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Ductile deformation explains the physics of friction and genesis of earthquakes

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Seismic hazard presents a significant global threat to both life and property, with increased urbanisation in the twenty-first century only intensifying the risk as populations concentrate near fault lines. It is therefore imperative to develop a clear understanding of the physical origins of earthquakes, with their associated hazards, and use that knowledge to work towards building more resilient societies. To this end, we show that ductile deformation on contact regions within fault zones explains the physics of fault friction, and the genesis of earthquakes. We find the empirical framework of rate-and-state friction may be derived from grain-scale creep processes, and that earthquakes are the macroscopic manifestation of ductile deformation at microscopic contacting regions. The governing equations are well behaved at low slip rates, the seismogenic layer emerges as a consequence of the pressure-temperature dependence of ductile creep processes, and we offer an explanation for the temporal distribution of earthquake clustering.

The physical origins of the laws of friction that govern the genesis of earthquakes have long been the subject of discussion and debate. Here we demonstrate that the empirical framework of rate-and-state friction is a natural consequence of grain-scale processes, and that fault slip is the macroscopic manifestation of creep on contact asperities, modulated by grain-size processes, at the microscopic scale. We find that common rate-and-state parameters derived from laboratory data and geodetic observations are entirely commensurate with known flow laws: diffusion creep, dislocation-accommodated grain-boundary sliding, and dislocation creep. Additionally, we find that the temperature, grain size, and stress dependence of these flow laws naturally give rise to the full spectrum of fault behaviour from stable creep, through slow slip and tremor, to bilateral ruptures. In particular a seismogenic layer emerges spontaneously from the interplay of these creep mechanisms, for which the stability is primarily determined by the grain-size dependence of the active flow law. Our framework unifies the work of friction experiments for localised deformation and flow laws governing distributed deformation, whilst simultaneously addressing a number of shortcomings of the Dieterich-Ruina form of rate-and-state friction, such as the non-physical divergence as the sliding velocity tends to zero. We present very close equivalence between rate-and-state friction and established flow laws, and provide an explanation for the emergence of the seismogenic layer.