Fault zone fluid migration and pore pressure evolution in earthquake sequence simulations

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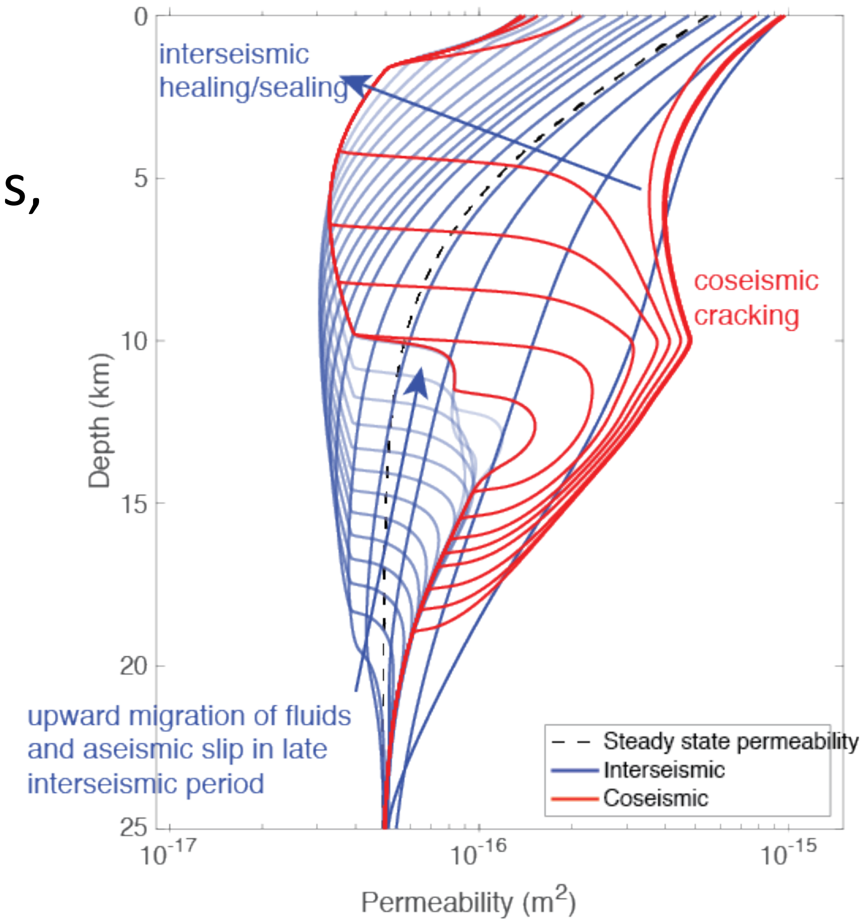
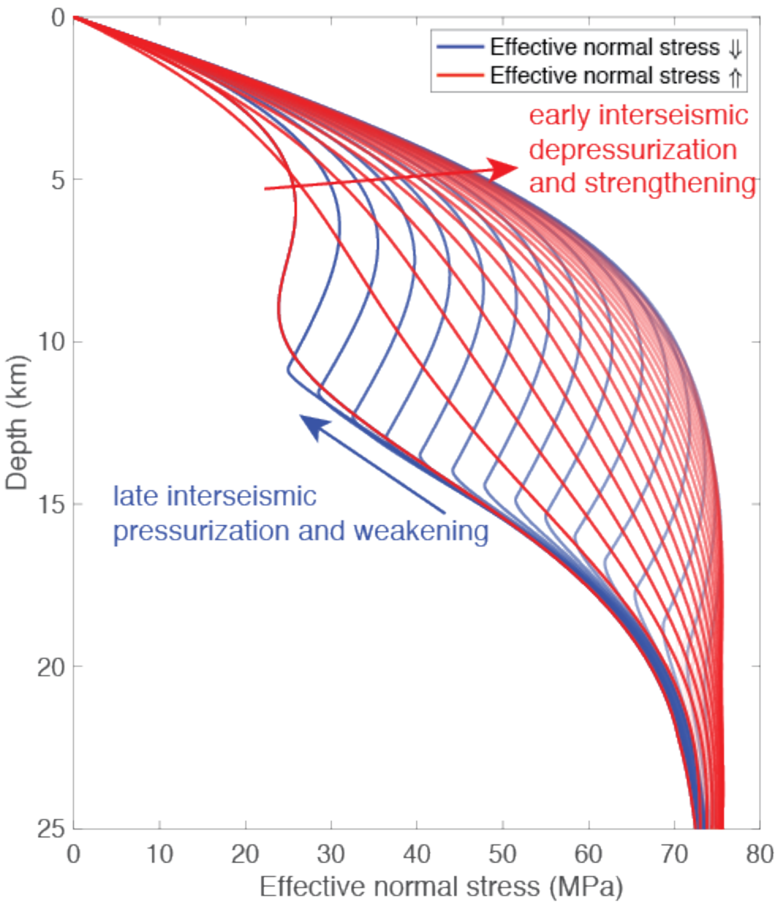
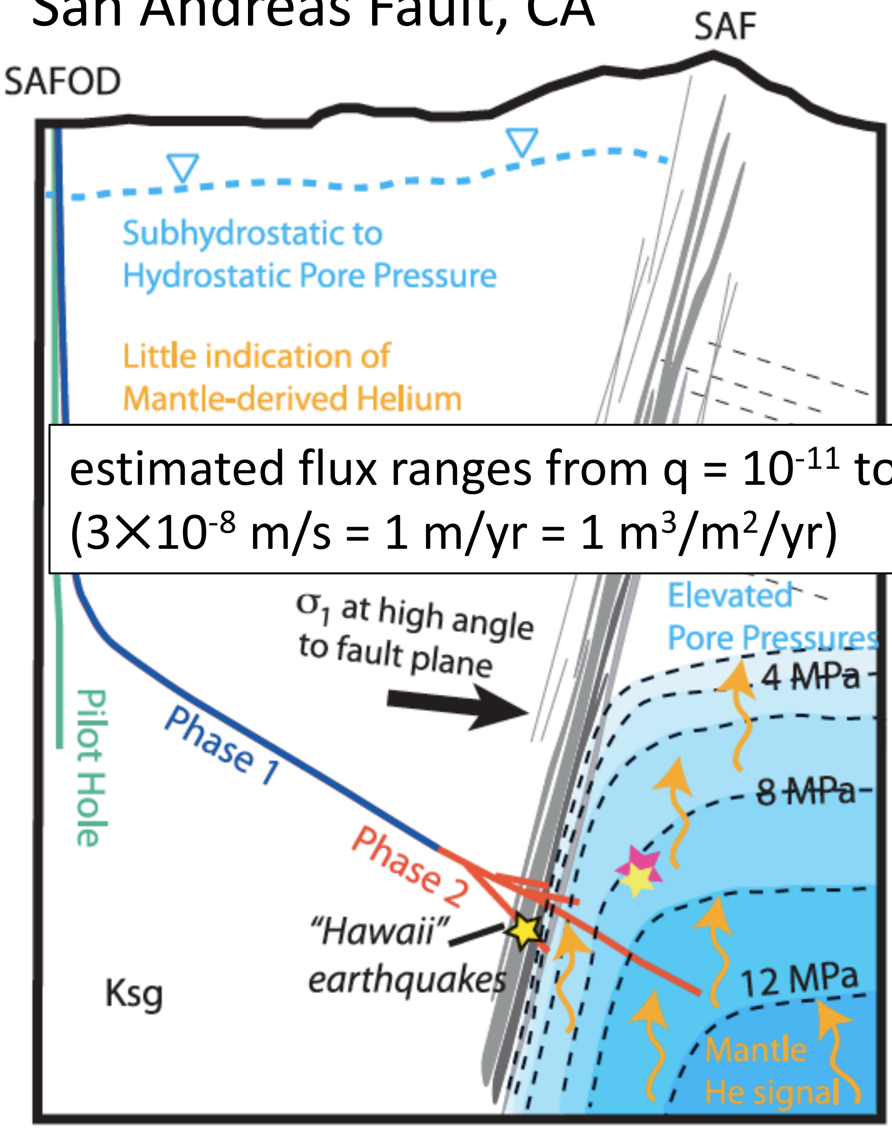
What processes control fault pore pressure, effective stress, and fault strength?





