Technical Report, 2018 SCEC Project #18047

Earthquake Sequences with Fluid Diffusion and Fault Zone Pore Pressure Evolution

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This project builds on SCEC-funded efforts by our group to develop earthquake sequence simulations with rate-and-state fault friction and additional process like viscoelastic or elastic-plastic off-fault response, coupling to an evolving temperature field, etc. This specific project focuses on fault zone fluid flow and poroelastic processes that influence pore pressure and hence fault strength. We believe this topic is of fundamental importance but has generally been neglected in almost all earthquake sequence modeling studies (for which pore pressure is simply specified a priori by the modeler and held fixed for the simulation).

Fault zone pore pressure determines effective normal stress and hence the frictional strength of the fault. The simplest distribution of pore pressure in the Earth is hydrostatic, which is valid when pore space is well connected from depth to Earth's surface and flow rates are small (so that viscous pressure drops are negligible). However, these conditions are not always met in the Earth. Pore fluids are produced at depth by metamorphic reactions, forming at pressures close to lithostatic pressure, and flow upwards through the crust. Fault damage zones provide permeable pathways that can channel fluid migration. However, low permeabilities at depth prevent fluid pressure equilibration to hydrostatic; they also increase viscous pressure drops during flow. These conditions can therefore promote pressures in excess of hydrostatic.

Geologists have documented much evidence for pore pressures in excess of hydrostatic pressure. Mineral veins and similar hydraulic fracture features require than pore pressure locally exceeds the minimum principal compressive total stress. There is also evidence for fluid pressure cycles. Sibson (1992) has advanced the idea of fault valving, in which ascending fluids temporarily stall when reaching regions of low permeability, causing pore pressures to increase. This pressure increase reduces fault strength and promotes slip instability. Sliding and associated cracking processes open pore space and increase permeability, allowing fluids to escape upward and depressurize the fault. Healing and sealing processes then reduce permeability over the interseismic period. While this fault valve model has much support geologically, it is not been explored quantitatively using earthquake sequence simulations. Over the past year, through this project, we addressed this issue by developing simulations of fault valving.

Our model consists of 2D antiplane shear deformation surrounding a vertical, strike-slip fault. The fault obeys rate-and-state friction with a transition from velocity-weakening over the seismogenic zone to velocity-strengthening at depth. The off-fault material is linear elastic and loaded by displacing the sides of the computational domain at constant rate. The fault is surrounded by a damage zone through which fluids flow vertically from a source at the bottom of the computational domain (a crude approximation to the metamorphic reaction source). Pore pressure obeys the 1-D diffusion equation (conservation of fluid mass, linearized compressibility of fluids and pore, and Darcy's law with gravity). Permeability obeys an evolution equation that captures permeability increase during sliding and permeability decrease with time from healing and sealing. These ingredients allow us to reproduce fault valving behavior (Figures 1-3).

