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Friction Laws, Elasticity, and Earthquake Nucleation

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In continuum models of the seismic cycle, spontaneous occurrence of earthquakes is mediated by a slip instability, in which an unstable and localized acceleration of the fault's sliding can emerge from the coupling of a weakening interface and the elastic deformation of the fault host rock. This unstable acceleration is ultimately limited by inertia, at which point an outward-propagating, dynamic rupture can initiate from the initial, compact acceleration. We examine and compare the development of such slip instabilities within continuum models of faults whose frictional strength follows commonly used and experimentally supported slip- and/or slip-rate dependent descriptions of fault frictional strength. Features of slip instabilities relevant to nucleation include: (i) whether there exists a characteristic length scale over which unstable acceleration occurs; (ii) whether the acceleration proceeds with a characteristic scaling in time; (iii) to what extent features such as (i) and (ii) are robust to changes in the constitutive description of fault strength; and (iv) whether the interplay between host rock elasticity and the fault strength description can otherwise affect instability development.

We focus on slip instabilities on faults with a slip rate and state-dependent friction [e.g., Dieterich, 1978; Ruina, 1983]. The common constitutive formulation on the basis of laboratory rock friction experiments includes an instantaneous (direct) rate-strengthening effect in response to changes in the sliding rate and a transient evolution effect that reflects the history of sliding rate changes, captured by a state variable. Early work established a characteristic nucleation length scale via a linear stability analysis of the evolution equations for slip rate and the state variable that result when coupling fault friction to the elastic deformation of the host rock [e.g., Rice and Ruina, 1983]. However, later examination of the non-linear acceleration regime indicated nucleation lengths differing from those of the linear stability analysis, the potential for chaotic progression of fault slip acceleration, and a strong influence of the state variable evolution law [e.g., Dieterich, 1992; Lapusta and Rice, 2003; Rubin and Ampuero, 2005, 2009; Kame et al., 2013; Bar-Sinai et al., 2013; and Bhattacharya and Rubin, 2014].

Recent work has shown that this diverse behavior and points (i–iv) can be well explained, understood, and explored within a single conceptual framework. We find that non-linear slip instability development under rate- and state-dependent friction can be considered in a manner akin to non-linear, time-dependent instabilities found in a variety of other fields, including fluid dynamics [Viesca, 2016 a,b]. Specifically, instability development can be understood in terms of dynamical systems as attraction towards a fixed point, which represents slip rate diverging with a known rate and spatial distribution. Within this framework, we account for the apparent dichotomy between universal and chaotic progression of the instability previously observed in numerical models of nucleation the so-called aging law; and the difference between nucleation under the aging law and other evolution laws, such as the so-called slip and Nagata laws, including the potential for elimination of a characteristic nucleation length scale; and how heterogeneous distributions of frictional parameters (e.g., so-called direct- and evolution-effect coefficients *a* and *b*) lead to preferential nucleation sites [Sohom and Ray, 2017].