Technical Report, 2019 SCEC Project #19074
Simulations of Fluid-Driven Aseismic Slip and Fault Valving
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This project continues SCEC-funded efforts by our group to develop earthquake sequence simulations that couple fault zone fluid migration and pore pressure evolution with rate-and-state fault friction. Work in 2018 focused on developing the coupled simulation methodology and performing preliminary simulations to explore system behavior like fluid pressure cycles and fault valving. During the 2019 project year, we focused our simulations on fluid-driven aseismic slip, which can occur both at the base of the seismogenic zone and within it. In the seismogenic, fluid-driven aseismic slip is often accompanied by migrating microseismicity, which model predictions bearing much similarity to earthquake swarms.

The motivation for our project stems from many geologic indicators of fluid pressure variations and flow along fault zones. Fault damage zones, in particular, are high permeability pathways for fluids. Fluids are sourced beneath the seismogenic zone from mantle dehydration and/or metamorphic reactions, or can derive from rainfall and groundwater that is driven downward and laterally into deep fault zones from topographic pressure gradients. Regardless of the fluid source, fluids at depth (specifically, below the brittle-ductile transition) are likely to reside at pressures close to lithostatic since viscoelastic creep closure of pores acts to equilibrate pore pressure and mean total stress. This creates an upward gradient in fluid pressure that exceeds the fluid weight, driving upward flow along faults. However, nonlinearities and feedbacks that control the evolution of porosity and permeability transform even steady fluid production rates into unsteady upward flow that is coupled to and modulated by fault slip behavior. In particular, permeability is reduced by healing and sealing processes of both mechanical and chemical nature over the interseismic period, and increased by cracking and dilatancy that accompanies fault slip. Thus, a healed, low permeability fault section acts as a temporary barrier to flow, with fluid influx causing pressurization and weakening of the fault. This, in turn, triggers slip which increases permeability to allow fluid discharge and depressurization.

We have translated this overall conceptual model for fault valving, developed by Sibson, Cox, and others, into a mathematical framework that permits quantitative investigation of fluid flux, pressure, and strength cycles as a function of parameters like the time scale of healing and sealing. This is done in the context of a vertical strike-slip fault, like the San Andreas, using a 2D antiplane shear earthquake sequence model (Figure 1). We assume that vertical fluid migration is confined to a high permeability fault zone and, for simplicity, replace dehydration and metamorphic reaction sources with specified fluid flux at the bottom of the model (well below the seismogenic zone and region experiencing cyclic modulations in permeability and flux). The fluid fluxes, of order 10^{-9} to 10^{-8} m/s (volume of fluid per unit horizontal cross-sectional area per time) explored in our simulations is based on estimates for plate boundary faults like the San Andreas, CA, and Alpine Fault, NZ. The main results are shown in Figures 2 and 3.

