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EARTHQUAKE SEQUENCE CALCULATIONS WITH DYNAMIC WEAKENING MECHANISMS

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1 INTRODUCTION

Mature faults sustain low shear stress interseismically and during coseismic slip, as indicated by measurements of near-fault stress orientations (e.g., [1]) and observations of low heat flux [2]. At the same time, earthquake stress drops are typically between 1 and 10 MPa (e.g., [3]) which is much smaller than an expected value of shear strength at seismogenic depths (~ 100 MPa). These observations suggest that most fault points have low shear stress before large earthquakes, slip mainly at even lower shear stresses, and lock with the final stress only modestly lower than the initial value. [4], [5], and [6] demonstrated that even if a fault is strong at low slip rates, a dynamic rupture can propagate on a low-stressed fault (shear stress / normal stress ~ 0.3 or less) if the strength of a fault dramatically decreases coseismically, and discussed the operation of a fault at a low long-term shear stress.

Our aim is to elucidate effects of coseismically activated weakening mechanisms on the long-term fault behavior by conducting earthquake sequence simulations, following [4]. We have expanded the methodology that allows to simulate long slip histories while accounting for inertial effects during earthquakes [7, 8] to include strong dynamic weakening due to flash heating (FH) of microscopic contacts and thermal pressurization (TP) of pore fluids. Improvements over [4] include a more stable numerical algorithm and code parallelization that allows to explore more realistic parameter regimes.

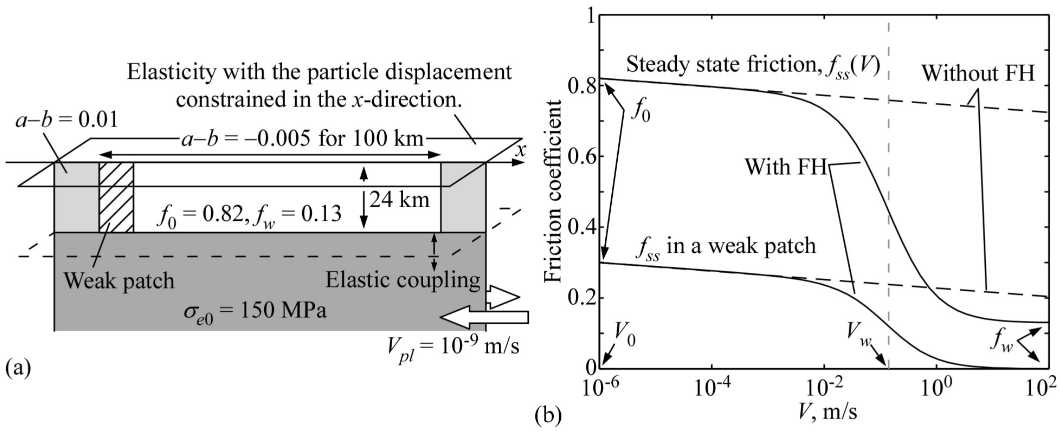

Figure 1. (a) A schematic diagram of the crustal-plane model. (b) Steady-state friction coefficient, $f_{ss}(V)$, in the law with strong rate weakening due to FH.

2 THERMAL WEAKENING MECHANISMS

Recent experimental studies (e.g. [9]) revealed that friction coefficients of rocks dramatically decrease at high slip rates (> 0.1 m/s). Such behavior can be explained by highly concentrated heat production in narrow shear zones and the resulting effects [10].

One such effect is temperature rise at microscopic frictional contacts (FH) which predicts $f \sim 1/V + const.$ at V larger than about 0.1 m/s, where f is the friction coefficient and V is the slip rate. We add this effect to the Dieterich-Ruina rate-and-state friction law (Figure 1b):

$$\tau = \sigma_e f(V,\theta) = \left(\sigma_n - p(y=0)\right) a \sinh^{-1}\left\{\frac{V}{2V_0}\exp\left(\frac{f_0 + b\ln\theta}{a}\right)\right\}$$

$$f_{ss}(V) = \frac{f(V, V_0/|V|) - f_w V/|V|}{1 + |V|/V_w} + f_w \frac{V}{|V|} \equiv f(V, \theta_{ss}(V)), \quad \dot{\theta} = \frac{|V|}{L}\left(\theta_{ss}(V) - \theta\right)$$

where τ is the shear stress, σ_e and σ_n are the effective and total normal stresses, p is pore pressure, y is the coordinate normal to the fault, θ is a state variable, a and b are rate and state parameters, L is the state evolution distance, V_0 and f_0 are the reference slip rate and friction coefficient, V_w is the slip rate at which FH becomes efficient, and f_w is the residual friction coefficient. Note that the aging effect in this law is important to simulate earthquake sequences including interseismic periods.

3 EARTHQUAKE SEQUENCES IN 2D CRUSTAL PLANE MODELS

In our simulation example, a 24-km deep elastic plate (depth-averaged to a crustal plane) is loaded by steady-state slip at 10^{-9} m/s at the deeper fault extension (Figure 1a). The depth-averaged elastodynamic equation for the strike-parallel displacement $u(x, y, t)$ incorporates the plate loading V_{pl} and is given as eq. (A1) in [8]. On the fault, slip rate and shear stress are given by $V = 2(\partial u(x, y{=}0^+, t)/\partial t)$ and $\tau = \mu\times(\partial u(x, y{=}0^+, t)/\partial y)$, respectively. We examine the behavior of a 100-km rate-weakening region surrounded by stable rate-strengthening areas.

