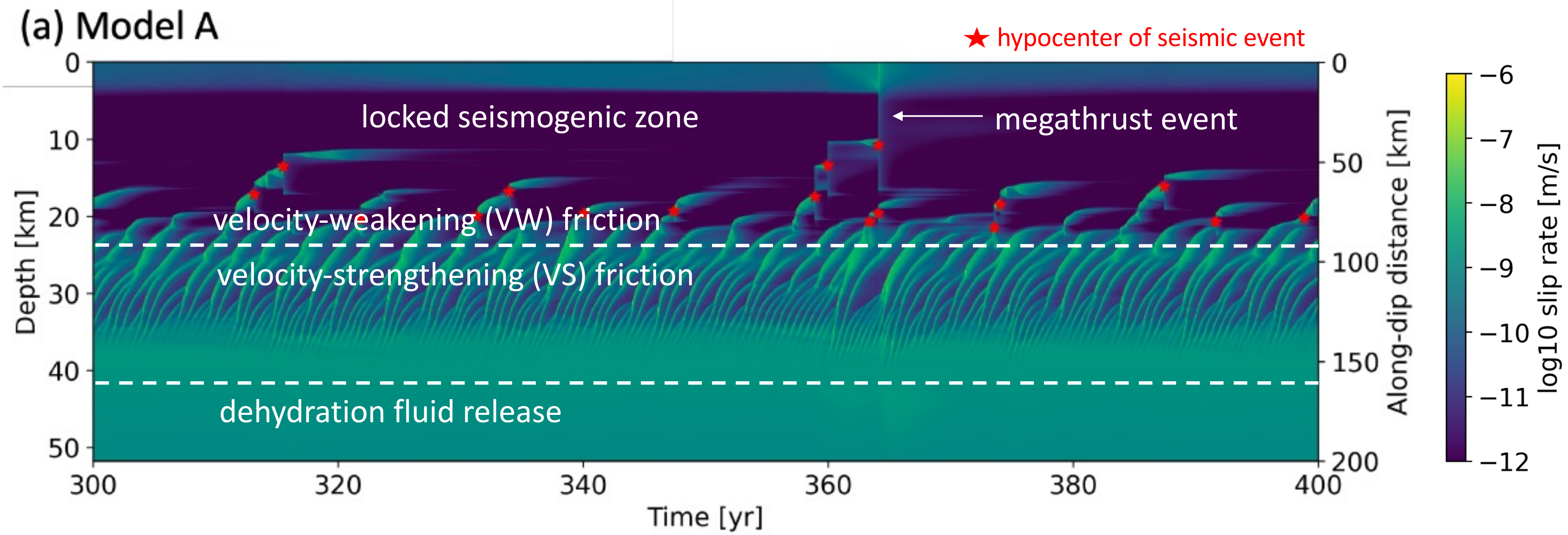

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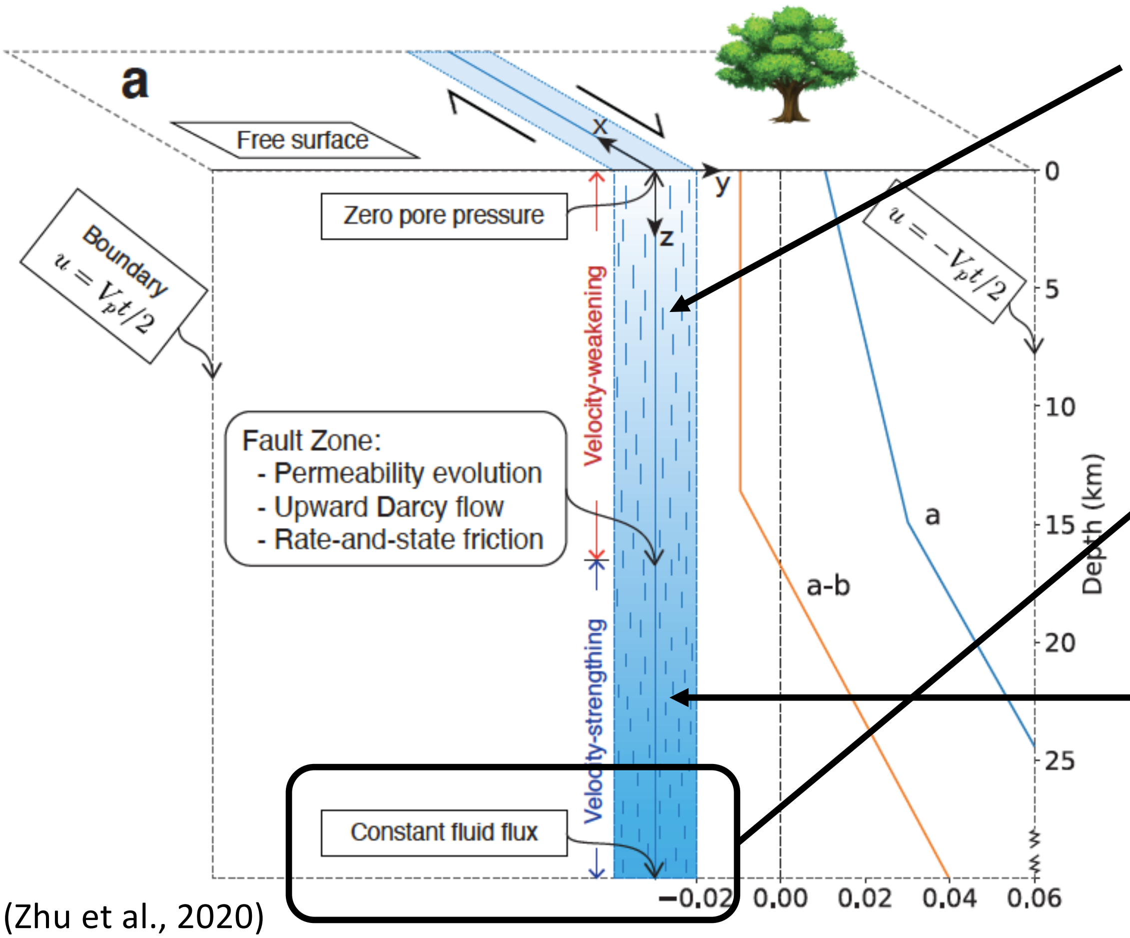
# Fault zone fluid migration and pore pressure evolution models



fluid flow confined to fault damage zone (fault-normal flow neglected)

steady fluid influx below seismogenic zone (dehydration reactions, mantle fluids, etc.)

nonlinearities and feedbacks will lead to cyclic pressurization and discharge events (fault valving) (e.g., Sibson, 1992)

(Zhu et al., 2020)

# Idealized model for permeability evolution

elastic dependence on
effective stress:

stress sensitivity
parameter ~10 MPa

$$k = k^* e^{-(\sigma - p)/\sigma^*}$$

minimally parametrized (but ad hoc) evolution equation for permeability:

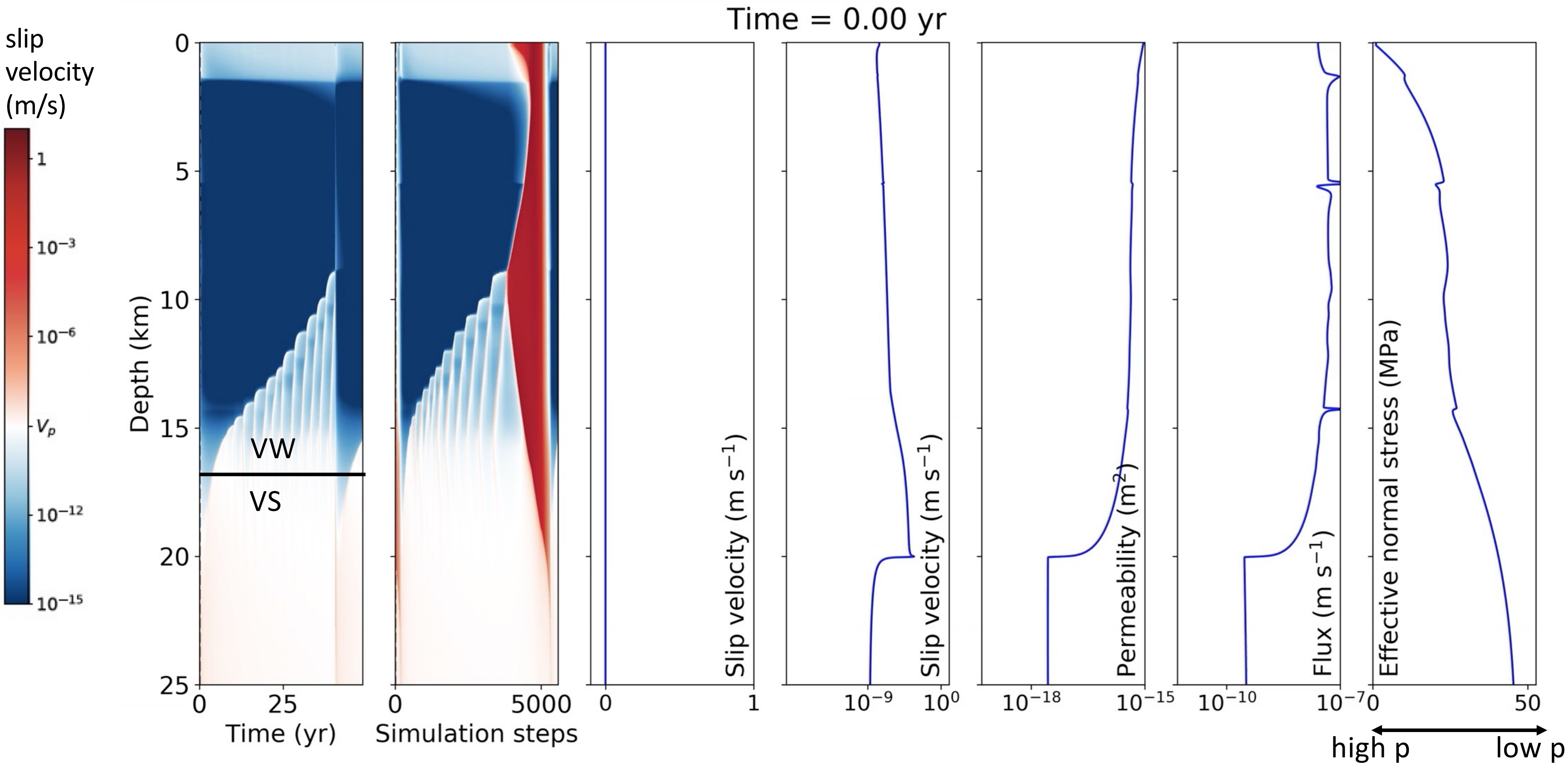
$$\frac{\partial k^*}{\partial t} = -\frac{V}{L}\left(k^* - k_{\max}\right) - \frac{1}{T}\left(k^* - k_{\min}\right)$$

permeability
increase with slip

permeability
decrease from
healing/sealing

→ constant $T$ and $L$ in Zhu et al. (2020), later depth-dependent

# Our original fault valving cycle simulations



(Zhu et al., 2020)

# Motivation for additional study

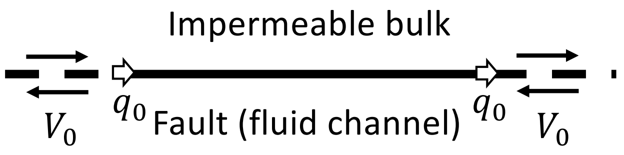
- Which processes and conditions are required for instability?
- Quantitative expressions for recurrence interval, slip pulse length, etc.
- Sensitivity to model assumptions (e.g., permeability evolution model)

Study with spatially uniform properties in homogeneous whole-space

- Linear stability analysis for perturbations about steady sliding ($V_0$) and steady fluid flow ($q_0$)
- Nonlinear simulations

# Fluid flow destabilizes steady sliding, even with velocity-strengthening friction

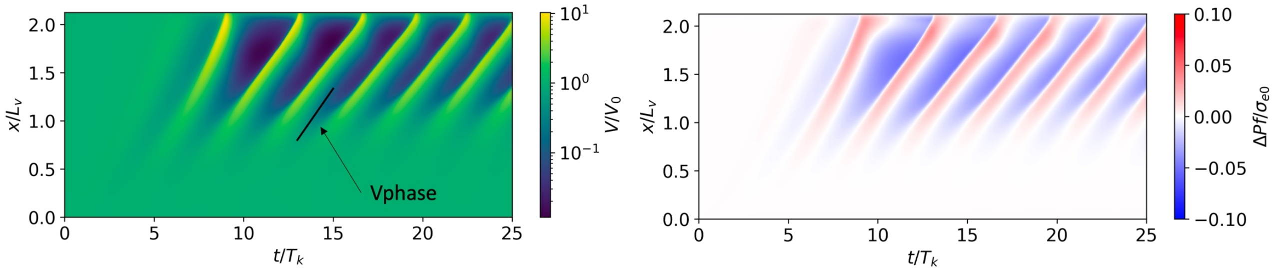
(example below)



Impermeable bulk

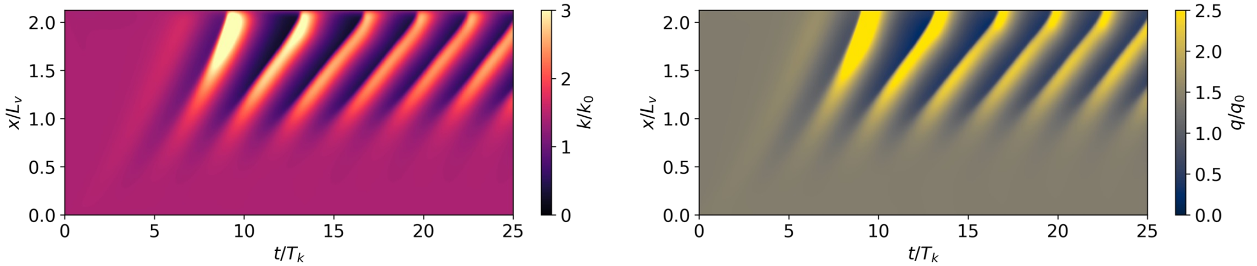
$q_0$ Fault (fluid channel) $q_0$

- fluid-driven aseismic slip fronts propagate in direction of fluid flow
- recurrence interval (and slip/event) controlled by permeability evolution timescale



(a) Slip Velocity

(b) Fluid Pressure



(c) Permeability

(d) Flow Rate

(Ozawa, Yang, & Dunham, 2024, in review)