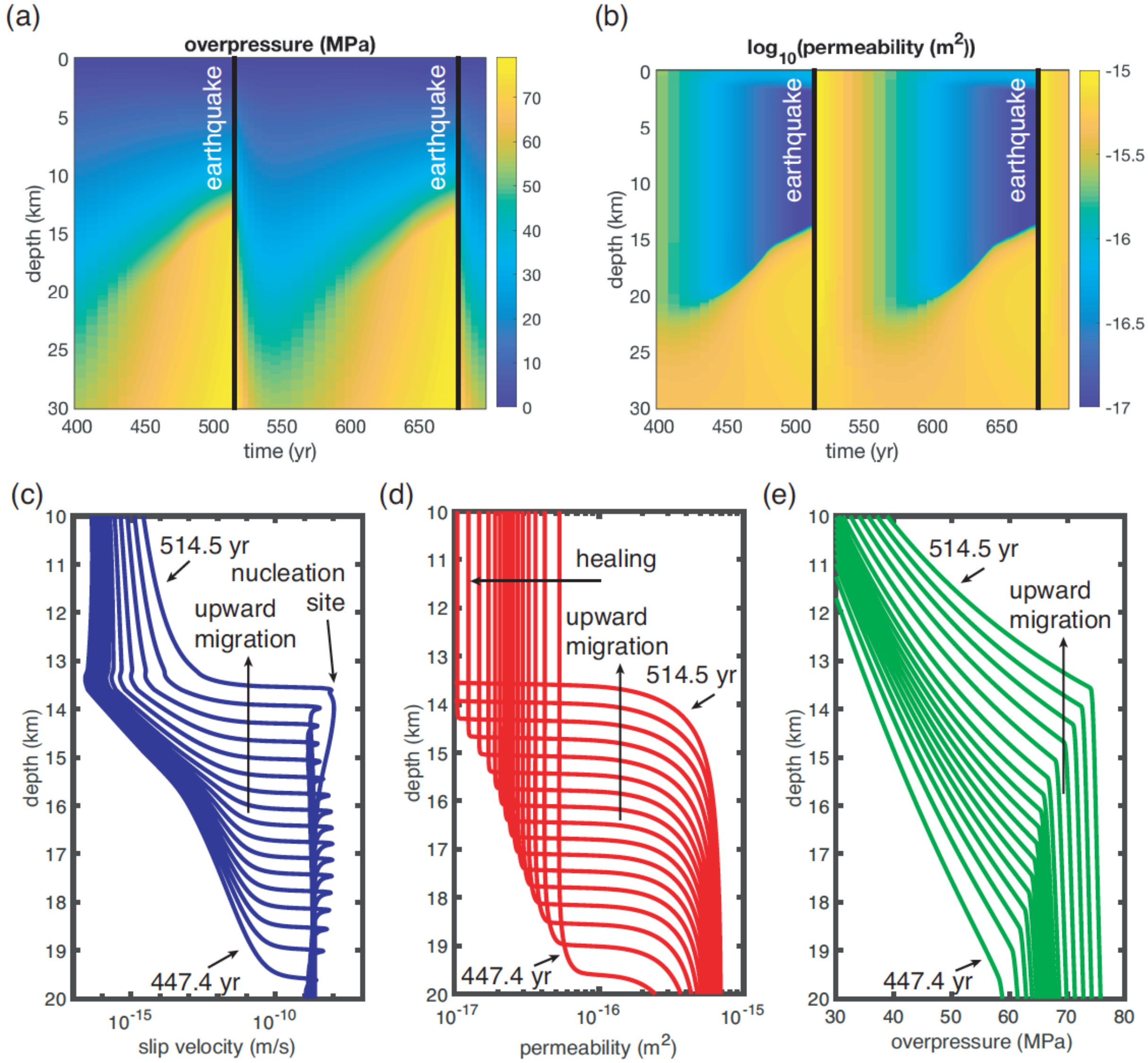

Figure 1. Strike-slip earthquake sequence simulation with coupled fluid migration, pore pressure diffusion, and rate-and-state friction. (a) Fluid overpressure (p-ρgz) and (b) permeability evolution over two earthquake cycles. Permeability reduction in the seismogenic zone during the interseismic period causes overpressure development as fluids sourced from depth stall. Rupture increases permeability, opening the fault valve and permitting depressurization. Pressure cycles are most pronounced in the aseismically slipping region below ~12 km. (c)-(e) Development and upward migration of an aseismic slip front occurs in the final ~50 yr of the interseismic period due to coupling between flow, pressurization, and sliding. Such behavior ought to be expressed in crustal deformation data.

The simulation shown in Figures 1-3 illustrates the cyclic build-up and release of overpressure in the lower portion of the seismogenic zone over the earthquake cycle. It also reveals an interesting and unexpected phenomenon, the formation of a coupled overpressure-slip front that advances upward along the fault in the decades preceding an earthquake. This phenomenon occurs in the velocity-strengthening portion of the fault below the seismogenic zone. The locked-creeping boundary at depth migrates upward. The onset of aseismic sliding is sufficient to reduce permeability, allowing influx of fluid and development of overpressure. That increased pressure weakens the fault and initiates additional sliding, a process facilitated by elastic stress transfer. This two-way coupling continues, leading to further upward migration.

