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A microphysical model explains rate-and-state friction

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The rate-and-state friction (RSF) laws were originally developed as a phenomenological description of the frictional behavior observed in lab experiments. In previous studies, the empirical RSF laws have been extensively and quite successfully applied to fault mechanisms. However, these laws can not readily be envisioned in terms of the underlying physics. There are several critical discrepancies between seismological constraints on RSF behavior associated with earthquakes and lab-derived RSF parameters, in particular regarding the static stress drop and characteristic slip distance associated with seismic events. Moreover, lab friction studies can address only limited fault topographies, displacements, experimental durations and P-T conditions, which means that scale issues, and especially processes like dilatation and fluid-rock interaction, cannot be fully taken into account. Without a physical basis accounting for such effects, extrapolation of lab-derived RSF data to nature involves significant, often unknown uncertainties. In order to more reliably apply experimental results to natural fault zones, and notably to extrapolate lab data beyond laboratory pressure, temperature and velocity conditions, an understanding of the microphysical mechanisms governing fault frictional behavior is required.

Here, following some pioneering efforts (*e.g. Niemeijer and Spiers*, 2007; *Den Hartog and Spiers*, 2014), a mechanism-based microphysical model is developed for describing the frictional behavior of carbonate fault gouge, assuming that the frictional behavior seen in lab experiments is controlled by competing processes of intergranular slip versus contact creep by pressure solution. The model basically consists of two governing equations derived from energy/entropy balance considerations and the kinematic relations that apply to a granular fault gouge undergoing shear and dilation/compaction. These two equations can be written as

$$\dot{\tau}/K = V_{imp} - L_t[\lambda\dot{\gamma}_{ps}^{sb} + (1-\lambda)\dot{\gamma}_{ps}^{bulk}] - L_t\lambda\dot{\varepsilon}_{ps}^{sb}\frac{\sigma_n}{\sigma_n(\tilde{\mu} + 2\tan\psi) - \tau(1-\tilde{\mu}\tan\psi)} \tag{1}$$

$$\dot{\phi}^{sb} = \frac{\tau(1-\tilde{\mu}\tan\psi) - \sigma_n(\tilde{\mu} + \tan\psi)}{\sigma_n(\tilde{\mu} + 2\tan\psi) - \tau(1-\tilde{\mu}\tan\psi)}\dot{\varepsilon}_{ps}^{sb}(1-\phi^{sb}) \tag{2}$$

They describe the evolution of shear stress (τ) and shear band porosity (ϕ^{sb}) in response to any boundary conditions imposed.

By solving these two controlling equations, and using standard creep equations to describe gouge compaction by pressure solution, typical lab-frictional tests were simulated, namely “velocity stepping” and “slide-hold-slide” test sequences, using velocity histories and environmental conditions employed in the experiments summarized above. The modeling results capture all of the main features and trends seen in the experimental data, including both steady-state and transient aspects of the observed behavior, with reasonable quantitative agreement. The model is the first mechanism-based model that I am aware of that can reproduce RSF-like behavior without recourse to the RSF law. Since it is microphysically based, the approach adopted should help provide a much improved framework for extrapolating friction data to natural conditions.