# Fault valve instability mechanism – fluid flow

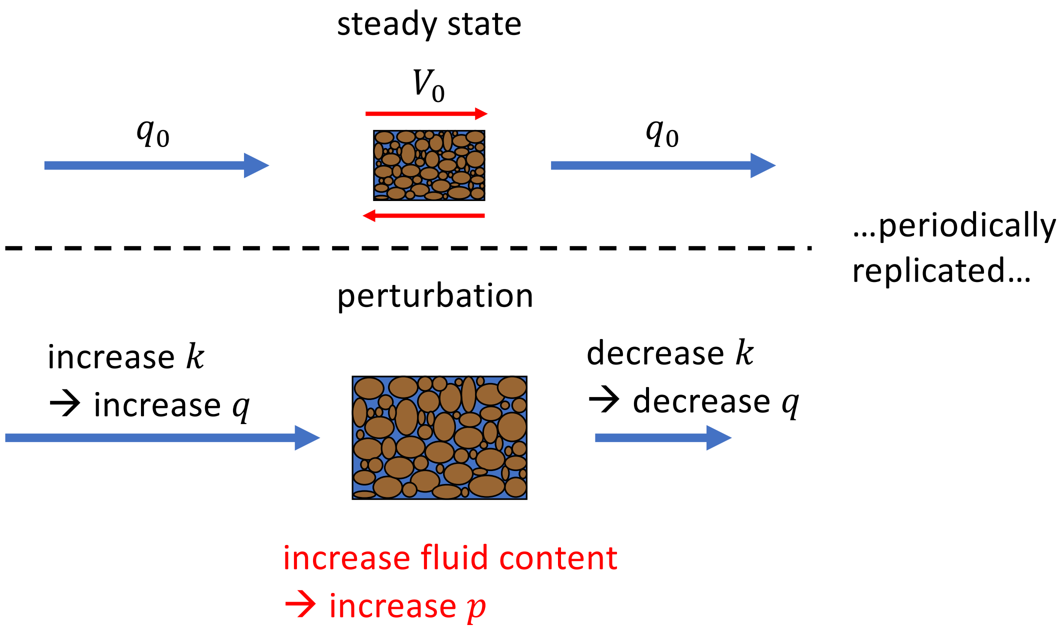
Linearization of pressure diffusion:

$$\beta\phi\frac{\partial p}{\partial t} - \frac{\partial}{\partial x}\left(\frac{k}{\eta}\frac{\partial p}{\partial x}\right) = 0.$$

$$\beta\phi\frac{\partial(p_0+p')}{\partial t} - \frac{\partial}{\partial x}\left(\frac{k_0+k'}{\eta}\frac{\partial(p_0+p')}{\partial x}\right) = 0.$$

$$\boxed{\beta\phi\frac{\partial p'}{\partial t}} - \boxed{\frac{k_0}{\eta}\frac{\partial^2 p'}{\partial x^2}} + \boxed{\frac{q_0}{k_0}\frac{\partial k'}{\partial x}} = 0,$$

diffusion stabilizing



steady state

$V_0$

$q_0$ $q_0$

…periodically replicated…

perturbation

increase $k$
→ increase $q$

decrease $k$
→ decrease $q$

increase fluid content
→ increase $p$

(Ozawa, Yang, & Dunham, 2024, in review)

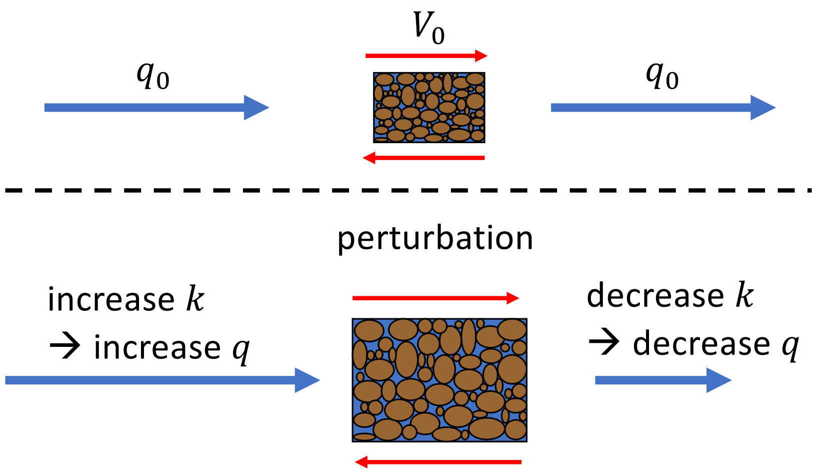
# Fault valve instability mechanism – frictional sliding

Linearization of fault strength:

$$\boxed{\frac{\mathrm{d}\tau}{\mathrm{d}t}} = \boxed{\frac{a\sigma_0}{V_0}\frac{\mathrm{d}V}{\mathrm{d}t}} + \boxed{f_0\frac{\mathrm{d}\sigma_e}{\mathrm{d}t}} - \cancel{\frac{V_0}{d_c}\left[\tau - \tau_{ss}(\sigma_e, V)\right]},$$

$$\tau_{ss}(\sigma_e, V) = \tau_0 + f_0(\sigma_e - \sigma_0) + (a-b)\sigma_0\frac{V - V_0}{V_0}.$$

elasticity stabilizing



steady state

$V_0$

$q_0$

$q_0$

...periodically replicated...

perturbation

increase $k$
→ increase $q$

decrease $k$
→ decrease $q$

increase fluid content
→ increase $p$

direct effect:
decrease $\sigma_e$ → increase $V$

(Ozawa, Yang, & Dunham, 2024, in review)

# Fault valve instability mechanism – frictional sliding

Linearization of fault strength:

$$\boxed{\frac{d\tau}{dt}} = \boxed{\frac{a\sigma_0}{V_0}\frac{dV}{dt}} + \boxed{f_0\frac{d\sigma_e}{dt}} - \cancel{\frac{V_0}{d_c}\left[\tau - \tau_{ss}(\sigma_e, V)\right]},$$

$$\tau_{ss}(\sigma_e, V) = \tau_0 + f_0(\sigma_e - \sigma_0) + (a-b)\sigma_0\frac{V - V_0}{V_0}.$$

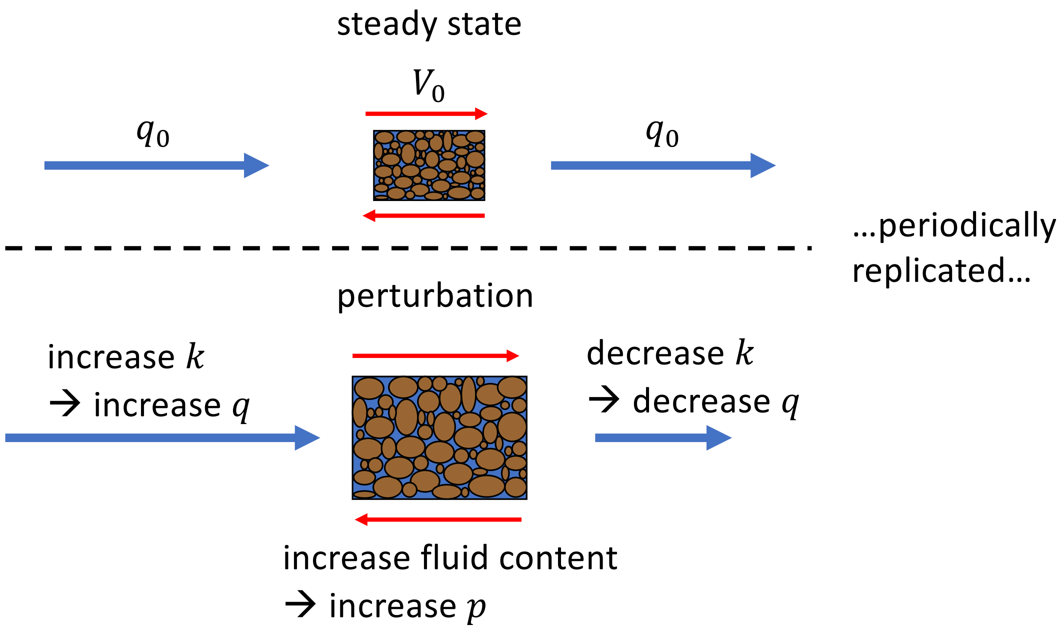
elasticity stabilizing

Linearized permeability evolution:

$$\boxed{\frac{dk}{dt}} = -\frac{k_0}{\sigma^*}\frac{d\sigma_e}{dt}\boxed{-\frac{1}{T_k}\left[k - k_{ss}^{lin}(V, \sigma_e)\right]},$$

$$k_{ss}^{lin}(V, \sigma_e) = k_0 - k_0\frac{\sigma_e - \sigma_0}{\sigma^*} + \boxed{\Delta k\frac{V - V_0}{V_0}},$$

but $k = k_{ss}(V)$ gives *wrong phase relation*, **no unstable feedback**



steady state

$V_0$

$q_0$

$q_0$

…periodically replicated…

perturbation

increase $k$
→ increase $q$

decrease $k$
→ decrease $q$

increase fluid content
→ increase $p$

direct effect:
decrease $\sigma_e$ → increase $V$

permeability evolution:
increase $V$ → increase $k$

(Ozawa, Yang, & Dunham, 2024, in review)