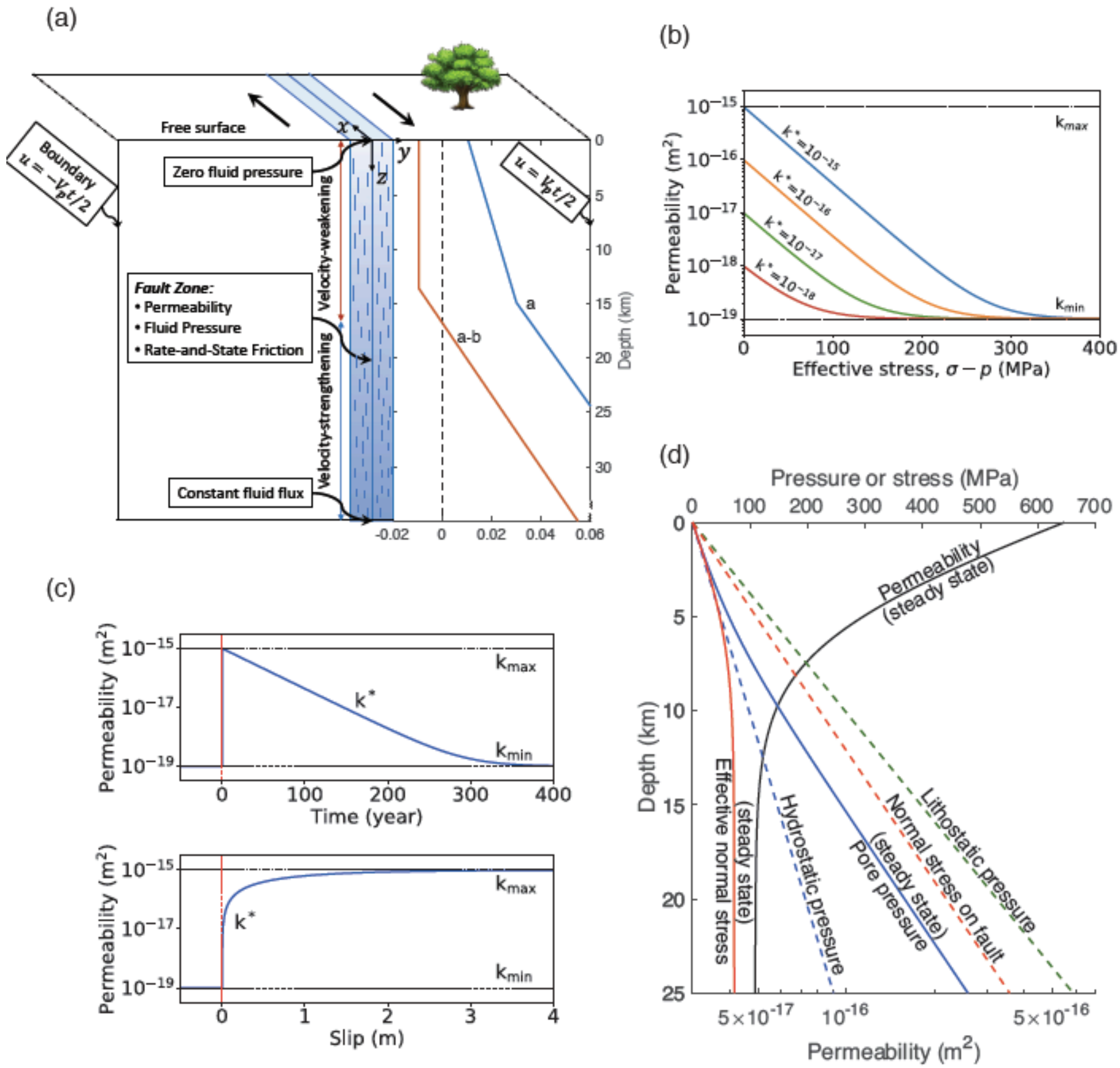


Figure 1. (a) Strike-slip earthquake sequence model with vertical fluid migration along permeable fault zone. Fluids are input at a constant, specified flux at the bottom of the model (which is placed much deeper than the 35 km depth shown). (b) Permeability decreases as effective normal stress increases and (c) decreases due to healing/sealing over a specified time scale and increases with slip due to cracking and dilatancy. (d) Depth distributions of stress, pressure, and permeability, shown for steady flow conditions at a flux of $q_0 = 10^{-9}$ m/s. Note how the pore pressure gradient approaches the fault normal stress gradient below a few kilometers depth, such that effective normal stress becomes independent of depth. Fault valving behavior will lead to departures from this steady state solution in the form of cyclic overpressure build-up during the interseismic period and loss in postseismic discharge events. From Zhu et al., in review, 2020.

