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Earthquake cycles and shear zones: interplay between earthquakes, aseismic fault slip, and bulk viscous deformation

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The interaction between the seismogenic portion of faults and their ductile roots is central to understanding the mechanics of seismic cycles. It is well established that faults are highly localized within the cold and brittle upper crust, but less is known about fault and shear zone structure in the warmer, more ductile, lower crust and in the upper mantle. Increasing temperature with depth causes two transitions in behavior: a frictional transition from seismic to aseismic fault behavior and a transition from brittle to ductile off-fault deformation (BDT). To explore the effects of these two transitions on seismic cycle characteristics (e.g., recurrence interval, nucleation depth, and down-dip limit of coseismic rupture), we simulate seismic cycles on a 2D strike-slip fault. All phases of the earthquake cycle are simulated, allowing the model to spontaneously generate earthquakes and to capture aseismic fault slip and off-fault viscous flow in the interseismic period. The fault is represented with rate-and-state friction. In the off-fault material, distributed viscous flow occurs through dislocation creep. We also consider two possible weakening mechanisms that may be active in lower crustal shear zones: shear heating and grain size reduction, which changes the ductile rheology from dislocation to diffusion creep. This model makes it possible to self-consistently simulate the variations of stress, strain rate, and grain size in the vicinity of a strike-slip fault.

We find that the viscous shear zone beneath the fault (defined as the region of elevated viscous strain rate) is roughly elliptically shaped, extending up to 10 km below the fault and with a width of 1 to 3 km. When weakening mechanisms are neglected, the BDT occurs below the depth of the transition from seismic to aseismic fault slip. In these cases, seismic cycle characteristics are similar to those of a traditional elastic cycle simulation that neglects viscoelastic deformation. However, the inclusion of shear heating, which produces a thermal anomaly relative to the background geotherm, shallows the BDT enough to limit the down-dip propagation of coseismic slip in some cases. In these cases, earthquakes penetrate 1-2 km into the shear zone, consistent with observations of zones in which both viscous flow and coseismic slip occur. Also, in these simulations, very little aseismic fault slip occurs. Instead, tectonic plate motion is accommodated primarily through coseismic slip and bulk viscous flow. Preliminary simulations that include the effects of grain size reduction within the shear zone show similar effects. Both weakening mechanisms narrow the shear zone by up to 20%, suggesting that the fault also plays a large role

in controlling shear zone localization.