# Fault valve instability mechanism – frictional sliding

Linearization of fault strength:

$$\boxed{\frac{d\tau}{dt}} = \boxed{\frac{a\sigma_0}{V_0}\frac{dV}{dt}} + \boxed{f_0\frac{d\sigma_e}{dt}} - \cancel{\frac{V_0}{d_c}\left[\tau - \tau_{ss}(\sigma_e, V)\right]},$$

$$\tau_{ss}(\sigma_e, V) = \tau_0 + f_0(\sigma_e - \sigma_0) + (a-b)\sigma_0\frac{V - V_0}{V_0}.$$

elasticity stabilizing

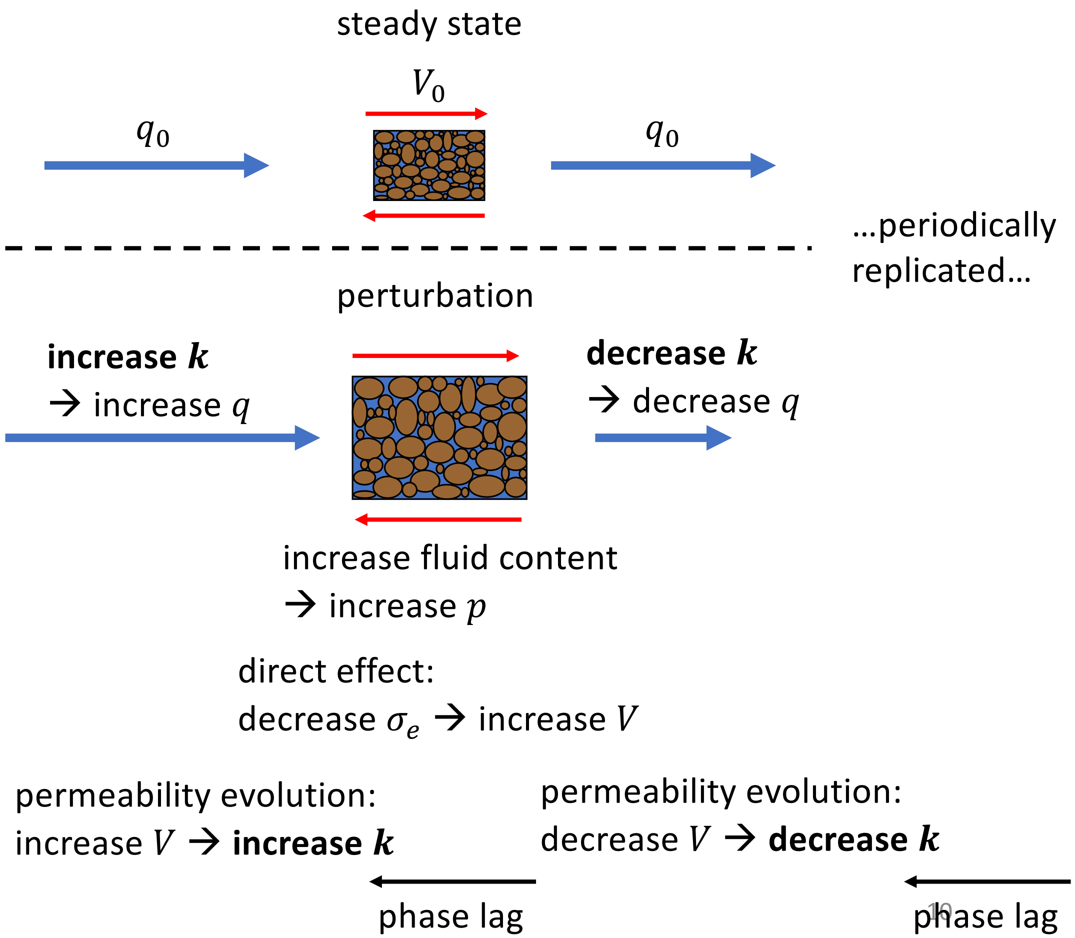
Linearized permeability evolution:

$$\boxed{\frac{dk}{dt}} = -\frac{k_0}{\sigma^*}\frac{d\sigma_e}{dt}\boxed{-\frac{1}{T_k}\left[k - k_{ss}^{lin}(V, \sigma_e)\right]},$$

$$k_{ss}^{lin}(V, \sigma_e) = k_0 - k_0\frac{\sigma_e - \sigma_0}{\sigma^*} + \boxed{\Delta k\frac{V - V_0}{V_0}},$$

adding evolution of $k$ toward $k_{ss}(V)$
lags phase → **unstable feedback!**

(Ozawa, Yang, & Dunham, 2024, in review)



steady state

$V_0$

$q_0$

$q_0$

...periodically replicated...

perturbation

**increase $k$**
→ increase $q$

**decrease $k$**
→ decrease $q$

increase fluid content
→ increase $p$

direct effect:
decrease $\sigma_e$ → increase $V$

permeability evolution:
increase $V$ → **increase $k$**

phase lag

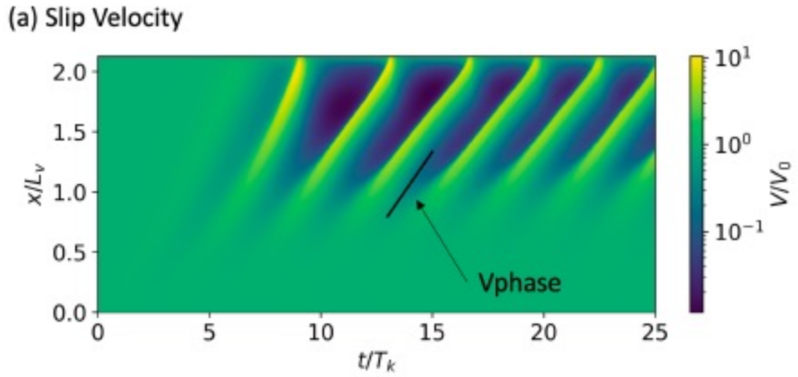
permeability evolution:
decrease $V$ → **decrease $k$**

