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Rate-and-State friction as a bulk visco-plastic flow law that includes generation, diffusion, and healing of distributed damage

Casper Pranger[1], Patrick Sanan[2], Dave May[3], and Alice Gabriel[1]
[1]Institute of Geophysics, LMU Munich, Germany
[2]Institute of Geophysics, ETH Zurich, Switzerland
[3]Scripps Institution of Oceanography, UC San Diego, USA

The rate- and state-dependent friction (RSF) laws (Dieterich, 1979, JGR; Ruina, 1983, JGR-SE) have been widely successful in capturing the behavior of sliding surfaces in laboratory settings, as well as reproducing a range of natural fault slip phenomena in numerical models.

Studies of exhumed fault zones make it clear that faults are not two-dimensional features at the junction of two distinct bodies of rock, but instead evolve into complex damage zones that show clear signs of multi-scale fracturing, grain diminution, hydro-thermal effects and chemical and petrological changes. Many of these observed factors have been experimentally verified, and several studies have furthered our theoretical understanding of earthquakes and other seismic phenomena as volumetric, bulk-rock processes, including Sleep (1995, 1997), Lyakhovsky and Ben-Zion et al. (2011, J. Mech. Phys. Solids; 2014, PAGeoph; 2014, J. Mech. Phys. Solids; 2016, GJI), Niemeijer, Chen, van den Ende et al. (2007, 2016, JGR-SE; 2018, Tectonophysics), Roubicek (2014, GJI), and Barbot (2019, Tectonophysics).

While the established numerical modeling approach of simulating faults as planar features undergoing friction can be a useful and powerful homogenization of small-scale volumetric processes, there are also cases where this practice falls short -- most notably when studying faults that grow and evolve in response to a changing tectonic environment. This is mainly due to the computational challenges associated with automating the construction of a fault-resolving conformal mesh.

Motivated by this issue, we formulate a generalization of RSF as a plastic or viscous flow law with generation, diffusion, and healing of damage that gives rise to mathematically and numerically well-behaved finite shear bands that closely mimic the behavior of the original laboratory-derived formulation. The proposed formulation includes the well-known RSF laws for an infinitely thin fault as a limit case as the damage diffusion length scale tends to zero. In contrast to previous theoretical work we focus only on a mathematical formalism that is used to generalize and regularize the existing RSF laws in order to retain close correspondence to existing experimental and numerical results. We will demonstrate the behavior of this new bulk RSF formulation with results of 1D and 2D numerical simulations, and hope to engage in a preliminary discussion of the physical implications.