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Controls on Lithospheric Strength and Nature of Deformation Below the Seismogenic Zone: Results from Thermomechanical Rate-and-State Earthquake Sequence Simulations

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Simulations of earthquake sequences with rate-and-state fault friction are widely used to study interactions between deep aseismic creep and shallower coseismic slip, recurrence intervals, slip per event, and many other fundamental aspects of earthquake physics. However, such simulations almost always assume elastic off-fault material response. Here we generalize 2D antiplane shear simulations of continental strike-slip faults by accounting for power-law viscous flow (with temperature- and stress-dependent effective viscosity). Temperature evolves in response to shear heating from viscous flow and frictional sliding as well as heat conduction. We investigate how thermomechanical processes, such as a reduction in effective viscosity from heating, alter lithospheric strength, the depth of coseismic slip, and the nature of deformation at the base of the seismogenic zone. Figure 1 shows results from a representative simulation utilizing feldspar and olivine dislocation creep flow laws in the crust and mantle, respectively, and a transition from velocity-weakening (VW) to velocity-strengthening (VS) friction at 16.2 km depth. We present a parameter-space study varying the background geotherm (parameterized by lithosphere-asthenosphere boundary depth, below which a mantle adiabat is assumed), fault effective normal stress gradient (i.e., degree of fluid overpressure), and fault shear zone width. Viscosity reductions from the shear heating thermal anomaly (i.e., the temperature difference from the 1D background geotherm) are well explained by a steady state model that neglects cycle-related modulations in slip velocity and viscous strain rate. Contributions to the thermal anomaly from frictional heating and viscous flow are comparable in magnitude, though concentrated at slightly different depths. Transient pulses of frictional heat from coseismic slip locally elevate temperatures by hundreds of degrees, but typically these do not persist long enough for appreciable viscous strain to accumulate.

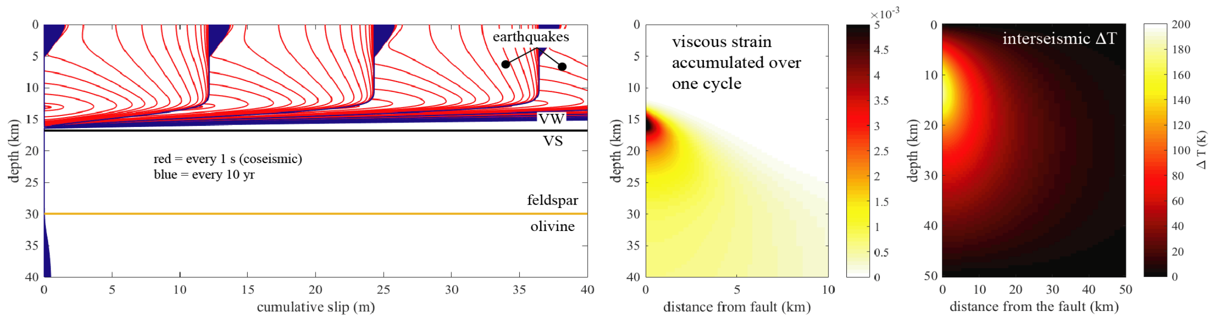

Figure 1. Thermomechanical earthquake cycle simulation. Coseismic slip (left) penetrates slightly below the frictional VW to VS transition; below this depth, most deformation is accommodated by viscous flow (center) due to elevated temperatures (right, showing thermal anomaly) from shear heating. A 1.2 km wide region at the base of the seismogenic zone experiences both coseismic slip and viscous flow.