Fluid migration along plate boundary faults

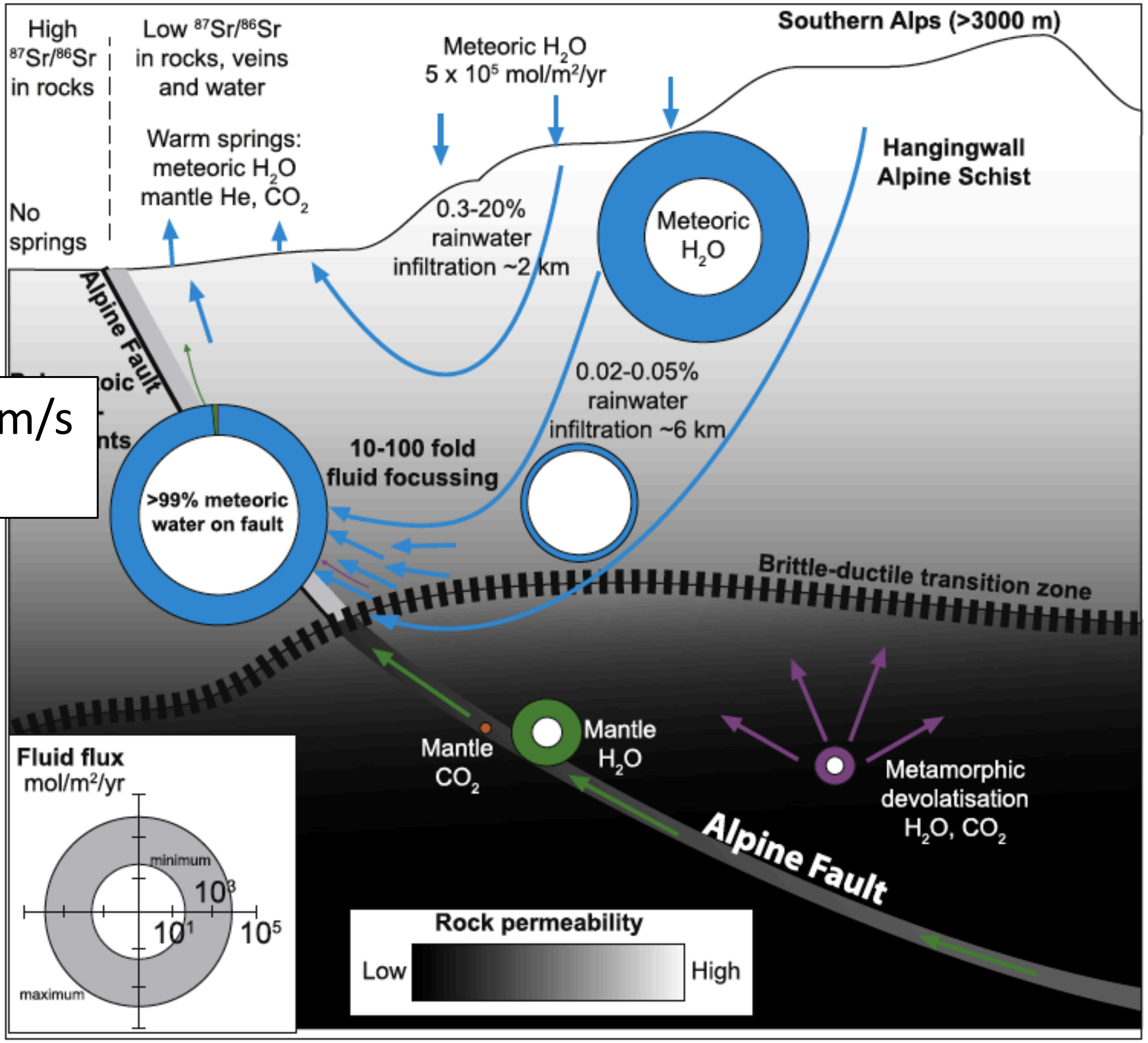
San Andreas Fault, CA



(Fulton and Saffer, 2008)

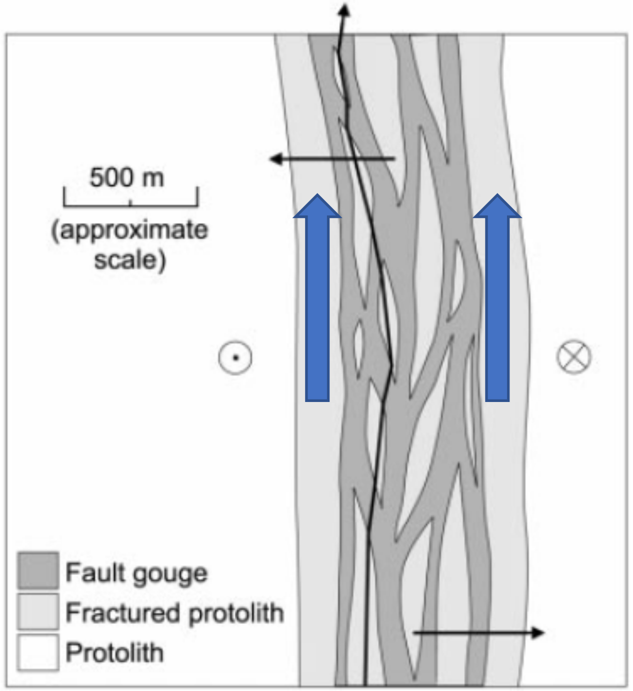
estimated flux ranges from $q = 10^{-11}$ to 10^{-7} m/s
(3×10^{-8} m/s = 1 m/yr = 1 $m^3/m^2/yr$)

Alpine Fault, New Zealand



(Menzies et al., 2016)

Fault damage zones act as conduits for upward fluid migration



(Faulkner and Rutter, 2001)

1D vertical transport model justified if damage zone permeability >> host rock permeability

$$n\beta\frac{\partial p}{\partial t}=\frac{\partial}{\partial z}\left[\frac{k}{\eta}\left(\frac{\partial p}{\partial z}-\rho g\right)\right]$$

