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Rock Friction from the Nanoscale to the San Andreas Fault

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Nucleation of earthquakes (EQs) and the resistance of faults to shearing during EQs are determined by nano-to-micro-scale frictional processes that occur on tectonic-scale faults. A first-order observation from rock-friction studies is that of ageing, i.e., the linear increase in friction with the log of the time of stationary contact, manifest as a positive or negative dependence of friction on sliding rate. A necessary condition for EQ nucleation is a negative rate dependence of friction. In spite of the success of friction 'laws' which encapsulate the rate and time dependences of friction in fitting experimental data and reproducing natural phenomena in EQ models, these laws lack a physical basis. Atomic force microscope (AFM) experiments on silica-silica contacts explore the physics of ageing, more specifically increases in adhesion of nanometers-sized contacts with time (Li et al., *Nature*, 2011). The experiments reveal prominent ageing which increases with humidity, as in rock friction tests, without increases in contact area due to creep (the canonical explanation for ageing in rock-friction tests). Ageing in the AFM tests is in fact much larger than in rock-friction tests, a discrepancy explained with a simple multi-asperity contact model. At EQ slip rates ($\geq$1 m/s) a variety of dynamic fault-weakening mechanisms may decrease the shear resistance of faults, which would have important consequences for the magnitudes of EQ stress drops, strong ground motions and accelerations, for the EQ energy budget, and for the state of stress on faults. Experiments on rocks found in the Earth's crust for slip rates up to $\sim$0.4 m/s over $\sim$40 mm of slip, reveal a dramatic $1/V$ decrease in frictional strength above a characteristic weakening velocity V_w of $\sim$0.1 m/s (Goldsby and Tullis, *Science*, 2011). Friction is also revealed to be a nearly pure function of slip rate, i.e., it adjusts to the ambient slip rate over only microns of slip. The observations are explained by 'flash heating', whereby microscopic asperity contacts become intensely frictionally heated and weakened above V_w. Dramatically lower friction due to flash heating may explain why heat flow along active faults like the San Andreas Fault is much lower than expected. Strong velocity-weakening friction and the rapid strength recovery with decreasing slip rate from flash heating may explain why EQ ruptures propagate as slip pulses rather than as cracks.