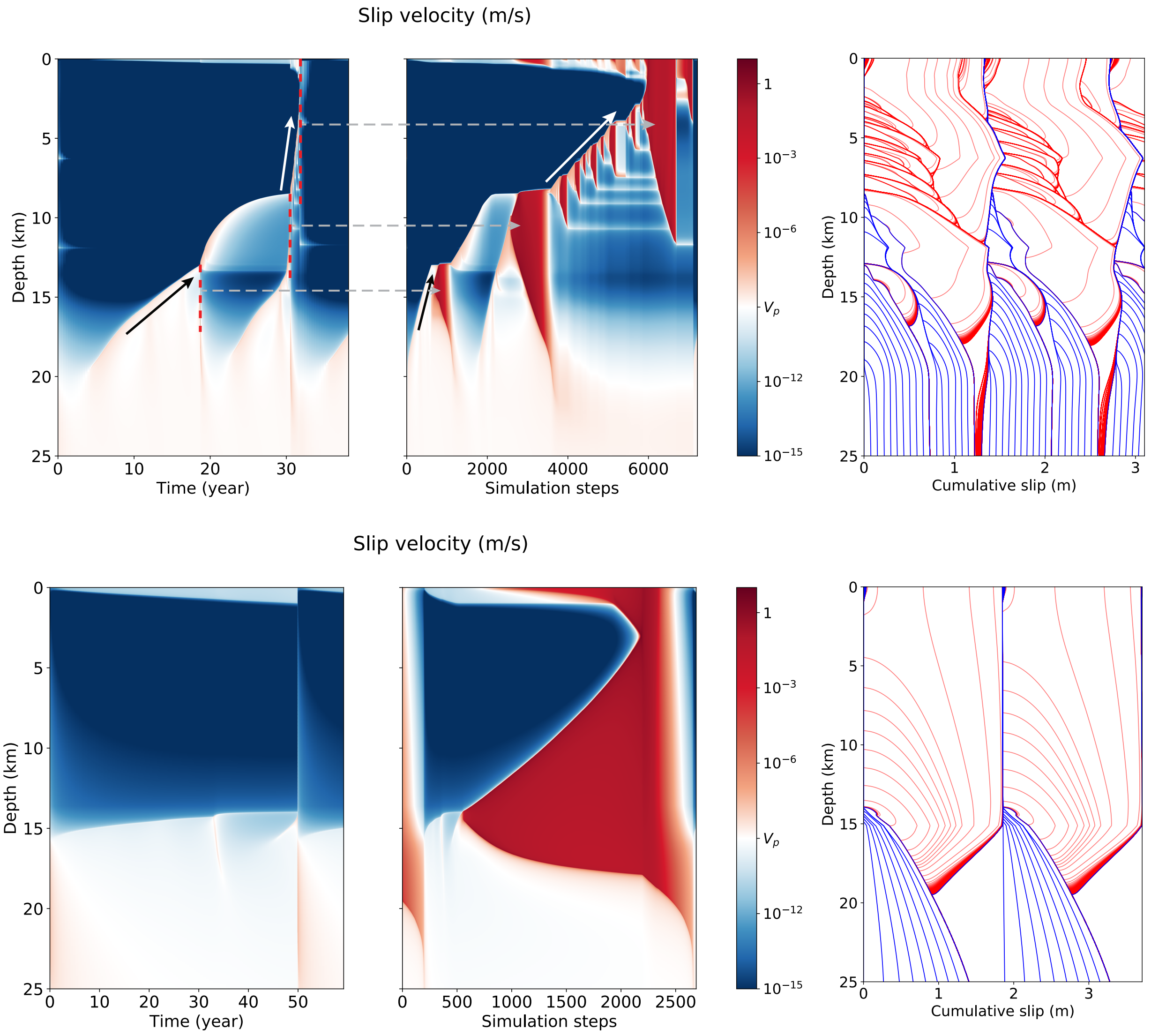
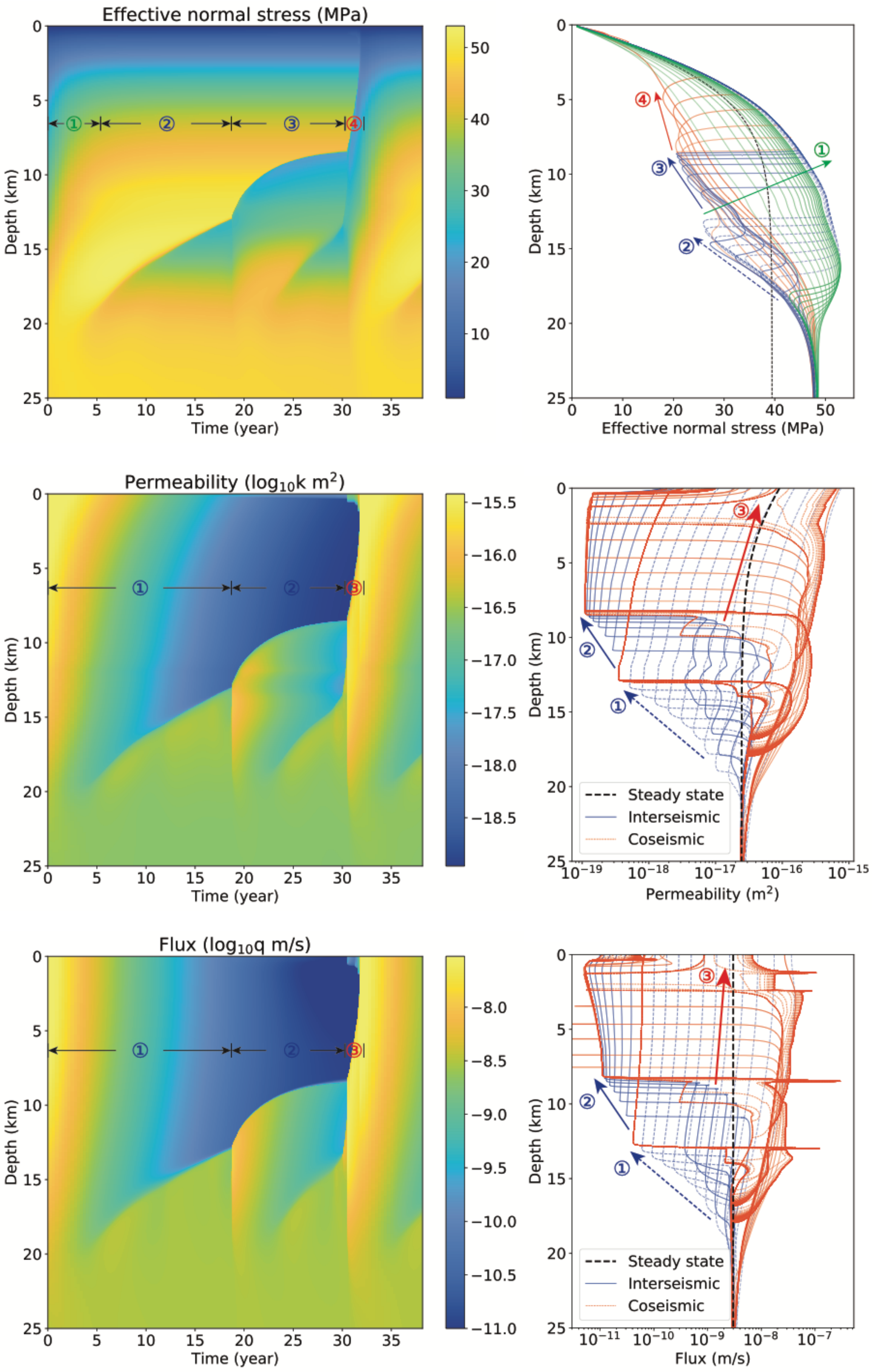