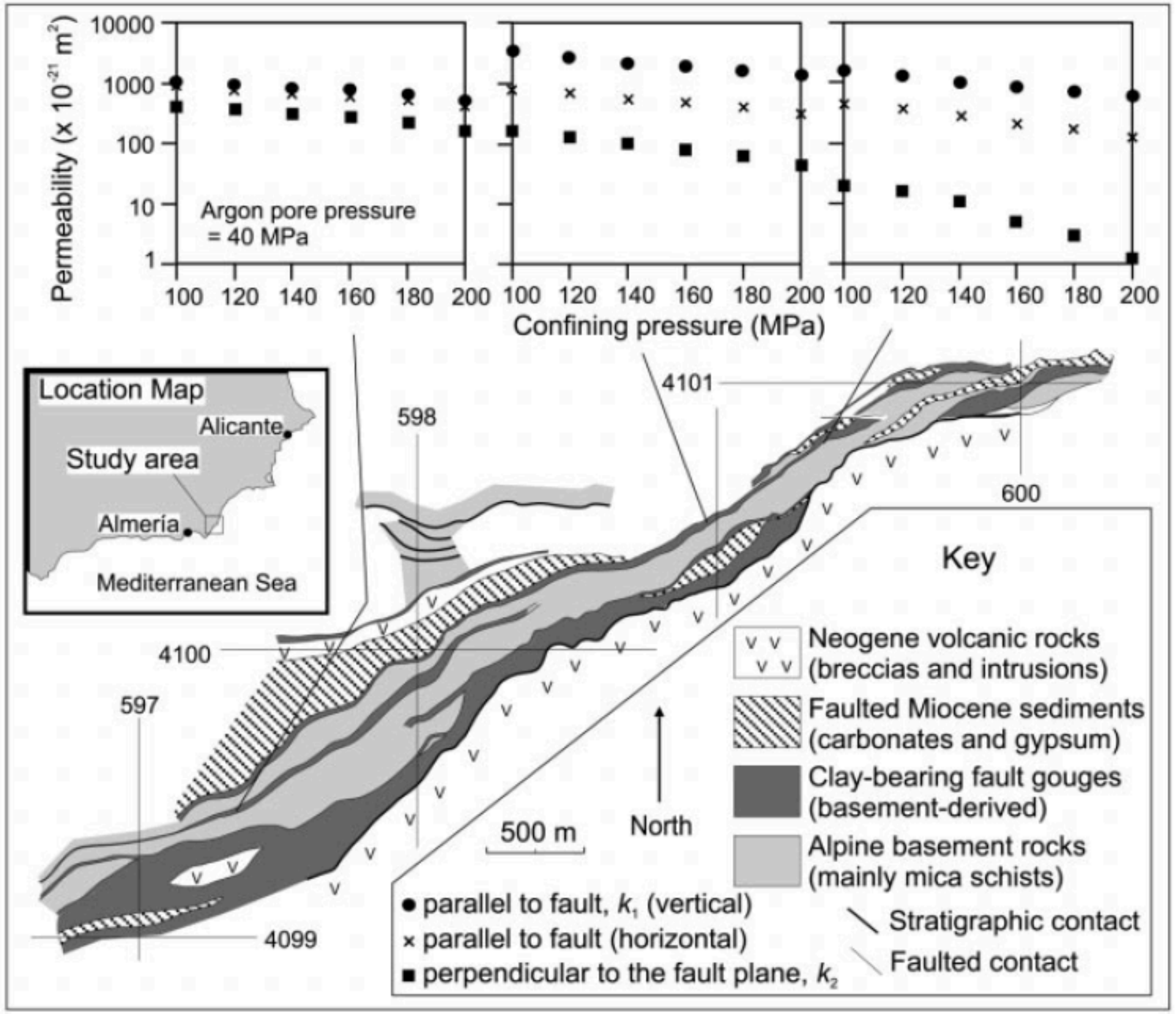
(standard porous flow: mass balance, fluid and pore compressibility, Darcy's law)

upward flows lead to ***overpressure*** (pore pressure > hydrostatic pressure):

for steady flux q and constant permeability k, just integrate Darcy's law $q=\frac{k}{\eta}\left(\frac{\partial p}{\partial z}-\rho g\right)$

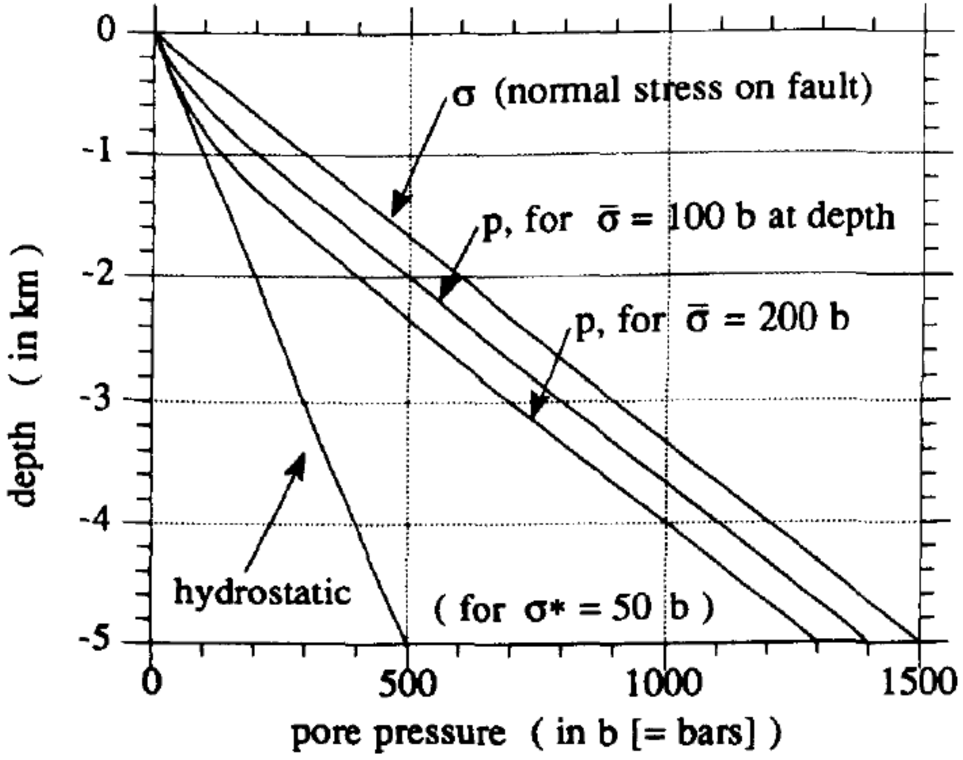
to get $p=\left(\underbrace{\rho g}_{\text{hydrostatic}}+\underbrace{\frac{\eta q}{k}}_{\text{overpressure}}\right)z$

Lab experiments show that permeability decreases as effective stress increases



(Faulkner and Rutter, 2001)

Rice (1992) showed that this leads to pore pressure gradient tracking lithostatic gradient, such that effective stress becomes independent of depth



(might help explain why stress drops are relatively independent of depth)

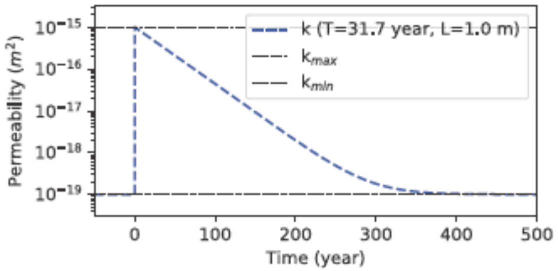
Other processes can change permeability, too