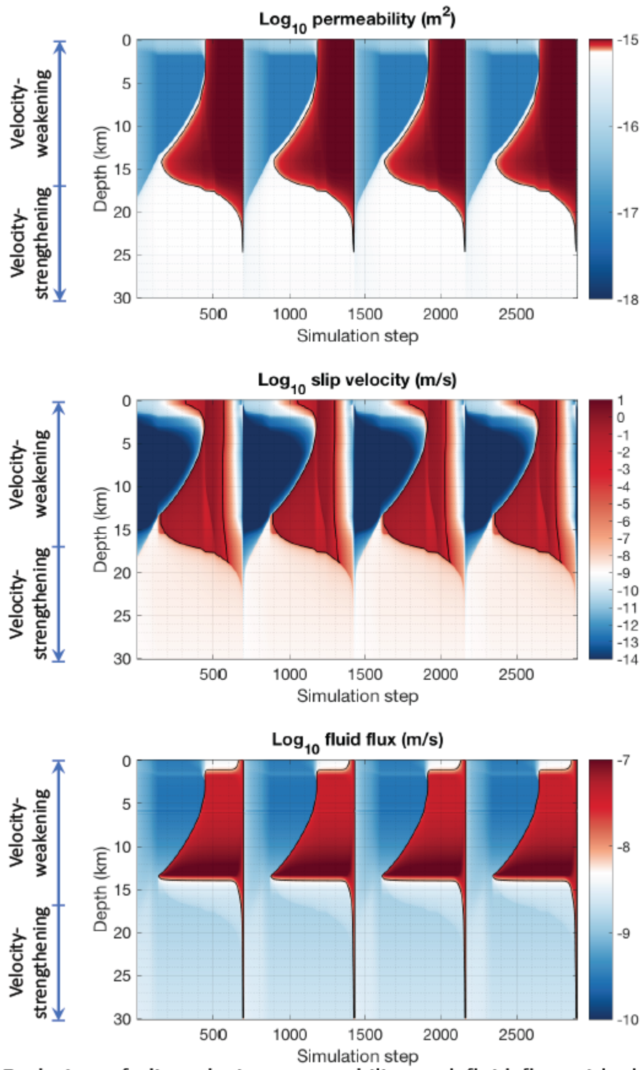

Figure 2 (left). Evolution of permeability, slip velocity, and fluid flux over several earthquake cycles, plotted as a function of simulation time step (instead of time) to emphasize the coseismic and postseismic response. Slip during the coseismic phase increases permeability by several orders of magnitude, allowing for upward fluid flow and depressurization.

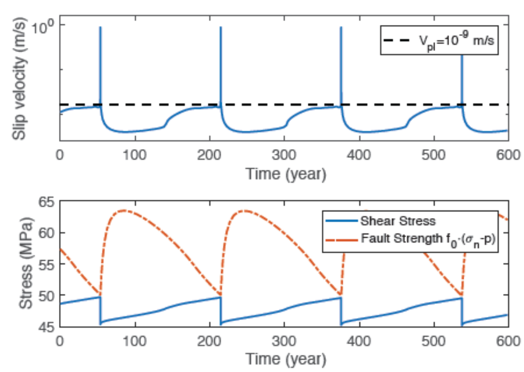

Figure 3 (above). Slip velocity, shear stress, and fault strength averaged over the seismogenic zone as a function of time. The cyclic build-up and release of fluids manifests in cyclic changes in strength, which influence the onset and timing of earthquakes in this model.