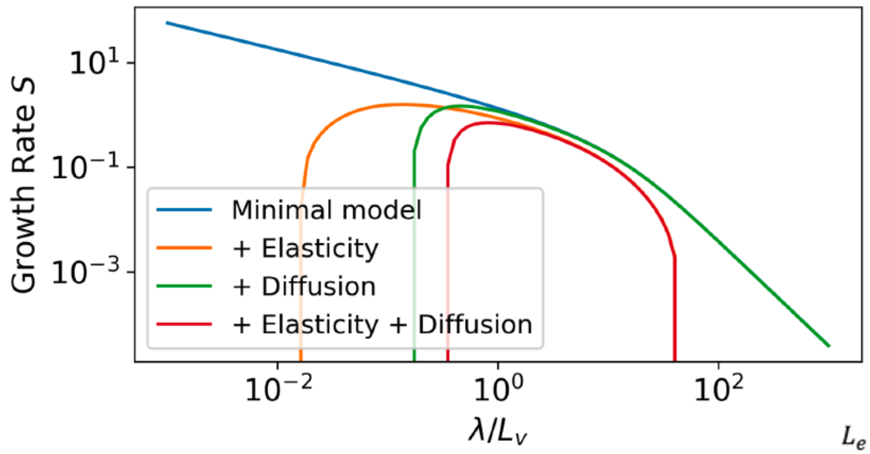
phase lag

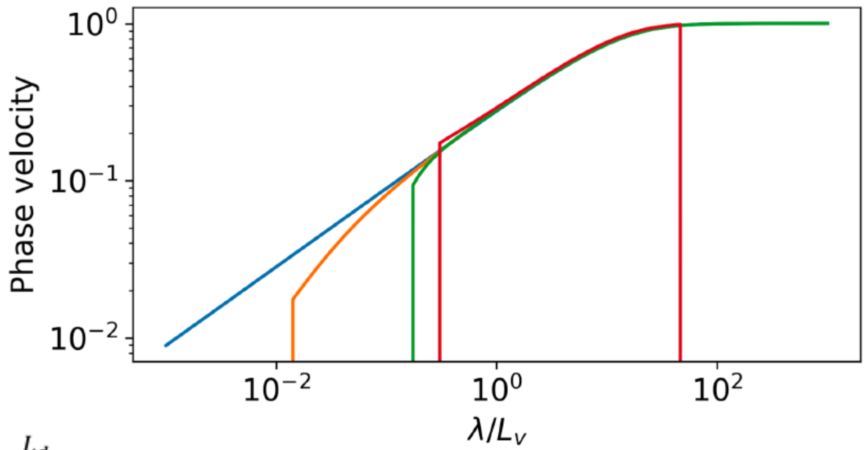
# Linear stability analysis predicts wavelength of max growth

Wavelengths $\sim L_v$ and timescales $\sim T_k$ selected in nonlinear simulations

$$L_v = \frac{f_0 q_0 \Delta k T_k}{k_0 \beta \phi a \sigma_0}$$ (fault valve length scale)







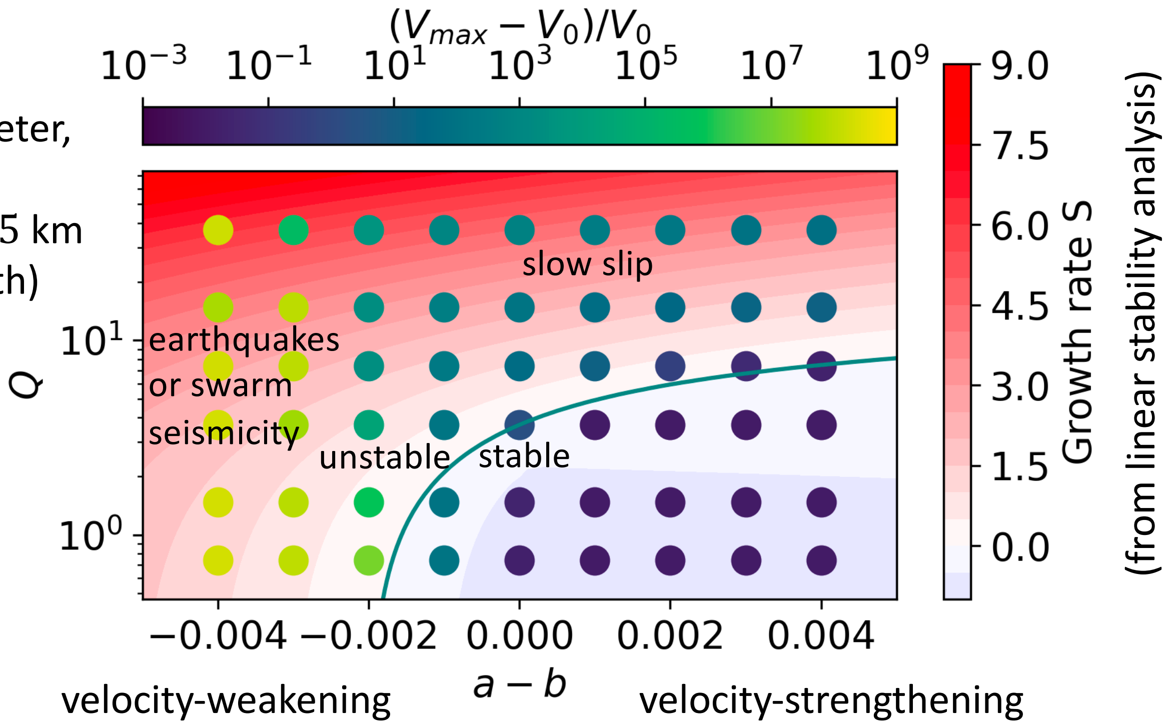
$$\frac{L_e}{L_v} = 0.27, \frac{L_d}{L_v} = 0.004$$

(Ozawa, Yang, & Dunham, 2024, in review)

# Transition between fault valve instability and classical rate-state frictional instability for VW friction

max slip velocity (in nonlinear simulations)

fault valve parameter,
$Q \propto q_0 \Delta k / k_0$,
evaluated at $\lambda = 5$ km
(half of fault length)



(from linear stability analysis)

velocity-weakening

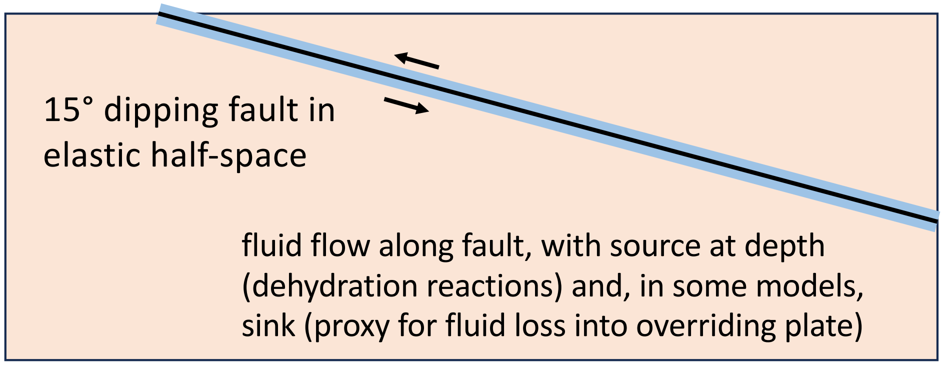
velocity-strengthening

(Ozawa, Yang, & Dunham, 2024, in review)

# Subduction zone simulations

Integrate $q = \frac{k}{\eta}\left(\frac{\partial p}{\partial z} - \rho g\right)$ → steady state $p(z)$ and $k(z)$ distributions, then unsteady…

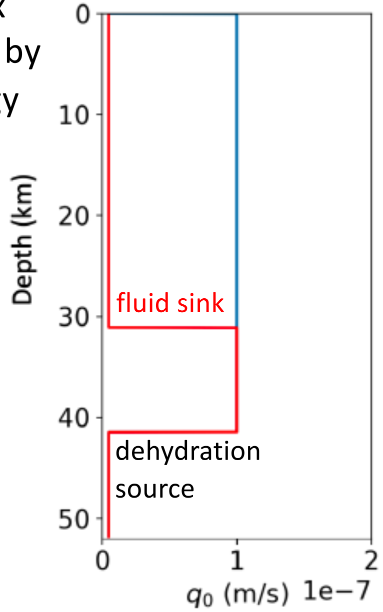
(4 models A-D, different colors in plots to follow)