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

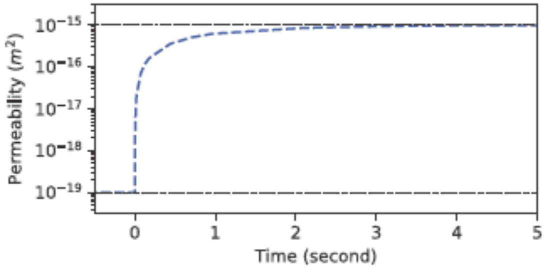
$$\frac{dk^*}{dt} = -\frac{V}{L}\left(k^* - k_{\max}\right) - \frac{1}{T}\left(k^* - k_{\min}\right)$$

increases with slip due to cracking
(V = slip velocity,
L = critical slip distance)

decreases with time due to healing and sealing
(T = healing/sealing time scale)



post/interseismic healing



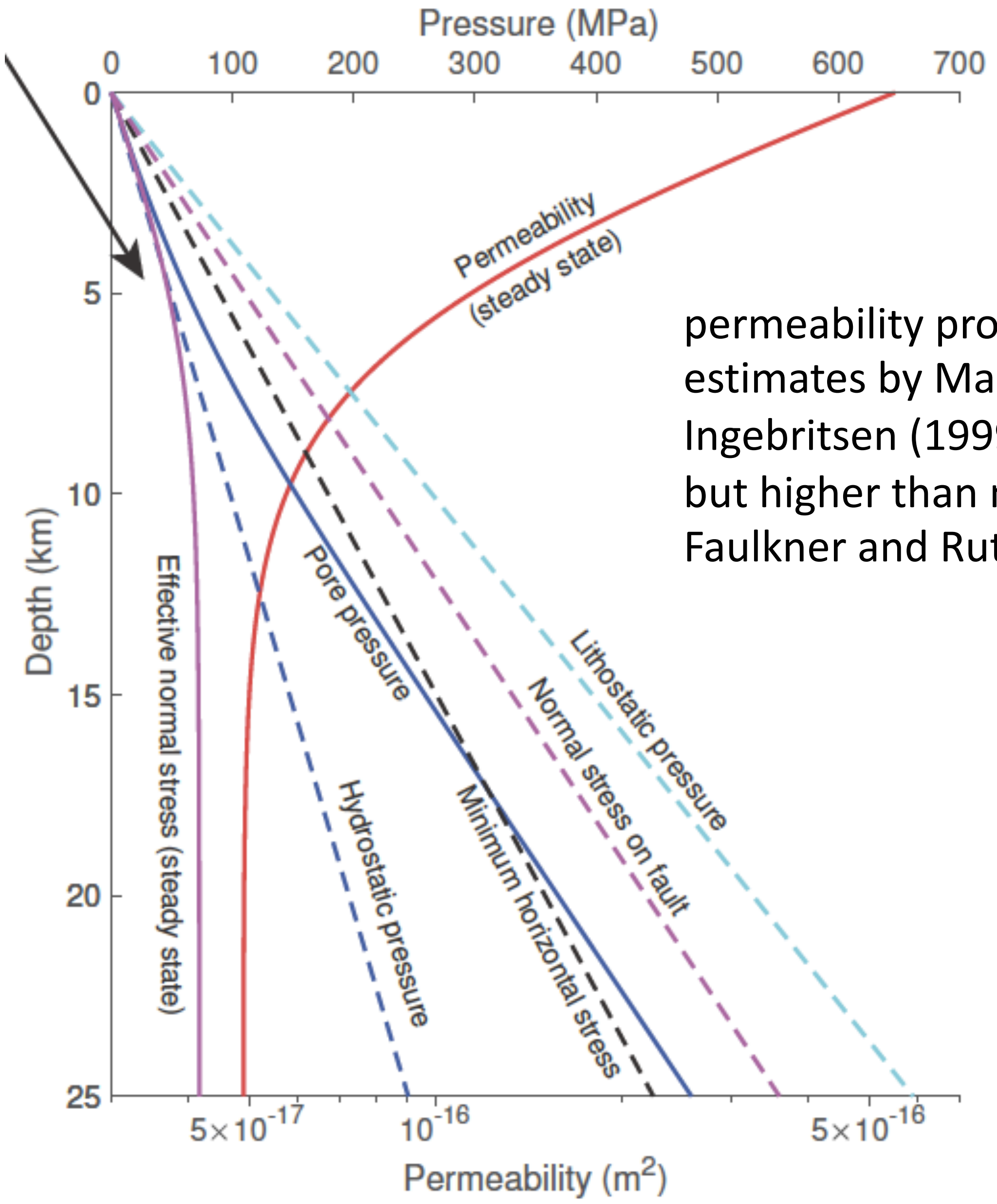
coseismic cracking

and then we account for direct dependence on effective stress:

$$k = \left(k^* - k_{\min}\right)\exp\left(\frac{\sigma - p}{\sigma^*}\right) + k_{\min}$$

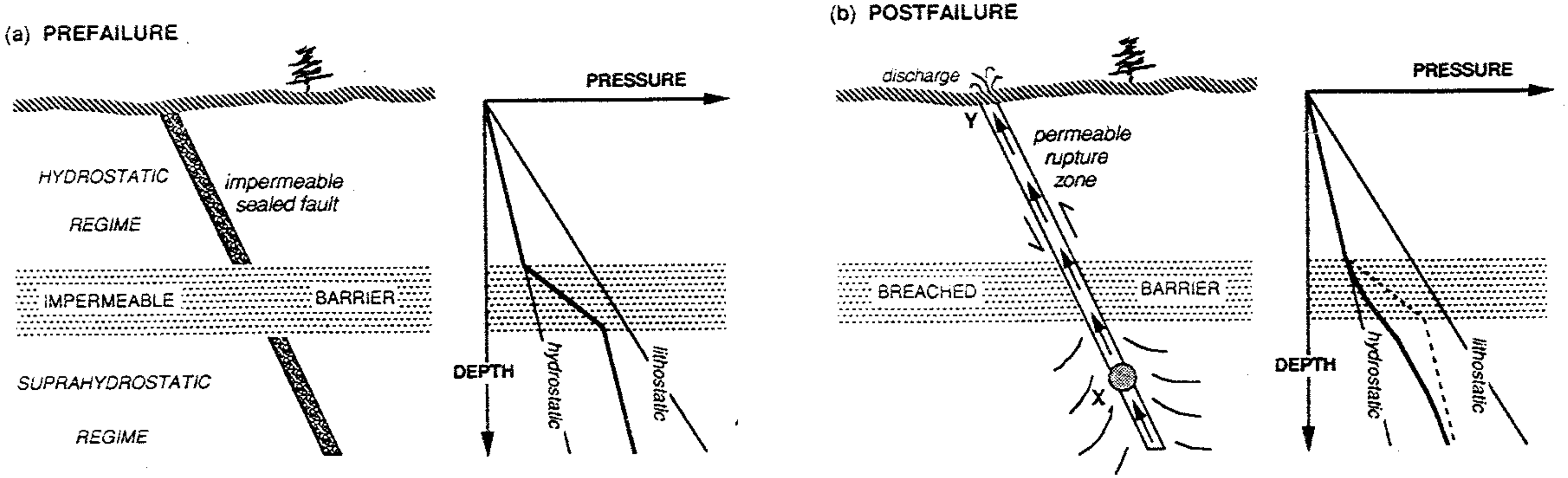
Example with steady flow

we’ll use this effective stress distribution, held fixed, as reference case in earthquake sequence simulation



