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Multi-asperity models of slow slip and tremor

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Field observations of exhumed faults indicate that fault zones can comprise mixtures of materials with different dominant deformation mechanisms, including contrasts in strength, frictional stability and hydrothermal transport properties. Computational modeling helps quantify the potential effects of fault zone heterogeneity on fault slip styles from seismic to aseismic slip, including slow slip and tremor phenomena, foreshocks sequences and swarms, high- and low-frequency radiation during large earthquakes. We will summarize results of ongoing modeling studies of slow slip and tremor in which fault zone structure comprises a collection of frictionally unstable patches capable of seismic slip (tremorgenic asperities) embedded in a frictionally stable matrix hosting aseismic transient slips. Such models are consistent with the current view that tremors result from repeated shear failure of multiple asperities as Low Frequency Earthquakes (LFEs). The collective behavior of asperities embedded in creeping faults generate a rich spectrum of tremor migration patterns, as observed in natural faults, whose seismicity rate, recurrence time and migration speed can be mechanically related to the underlying transient slow slip rate. Tremor activity and slow slip also responds to periodic loadings induced by tides or surface waves, and models relate tremor tidal sensitivity to frictional properties, fluid pressure and creep rate. The overall behavior of a heterogeneous fault is affected by structural parameters, such as the ratio of stable to unstable materials, but also by time-dependent variables, such as pore pressure and loading rate. Some behaviors are well predicted by homogenization theory based on spatially-averaged frictional properties, but others are somewhat unexpected, such as seismic slip behavior found in asperities that are much smaller than their nucleation size. Two end-member regimes are obtained in rate-and-state models with velocity-weakening asperities embedded in a matrix with either (A) velocity-strengthening friction or (B) a transition from velocity-weakening to velocity-strengthening at increasing slip velocity. The most conventional regime is tremor driven by slow slip. However, if the interaction between asperities mediated by intervening transient creep is strong enough, a regime of slow slip driven by tremors emerges. These two regimes lead to different statistics of inter-event times of LFE sequences, which we confront to observations from LFE catalogs in Mexico, Cascadia and Parkfield. These models also suggest that the depth dependence of tremor and slow slip behavior, for instance their shorter recurrence time and weaker amplitude with increasing depth, are not necessarily related to depth dependent size distribution of asperities, but could be due to depth-dependence of the properties of the intervening creep materials. Simplified fracture mechanics models illustrate how the resistance of the fault zone matrix can control the effective distance of interaction between asperities, and lead to transitions between Gutenberg-Richter to size-bounded (exponential) frequency-magnitude distributions. Structural fault zone properties such as the thickness of the damage zone can also introduce characteristic length scales that may affect the size distribution of tremors. Earthquake cycle simulations on heterogeneous faults also provide insight into the conditions that allow asperities to generate foreshock activity and high-frequency radiation during large earthquakes.