15° dipping fault in elastic half-space

fluid flow along fault, with source at depth (dehydration reactions) and, in some models, sink (proxy for fluid loss into overriding plate)

fluid flux inspired by petrology



+ aging law rate-state friction, transition from VW to VS around 22 km depth

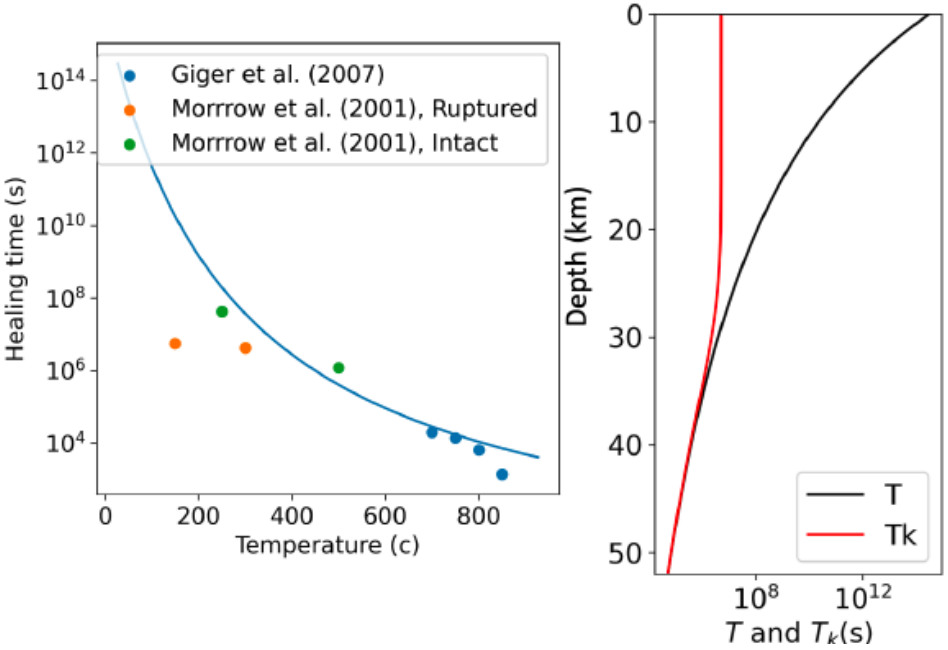
(Ozawa, Yang, & Dunham, 2024, in review)

# Subduction zone simulations

Integrate $q = \frac{k}{\eta}\left(\frac{\partial p}{\partial z} - \rho g\right)$ → steady state $p(z)$ and $k(z)$ distributions, then unsteady…

(4 models A-D, different colors in plots to follow)

temperature and hence
depth-dependent healing time



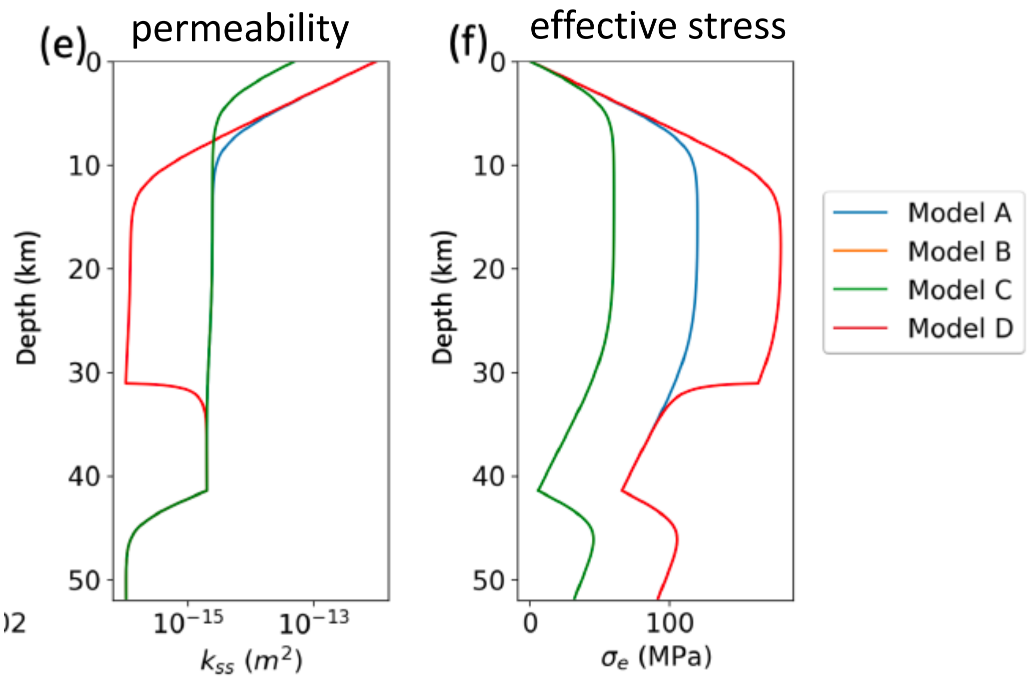
(Ozawa, Yang, & Dunham, 2024, in review)

# Subduction zone simulations

Integrate $q = \frac{k}{\eta}\left(\frac{\partial p}{\partial z} - \rho g\right)$ → steady state $p(z)$ and $k(z)$ distributions, then unsteady…

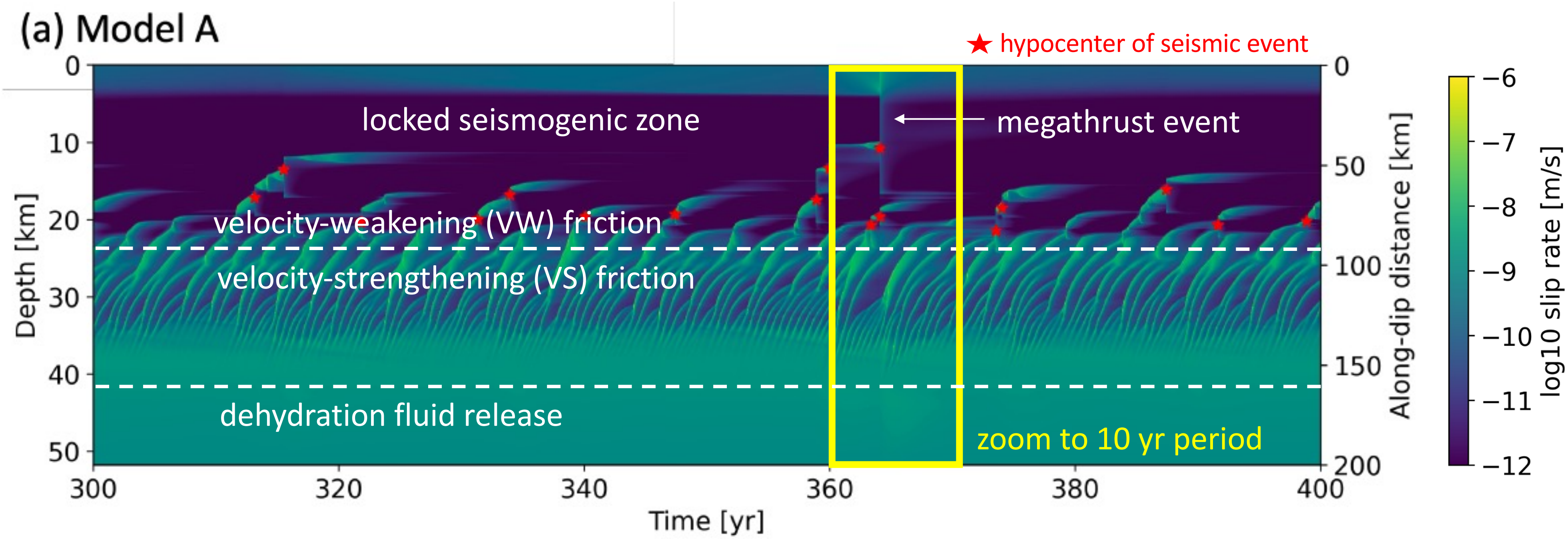
(4 models A-D, different colors in plots to follow)

steady state solutions



(Ozawa, Yang, & Dunham, 2024, in review)

# Reference subduction model



(Ozawa, Yang, & Dunham, 2024, in review)