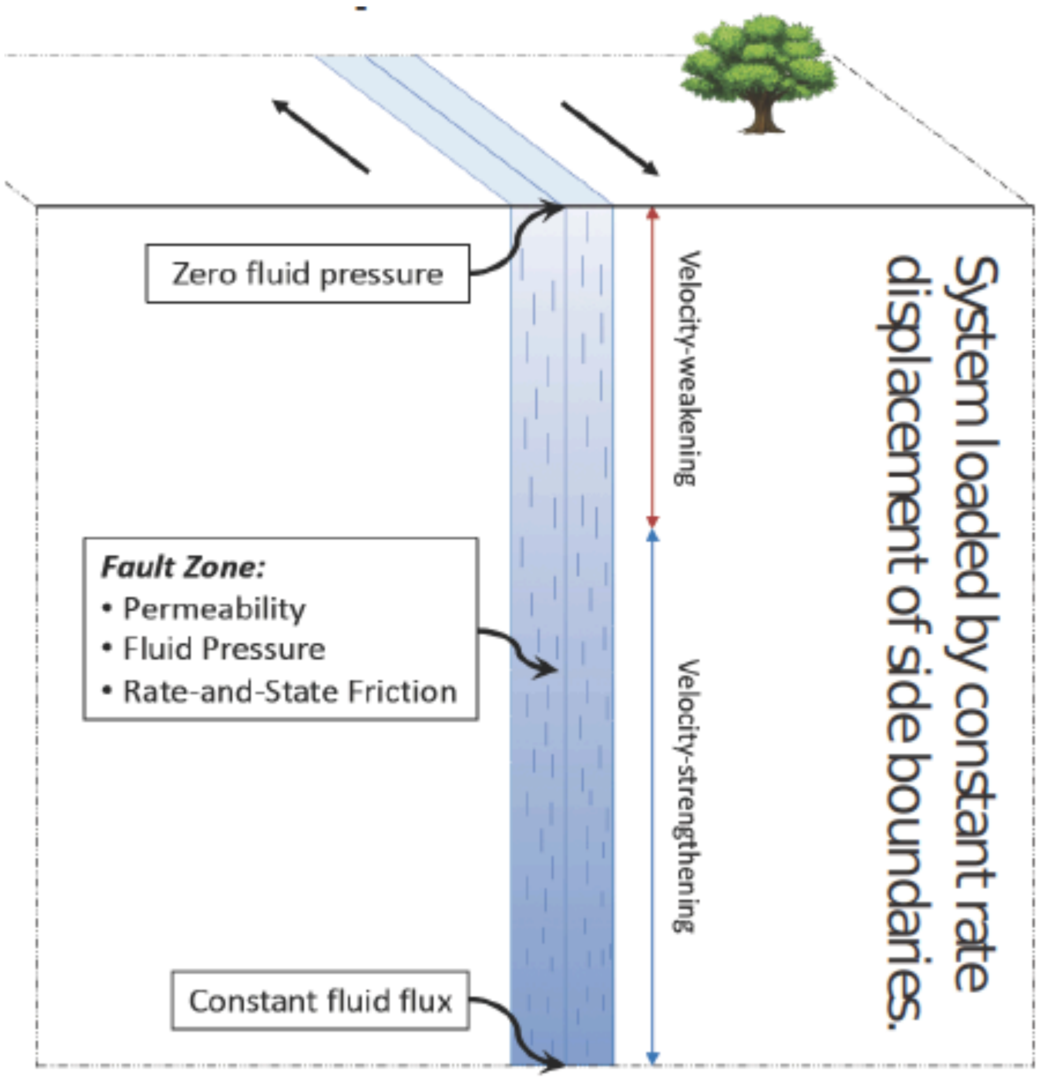
permeability profile similar to estimates by Manning and Ingebritsen (1999) and others, but higher than measured by Faulkner and Rutter (2001)

Sibson (1992) argues these processes lead to intermittent “fault valving” behavior



our objective: transform this idea from cartoon into quantitative model

Introduce fluids and pore pressure evolution into 2D earthquake sequence simulation

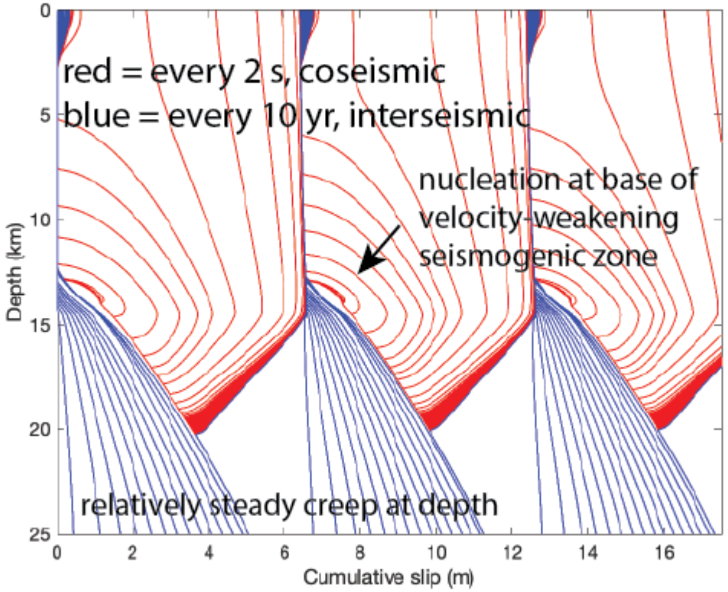


simulations using finite difference code SCycle* (Allison and Dunham, 2018) extended by Zhu, Allison, Dunham to handle fluids

*open-source: bitbucket.org/kallison/scycle

Earthquake sequence simulations

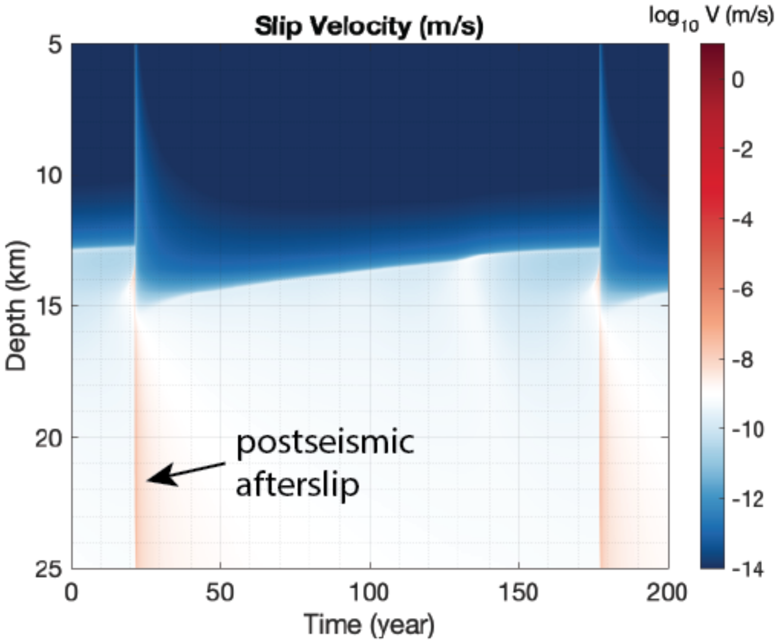
fixed effective stress
(reference case)



red = every 2 s, coseismic
blue = every 10 yr, interseismic

nucleation at base of
velocity-weakening
seismogenic zone

relatively steady creep at depth

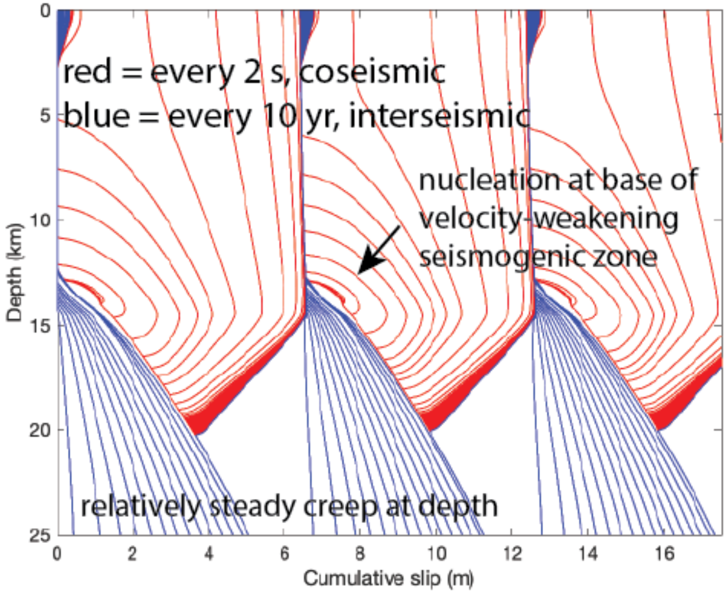


postseismic
afterslip

(Zhu, Allison, Dunham,
work in progress, 2019)

