

Earthquake cycle simulation with a rate-, temperature- and state-dependent friction law

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The Dieterich-Ruina rate- and state-dependent friction laws [Dieterich, 1978; Ruina, 1983] have been widely used in numerical simulations to produce earthquake cycles, including nucleation and propagation of multiple earthquake ruptures and aseismic slip. It is well known that the steady-state rate dependence of friction varies with temperature, and such experimentally observed variations have been translated into depth distributions of steady-state friction parameters in many earthquake models.

However, friction experiments have demonstrated additional temperature-dependent effects that are not included in commonly used rate and state formulations. Temperature-step tests have shown friction responses similar to velocity-step tests (e.g., Chester, 1994). An abrupt decrement in temperature results in an abrupt increase in friction followed by a decay to a new steady state. Chester [1994] explained this behavior by Arrhenius-type time-temperature superposition for two processes governing the direct effect and the evolution effect. Kato [2001] analyzed the response of the rate-, temperature-, and state-dependent friction law proposed by Chester [1994] in a spring-slider model. He showed that the increase in temperature makes the system less stable, leading to lower critical stiffness and earlier occurrence of an instability defined as slip with at the slip rate exceeding 1 mm/s.

In this work, we explore these temperature effects using 3D elastodynamic continuum modeling of earthquake cycles. We have formulated and tested several versions of the rate-, temperature-, and state- dependent friction laws without high velocity weakening. The formulations are based on the developments by Chester [1994] and representations of thermally activated microscopic slip processes at contact junctions [e.g., Nakatani, 2001; Rice et al., 2001; Noda, 2008] that account for the cut-off of time-dependent contact growth. The simulations are done using the spectral boundary integral method [Lapusta and Liu, 2008], modified to account for heat conduction from the shear zone. 1D fault-normal heat conduction is assumed in this work. The fault-parallel heat conduction from one fault cell to another is negligible on the time scale of heat-inducing slip, as it takes on the order of 100 years for the heat to penetrate the length scale comparable to the fault-parallel grid spacing of 100 m. For computational efficiency, we solve the heat conduction with a spectral method that involves grid optimization in the wave number domain. This method for heat conduction is unconditionally stable, making it suitable for the adaptively changing time steps. It also requires a much smaller amount of memory compared to the boundary integral and finite difference methods.

For all versions of the rate-, temperature-, and state- dependent friction laws that we examined so far, the temperature increase suppresses the occurrence of large seismic events in our simulations. The slip initially accelerates due to rate weakening but the further development of the instability is suppressed by temperature-strengthening behavior that arises in our constitutive models for a certain range of slip rates. Such temperature strengthening is consistent with the experimental study of Blanpied et al. [1995] which reported temperature strengthening of steady state friction for the wet granite gouge in the rate-weakening regime. Our simulations show that to produce large earthquakes we need to include dynamic weakening mechanisms at high slip rates [e.g. Noda et al., poster presentation in this meeting]. Our results indicate that rapid dynamic weakening may be essential for producing large earthquakes. In the absence of conditions for such weakening, the fault slip consists of aseismic transients with occasional small events. Hence our model may be a step towards explaining observations of slow slip accompanied by seismic tremor.