The simulations shown above account for permeability evolution with slip and time but neglect the direct dependence of permeability on effective normal stress. We have recently generalized our model to account for that direct dependence. For that case, permeability is greatly reduced at depth, where effective normal stress is highest, leading to much higher pore pressures at depth. In fact, Rice (1992) showed how such dependence gives rise to pore pressure that eventually begins tracking the lithostatic gradient at sufficient depth, something we see in our simulations, too. Furthermore, the migrating locked-creep boundary phenomenon remains a robust feature in these simulations. We have also done further calibration of the model by adjusting source fluid flux and permeability distributions to realistic values. We plan to systematically study how model parameters (e.g., the permeability reduction time scale in our permeability evolution equation) influence overpressure development and fault valving.

A natural extension of this model is to switch from a linear elastic off-fault rheology to a viscoelastic rheology. We have all of the necessary ingredients for this in our code, as explained in our other 2018 SCEC project report. Viscous flow of the solid matrix at depth will allow for creep closure of pores, which will pressurize pore fluids until pore pressure equilibrates with mean total stress. This will tend to promote fluid pressures reaching lithostatic—which will dramatically reduce fault effective normal stress, fault strength, and overall levels of deviatoric stress in the lower crust and upper mantle. We anticipate that this will reduce shear heating effects, which we found in our other project could be quite substantial. Integrating these two previously independent lines of work constitutes our major goal for the next year or more.

In addition to the project described above, we have a related project on fault-zone poroelastic effects. Here we utilize a more sophisticated description of the material adjacent to the fault slip surface, accounting for pore pressure changes in response to mechanical compression or dilation of the fluid-saturated rock and the accompanying fluid flow in response to pore pressure gradients that develop. The model is shown in Figure 5.