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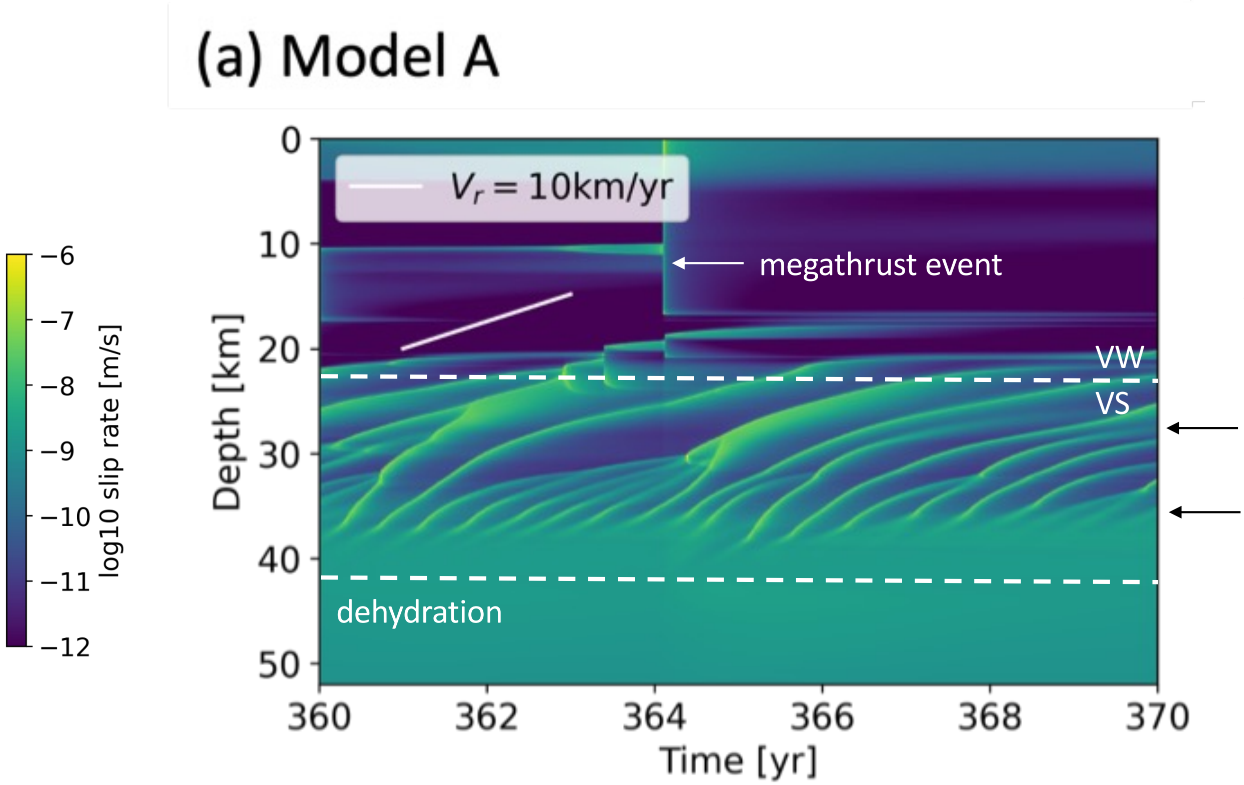


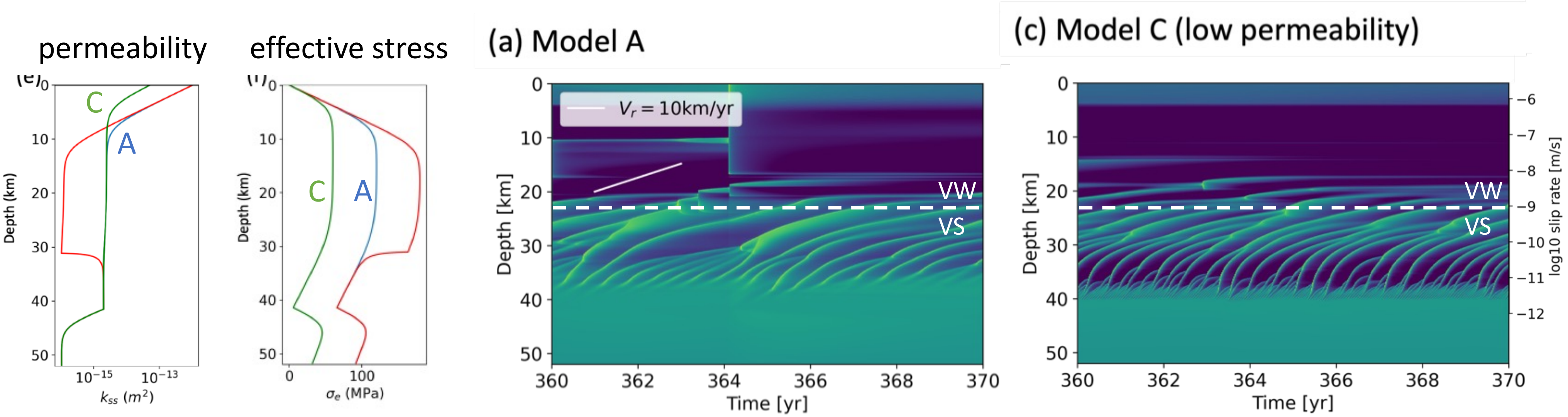
depth-dependent properties of slow slip broadly consistent with observations:

- longer recurrence interval, larger slip/event
- shorter recurrence interval, smaller slip/event

caused by depth-dependent healing time and spatially variable loading from deep creep

(Ozawa, Yang, & Dunham, 2024, in review)

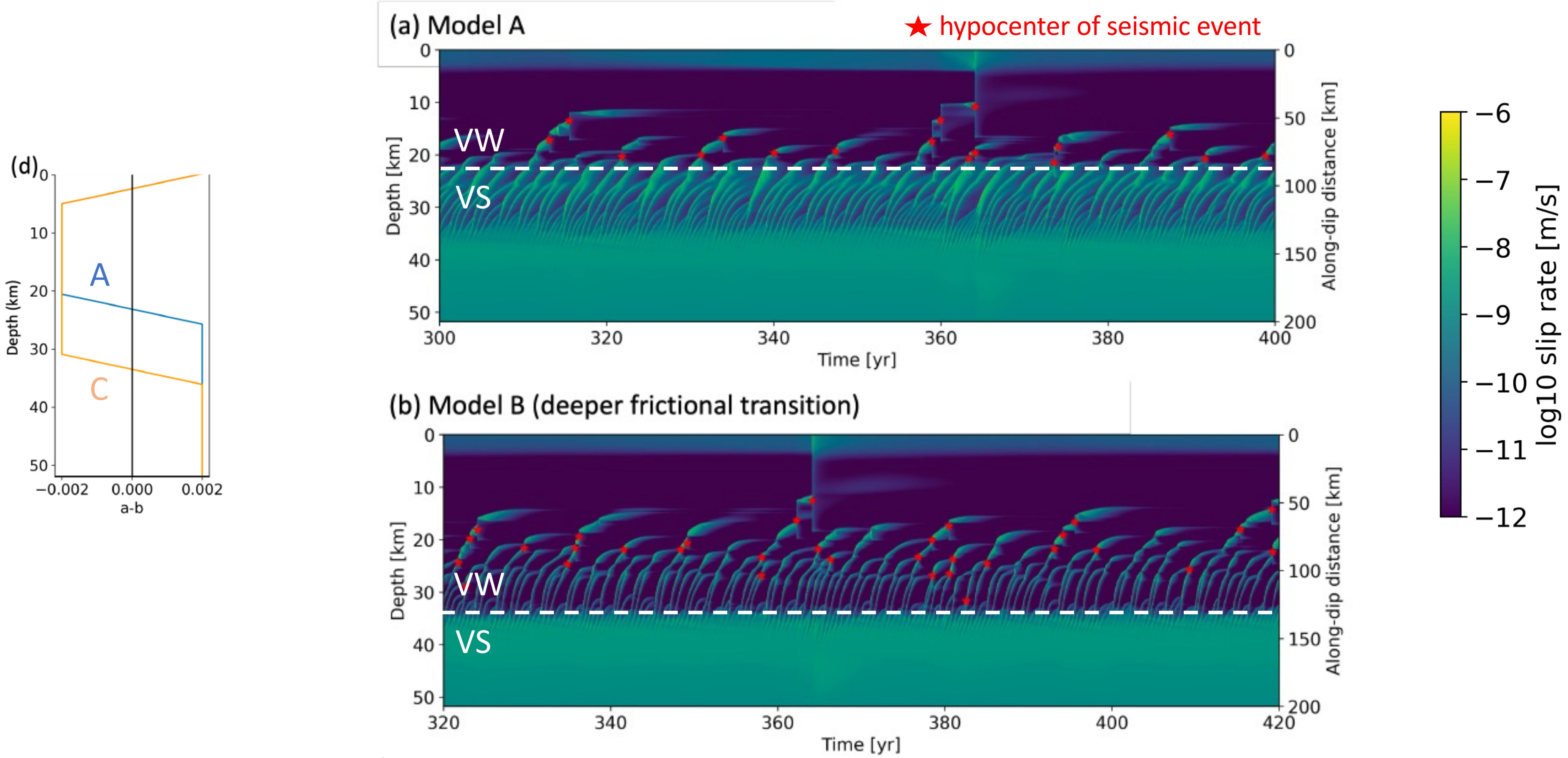
# Reducing effective stress to ~1-10 MPa in slow slip region (by reducing shallow permeability) increases recurrence interval and decreases slip/event



