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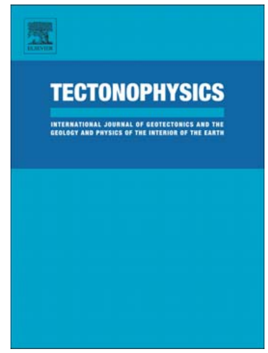

Stability of faults with heterogeneous friction properties and effective normal stress

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Stability of faults with heterogeneous friction properties and effective normal stress

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Abstract

Abundant geological, seismological and experimental evidence of the heterogeneous structure of natural faults motivates the theoretical and computational study of the mechanical behavior of heterogeneous frictional interfaces. Fault zones are composed of a mixture of materials with contrasting strength, which may affect the spatial variability of seismic coupling, the location of high-frequency radiation and the diversity of slip behavior observed in natural faults. To develop a quantitative understanding of the effect of strength heterogeneity on the mechanical behavior of faults, here we investigate a fault model with spatially variable frictional properties and pore pressure. Conceptually, this model may correspond to two rough surfaces in contact along discrete asperities, the space in between being filled by compressed gouge. The asperities have different permeability than the gouge matrix and may be hydraulically sealed, resulting in different pore pressure. We consider faults governed by rate-and-state friction, with mixtures of velocity-weakening and velocity-strengthening materials and contrasts of effective normal stress. We systematically study the diversity of slip behaviors generated by this model through multi-cycle simulations and linear stability analysis. The fault can be either stable without spontaneous slip transients, or unstable with spontaneous rupture. When the fault is unstable, slip can rupture either part or the entire fault. In some cases the fault alternates between these behaviors throughout multiple cycles. We determine how the fault behavior is controlled by the proportion of velocity-weakening and velocity-strengthening materials, their relative strength and other frictional properties. We also develop, through heuristic approximations, closed-form equations to predict the stability of slip on heterogeneous faults. Our study shows that a fault model with heterogeneous materials and pore pressure contrasts is a viable framework to reproduce the full spectrum of fault behaviors observed in natural faults: from fast earthquakes, to slow transients, to stable sliding. In particular, this model constitutes a building block for models of episodic tremor and slow slip events.

Keywords: fault heterogeneity; heterogeneous pore-pressure; slip instability; earthquakes; rate-and-state friction; linear stability analysis

Highlights:

1. A comprehensive study of slip behaviors in fault models with mixed velocity-strengthening / velocity-weakening materials and heterogeneous effective normal stress
2. Fault stability investigated with numerical rate-and-state simulations and analytical linear stability analysis
3. Rich range of slip behaviors including steady-slip, slow aseismic slip transients, ruptures localized in part of the fault (P-instability), ruptures breaking the whole fault (T-instability) and combinations of both
4. Closed form equations that accurately describe the stability conditions for P-instabilities and T-instabilities
5. A useful framework to understand the full spectrum of slow-to-fast earthquakes