Figure 2. Slip histories from sequence simulations in the reference model (bottom row, with pore pressure and effective normal stress held fixed to steady state solution in Figure 1d) and a model with permeability and pore pressure evolution (top row). In the reference model, periodic earthquakes rupture the entire seismogenic zone, and the locking depth changes by only ~1 km over the earthquake cycle. In contrast, permeability and pressure evolution, when coupled to frictional dynamics, give rise to a complex sequence of aseismic slip, microseismicity, and large ruptures. Black arrow shows aseismic creep at depth (i.e., the locking depth) infiltrating the locked seismogenic zone at a rate of 0.5 km/yr. Two similar creep events, coexisting at different depth, are seen from 10-20 yr. White arrow tracks an earthquake swarm that ascends upward through the mid-seismogenic zone. Figure 3 explains how these behaviors are associated with ascending high pressure fluids. From Zhu et al., in review, 2020.



Effective normal stress (MPa)
Depth (km)
Time (year)
① ② ③ ④
Effective normal stress (MPa)
Permeability ($\log_{10}$k m^2)
Permeability (m^2)
Steady state
Interseismic
Coseismic
Flux ($\log_{10}$q m/s)
Flux (m/s)

Figure 3. Evolution of effective stress (top row), permeability (middle row), and fluid flux (bottom row) in the model with permeability and pressure evolution. Following a large earthquake, high pressure fluids are discharged from the seismogenic zone and the fault strengthens (phase 1 in top row). Healing then reduces permeability, which reduces fluid flux (phase 1 in middle and bottom rows). However, fluids push upward into the base of the seismogenic zone at this time, driving aseismic slip and permeability increase. This fluid-driven aseismic slip migrates upward until year 20 and triggers a small earthquake near the base of the seismogenic zone. A similar phenomenon occurs between years 20 and 30, but now involving two aseismic slip fronts migrating upward at different depths and again ending in another earthquake at the base of the seismogenic zone up to about 8 km depth (Figure 2). This is followed a year later by an earthquake swarm that migrates upward from 8 km to 3 km depth, involving about 8 small earthquakes occurring in rapid succession as the elevated pressure fluids and high permeability front moves upward. This leads into the largest earthquake in the sequence that ruptures from the surface down to 12 km depth, which completes the opening of the "fault valve" and allows discharge of the fluids out to the surface. From Zhu et al., in review, 2020.

This project supported two PhD students (Weiqiang Zhu, who did the simulations shown here, and Yuyun Yang, who will be continuing this line of research for the remaining two years of her PhD) and a postdoc (Kali Allison, formerly a PhD student at Stanford and now postdoc at University of Maryland). This work was presented at the SCEC and AGU meetings:

Dunham, E. M., W. Zhu, K. L. Allison, & Y. Yang (2019). Fault valving and pore pressure evolution in simulations of earthquake sequences and aseismic slip. Poster Presentation at 2019 SCEC Annual Meeting.

Dunham, E. M., K. L. Allison, Y. Yang, W. Zhu, & K. Duru (2019). Earthquake sequence simulations with inertia, viscoelasticity, shear heating, and fault zone fluid migration. Abstract S33A-01 presented at 2019 AGU Fall Meeting.

and is currently in review for publication:

Zhu, W., K. L. Allison, E. M. Dunham, and Y. Yang, Fault valving and pore pressure evolution in simulations of earthquake sequences and aseismic slip, in review.