affects inter-SSE aseismic creep
and SSE propagation velocity,
recurrence interval, slip/event

(Ozawa, Yang, & Dunham, 2024, in review)

# Slow slip events “sharpen” if VW friction extends deeper


(a) Model A

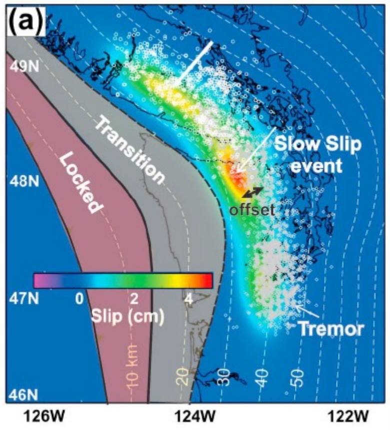
★ hypocenter of seismic event

(b) Model B (deeper frictional transition)

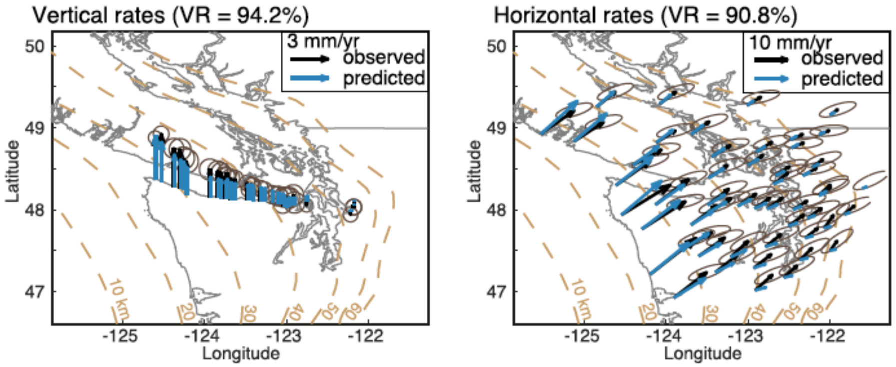
(Ozawa, Yang, & Dunham, 2024, in review)

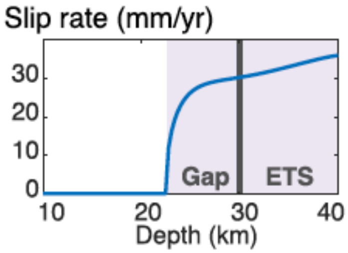
# Transition zone (or gap) between seismogenic zone and episodic tremor and slip (ETS) in some subduction zones

Cascadia



(Hyndman et al., 2015, after Kao et al., 2009; Wang et al., 2008)

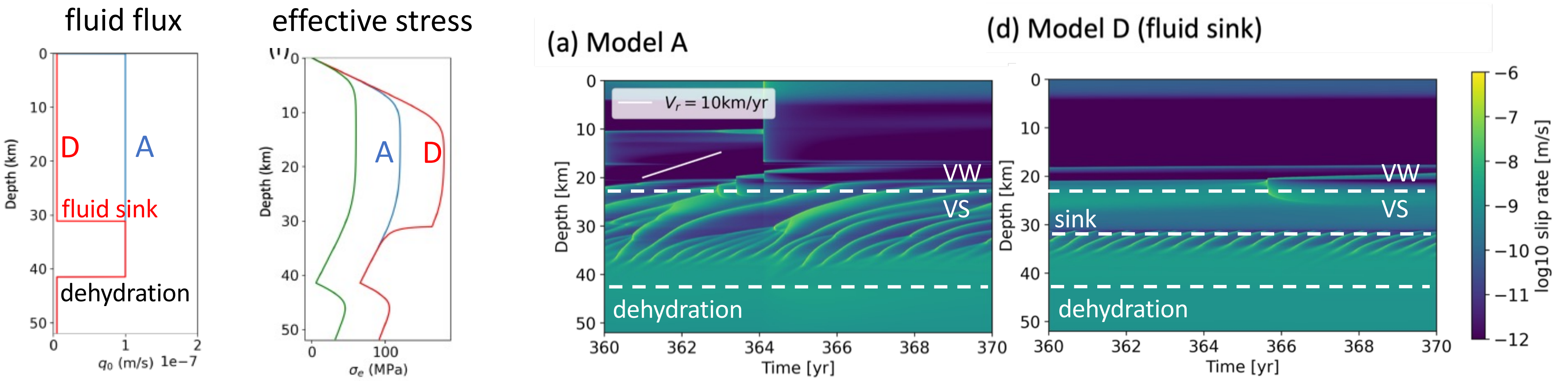




(Bruhat & Segall, 2017, geodetic inversion)

Transition zone in Cascadia appears to be partially coupled (over past ~20 yr). Does it catch up in megathrust events? Or through some form of aseismic slip or distributed viscous shear? Major differences in hazard!

# Fluid sink (near mantle wedge) corner creates transition zone between seismogenic zone and slow slip events



- sliding in transition zone is stabilized against fault valving by reduced flow rate
- slow slip events less complex, more periodic
- variable slip rate (coupling) in transition zone over cycle

(Ozawa, Yang, & Dunham, 2024, in review)

# Conclusions and future directions

Fault valving instability might explain slow slip

- Requires pressure-sensitive frictional slip, not distributed viscous flow
- Robust to frictional parameters (velocity-weakening or velocity-strengthening) and effective stress
- Recurrence interval (and slip/event) controlled by depth-dependent healing time
- Complexity (or periodicity) controlled by fault width (relative to length scale that depends on flow rate)

But:

- Propagation rates slower than observed (but increase as effective stress decreases)
- Propagation only in direction of fluid flow (for velocity-strengthening friction)
- 3D simulations (in progress!) required to understand along-strike propagation

Priorities for future work:

- *Fault-normal flow*, especially upward flow into overriding plate in subduction zones
- Accounting for *fault zone structure*, distinguishing between pressure & transport properties on slip surfaces (controlling fault strength) and in damage zone (controlling along-fault transport)
- Process-specific *porosity and permeability evolution models* (e.g., cracking & dilatancy in damage zone, vein formation & sealing by precipitation, silica transport)
- *Chemistry*: dehydration reactions; reaction kinetics for dissolution & precipitation of silica and similar minerals; lithology-dependent silica sources
- Coupling to *evolving temperature* from conduction and advective heat transport, as well as shear heating