The region has a 10-km weak region of low f_0 at one end which produces frequent nucleation of seismic ruptures. $f_{ss}(V)$ in the seismogenic region is shown in Figure 1b.

Although the strength at each point on the fault at low slip rates is high ($\sigma_e f_0$ ~ 100 MPa), averaged shear stress on a fault is low because of low coseismic shear stress and frequent rupture nucleation, consistent with the results of [4], [5], [6]. Long-term shear stress distribution and averaged shear stress in the seismogenic region (-50 km < x < 50 km) is shown in Figures 2a and b, respectively, for cases with L = 10 mm.

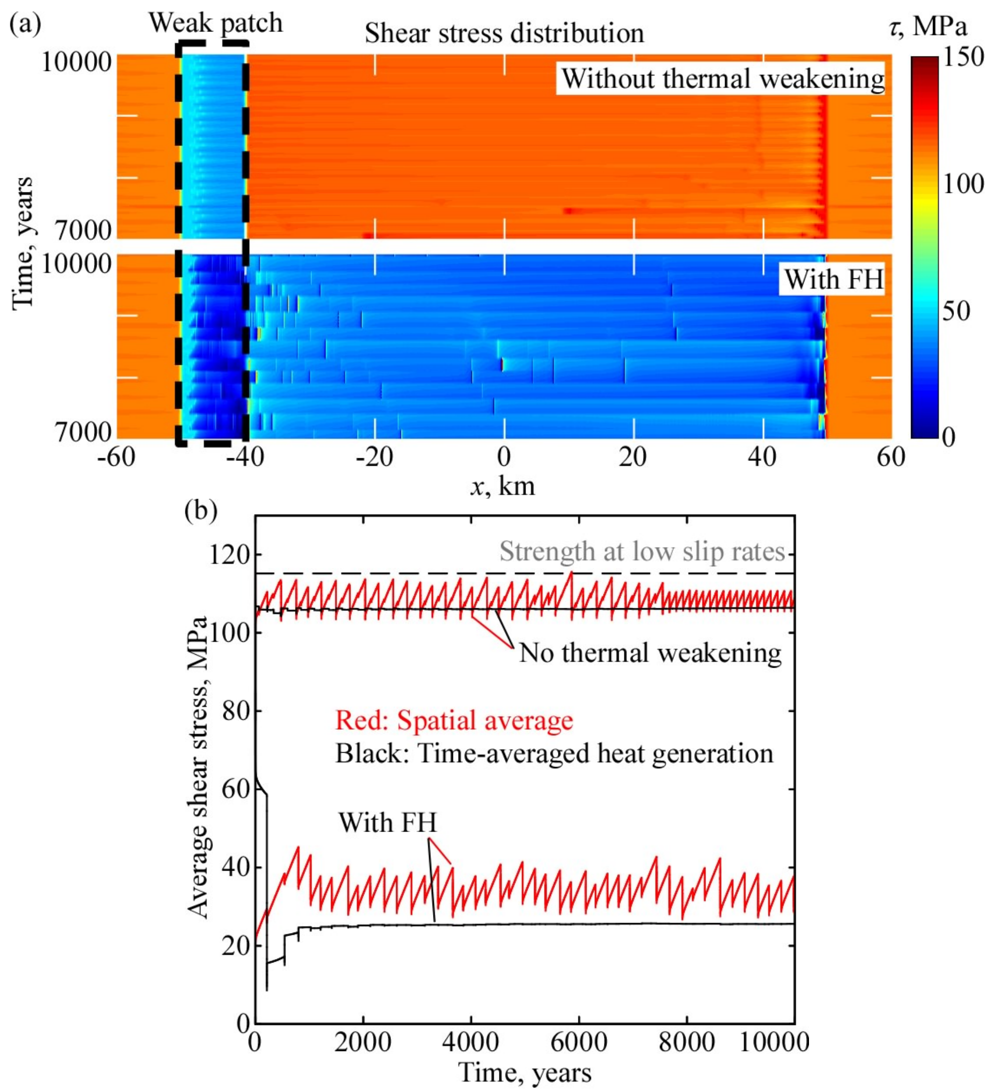

Figure 2. (a) Shear stress distribution between 7000-10000 years from the initiation of calculation without thermal weakening (top) and with FH (bottom). (b) Average shear stress (red) and time-averaged heat generation rate (black) in the seismogenic region (-50 km < x < 50 km). Interseismic shear stress and long-term heat generation are significantly reduced by thermal weakening due to flash heating.

4 CONCLUSIONS

Fault models that combine high static strength as shown in the lab, low dynamic strength due to flash heating, and locations for earthquake nucleation result in fault operation under low overall shear stress and with low heat production, as supported by observations. This is demonstrated by our long-term simulations of fault slip that incorporate both tectonically slow loading and inertial effects during seismic events.

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Summary, to appear at start of published version:

There are multiple lines of evidences that major faults which host large earthquakes (e.g., San Andreas fault) are operating at much lower shear stresses than what is predicted by Byerlee's law and a litho- and hydro-static stress state. Recent lab-experimental studies suggest that a fault weakens dramatically at coseismic slip rates. We have taken the experimentally derived dynamic weakening into account in the earthquake sequence simulations, and have revealed that the overall stress level at which a fault operates is controlled by the frictional resistance at coseismic slip rates, not that at low slip rates near the plate velocity.