Earthquake sequence simulations

fixed effective stress
(reference case)


red = every 2 s, coseismic
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nucleation at base of velocity-weakening seismogenic zone
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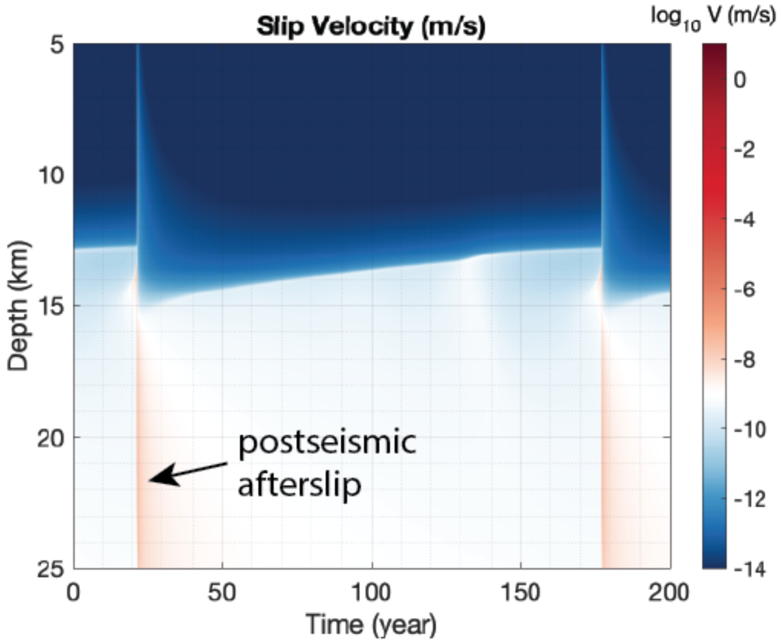
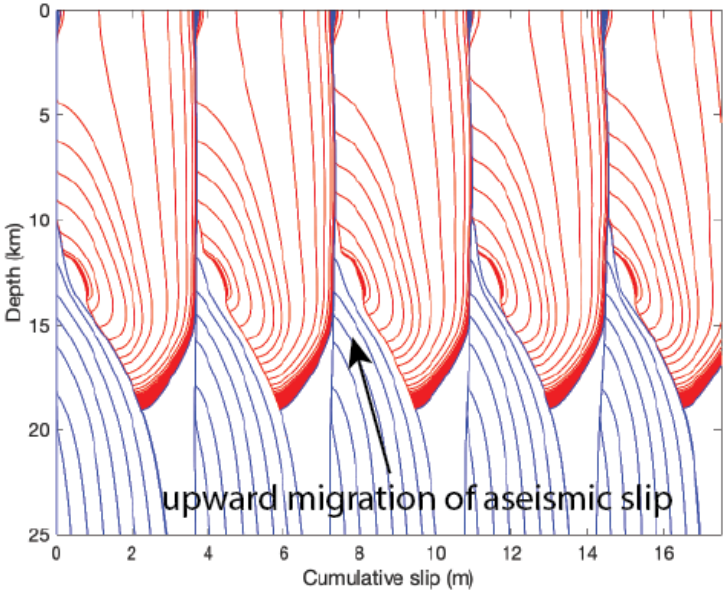
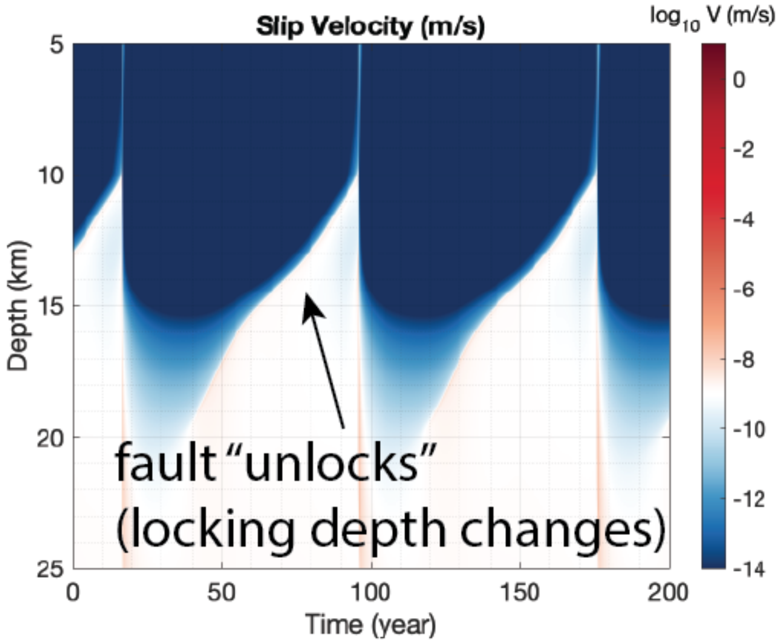

postseismic afterslip

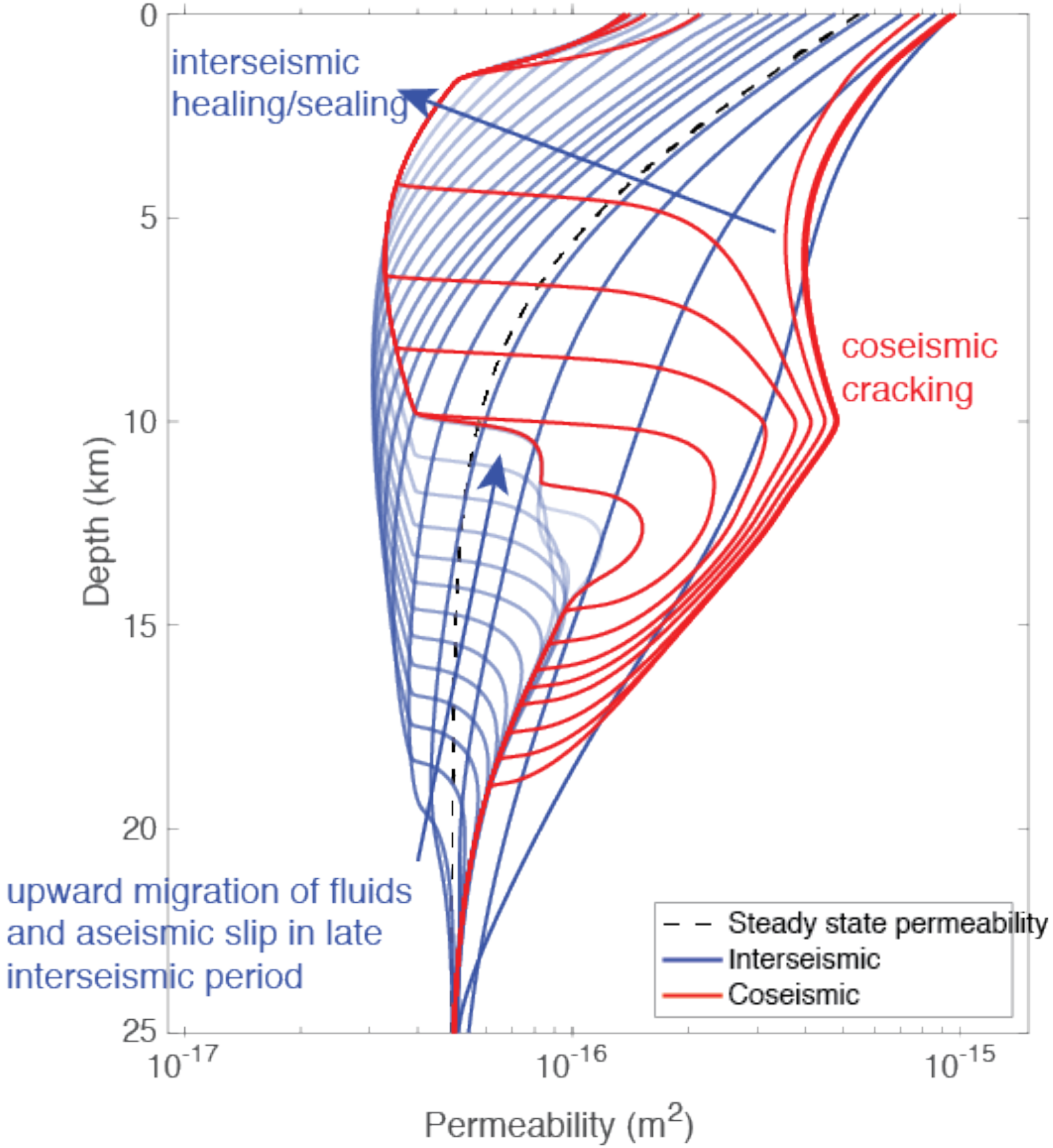
variable effective stress from upward fluid transport and permeability evolution