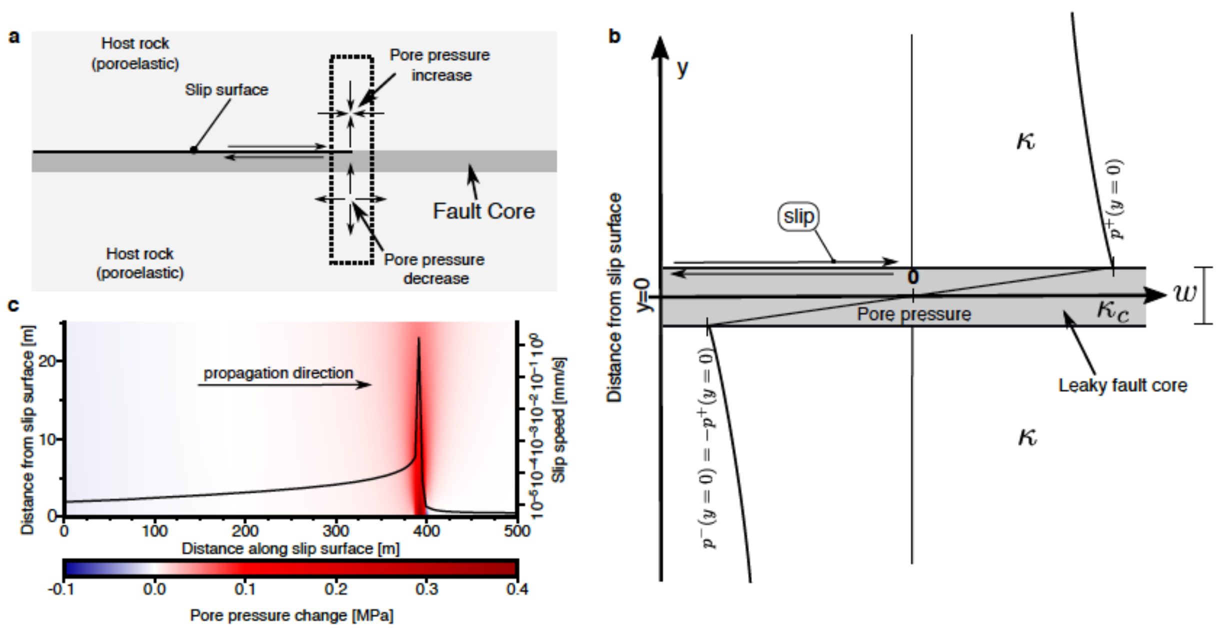

Figure 5. (a) Fault in a poroelastic medium. Slip compresses material on one side of the fault and dilates material on the opposite side, creating pressure changes as shown in (b). If the fault core is relatively impermeable, and slip is localized on one side of the core, then the fault will experience changes in effective normal stress and hence fault strength, which are asymmetric about the slip patch. Reduction of strength in one direction, to the right in the figure, leads to

spontaneously nucleating and propagating slow slip pulses with mildly rate-strengthening friction. An example of a slow slip pulse is shown in (c).

We found that steady sliding with (mildly) rate-strengthening friction can actually become unstable because of poroelastic pore pressure changes. Only a range of wavelengths are unstable, with one wavelength having maximum growth rate. Numerical simulations show that steady sliding destabilizes, with the instability taking the form of a slow slip pulse (Figure 6). The wavelength of maximum growth rate sets the length scale that determines the slip pulse length.

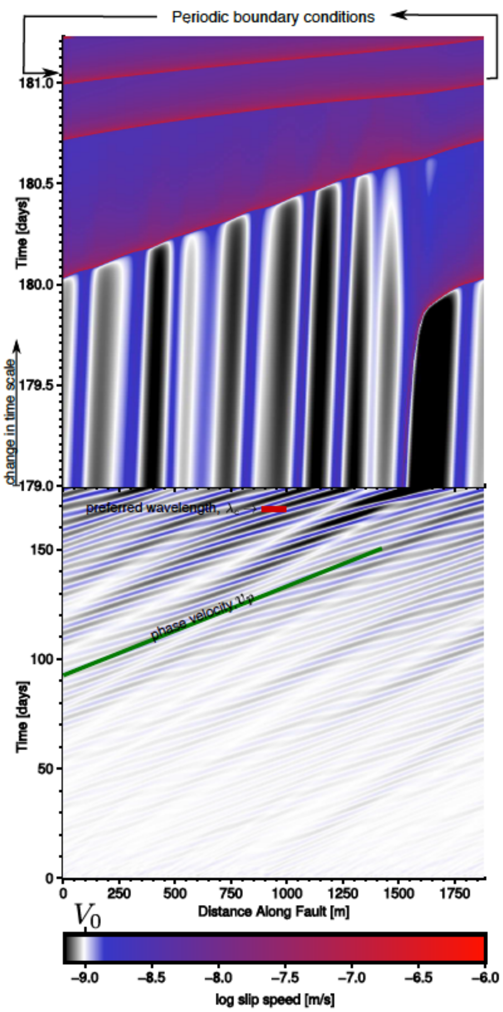

Figure 6. Space-time plot of slip velocity on an interface between two poroelastic solids with rate-strengthening friction on the interface. Steady sliding with small perturbations destabilizes to form a slow slip pulse. Note the change in time scale at 179 s. (From Heimisson et al., 2019.) We suspect this phenomenon might explain some slow slip events on faults.

Project results were reported in two SCEC posters:

Heimisson, E. R., Dunham, E. M., & Almquist, M. (2018). Nucleation and propagation of slow slip pulses on rate-strengthening faults. Poster Presentation at 2018 SCEC Annual Meeting.

Zhu, W., Allison, K. L., & Dunham, E. M. (2018). Coupled interactions of fluid-pressure and earthquake cycles: Numerical simulations of fault-valve behavior. Poster Presentation at 2018 SCEC Annual Meeting.

and one publication (on the poroelastic project):

Heimisson, E. R., Dunham, E. M., & Almquist, M. (2019). Poroelastic effects destabilize mildly rate-strengthening friction to generate stable slow slip pulses. Journal of The Mechanics and Physics of Solids, (under review).

A second publication on the fault valving project is in preparation.