Numerical simulation of the transition from frictional weakening to thermal pressurization introducing a remesh technique

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Thermal pressurization is one of the possible mechanisms that reduce frictional stress during seismic slip. Prior to the onset of thermal pressurization, slip nucleation is thought to be governed by rate- and state-dependent friction. We numerically simulate the effect of thermal pressurization from the nucleation to the dynamic slip stage, including both thermal and pore fluid transport, coupled with rate and state dependent friction. Radiation damping is employed to approximate inertial effects. To date our results are limited to one-dimensional transport perpendicular to the fault, with no along-strike variations.

Modeling full earthquake cycles including thermal and frictional effects, in a numerically efficient manner, is a significant challenge. We adopted a remeshing technique to calculate the evolution of the thermal field from the nucleation stage. A fine spatial grid is required to accurately compute the thermal and pore-pressure field during rapid slip (slip velocity ~0.1 - 1 m/s). Such a fine grid increases computation time because the spatial mesh size (dx) requires the smaller time step (dt) than dx^2 / (2 c) (where c is thermal diffusivity) in the explicit finite difference scheme. Thus, we remesh as the slip speed increases, using a finer mesh when the error in the spatial derivative exceeds a specified threshold. In addition, when the transport properties are spatially uniform, we introduce an analytical relationship between temperature and pore pressure by Rice (2006), such that pore pressure is automatically calculated from the thermal field, and we can also save the computational time. This problem is solved by MATLAB ODE solver. Our code successfully reproduces an analytic result due to Rice (2006) assuming constant coefficient of friction and slip velocity.

Segall and Rice (2006) estimated the critical velocity where the influence of thermal pressurization becomes dominant in the nucleation of earthquakes, determined as the slip speed at which the rate of weakening due to thermal pressurization equals that due to friction. For example, the critical velocity is about 0.05 mm/s, when d_c is 1 mm, and the thermal and hydraulic diffusivities are 1.0 and 1.8 mm^2/s, respectively. Our numerical results with full coupling support the analytical estimates of critical velocity, suggesting that thermal coupling can be ignored at lower slip speeds where the small rate of heat production is balanced by conduction.

Our simulations predict large slip velocities (~1 m/s), displacement, and stress drop after the thermal pressurization becomes dominant. We find that the, slip weakening distance with thermal pressurization can be less than the d_c in the rate-state friction law, suggesting that thermal pressurization may not explain the apparent large slip weakening distances inferred from seismological observations. While the slip weakening distance is similar to the characteristic length of thermal pressurization given by Rice (2006) for constant slip speed, the drop in strength is more rapid in the numerical results, due to increased rate of weakening with increasing slip-rate.

Because our numerical code with remeshing largely reduces computational time and requirement of memory, one numerical simulation is completed within 1 minute on PC. This technique enables simulations of thermal pressurization from the nucleation to the dynamic slip stage in 2-dimensional elastic medium.