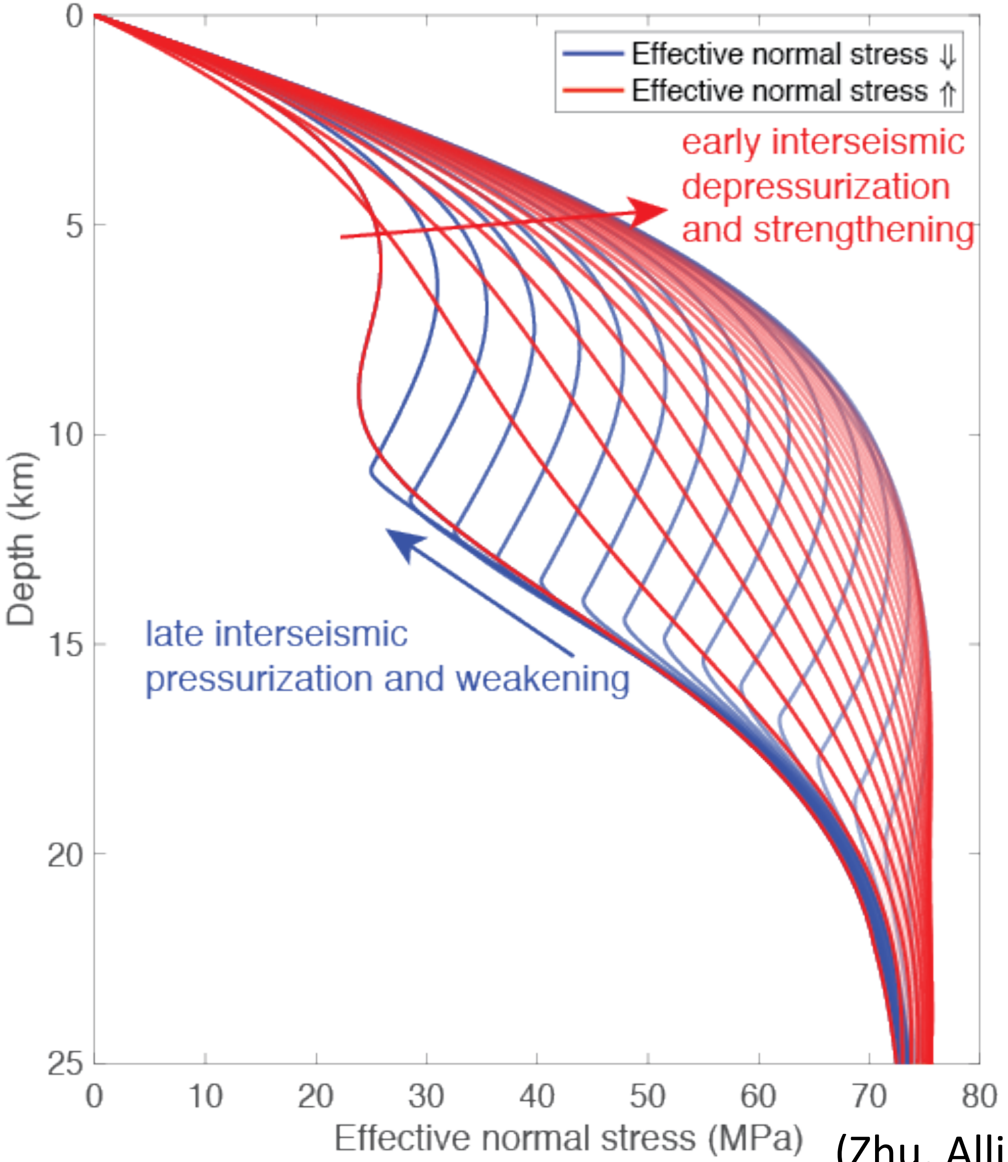

upward migration of aseismic slip


fault "unlocks"
(locking depth changes)

(Zhu, Allison, Dunham, work in progress, 2019)

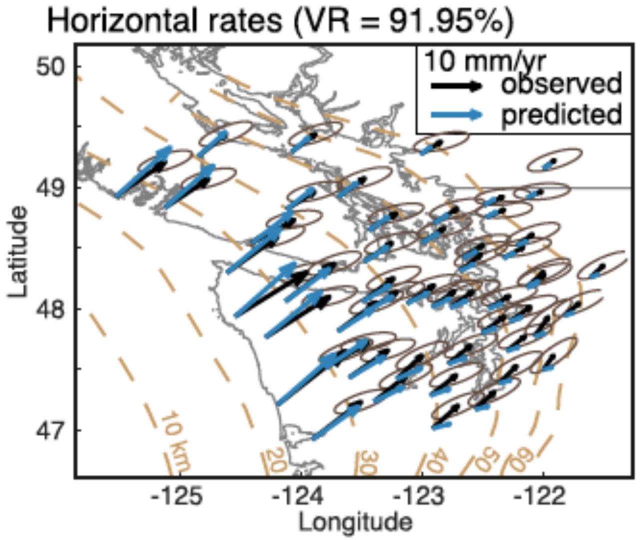
What drives upward migration of aseismic slip?



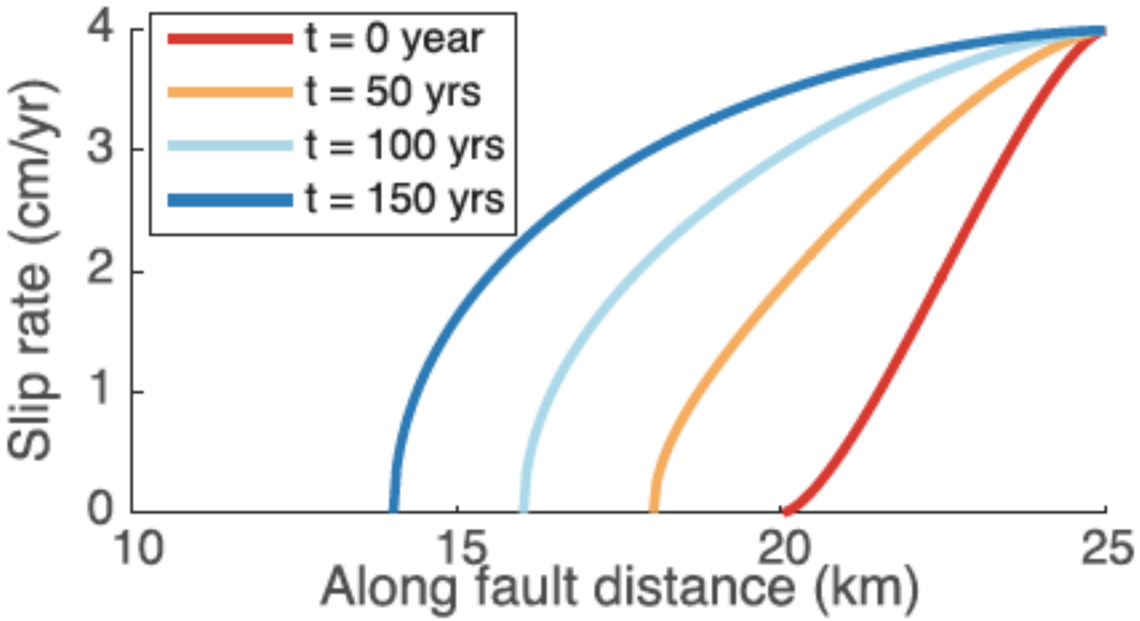


(Zhu, Allison, Dunham, work in progress, 2019)

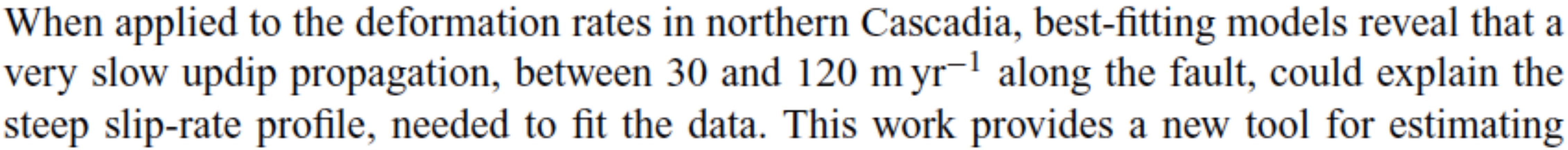
Upward migration of aseismic slip might be happening in Cascadia, in region above ETS



fit to 2000-2015 GPS as well as
decadal scale leveling and tide gauges



(Bruhat and Segall, 2017)



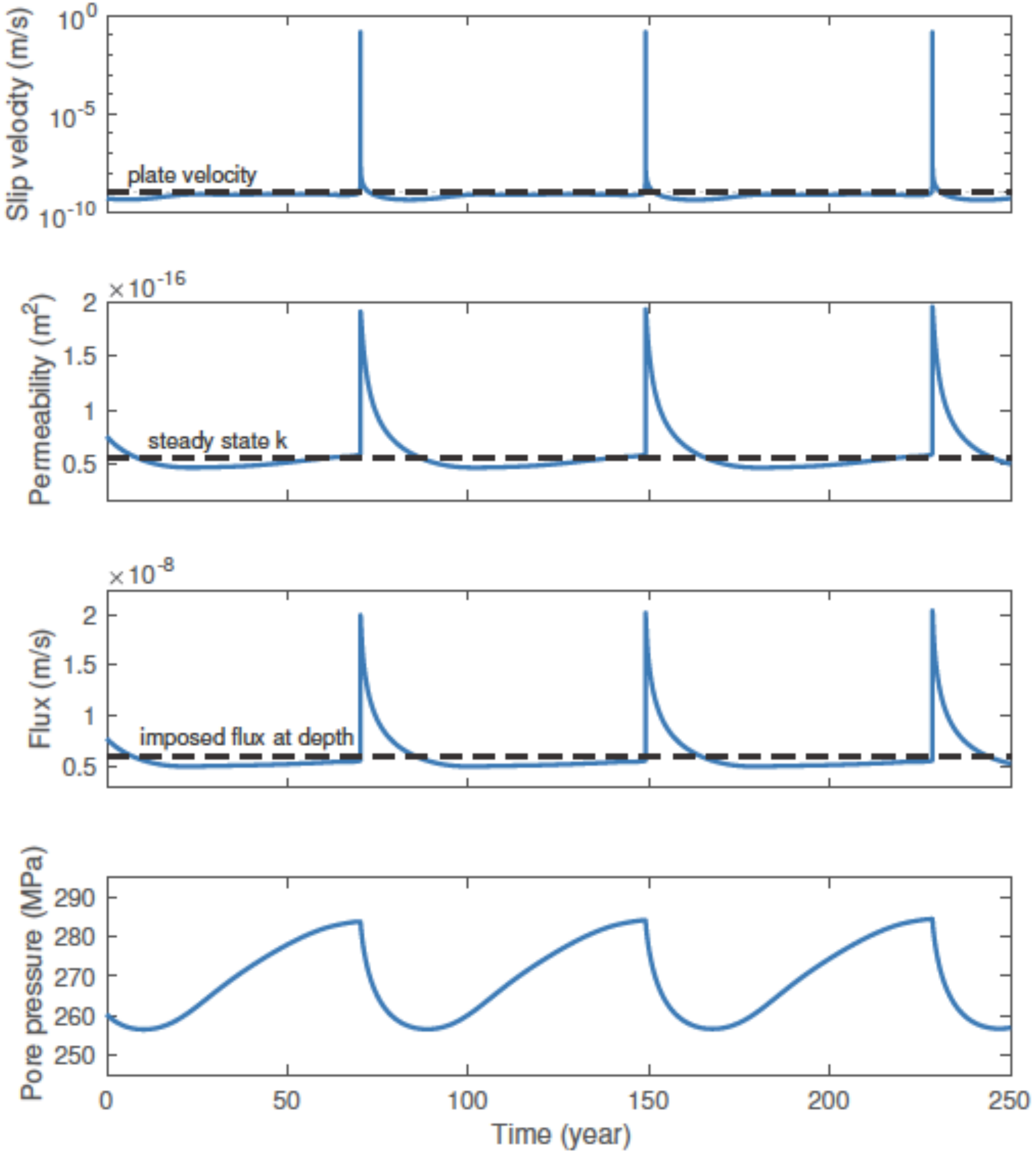
When applied to the deformation rates in northern Cascadia, best-fitting models reveal that a very slow updip propagation, between 30 and 120 m yr^{-1} along the fault, could explain the steep slip-rate profile, needed to fit the data. This work provides a new tool for estimating

(our model, completely untuned, predicts ~150 m/yr migration speed)

Fault valving cycles

(fields averaged over
5-30 km depth)

quite similar to what Sibson has envisioned, but pressures remain well below lithostatic (for these parameter choices)



Conclusions and next steps

- reasonable, generic assumptions about permeability and fluid flow can generate substantial overpressure
- pore pressure and effective stress are highly dynamic quantities over seismogenic zone
- changes in strength from pore pressure changes are possibly larger than those from friction changes
- pore pressure likely equilibrates toward lithostatic in lower crust due to viscous flow of matrix (switch from poroelastic to poroviscoelastic fault zone, combine with bulk power-law viscoelasticity)