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The seismic cycle at subduction thrusts: benchmarking geodynamic numerical simulations and analogue models

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The physics governing the long-term seismic cycle in subduction zones remains poorly understood due to its spatial inaccessibility, complex tectonics and geometry, and the limited observation time. However, modeling approaches for large-scale subduction and small-scale dynamic rupture processes are well developed, and could help to overcome limited seismic observations for improved studies of the long-term seismic cycle at subduction thrusts. Such a continuum mechanic, geodynamic model includes a more realistic geometry and rheology with spontaneously developing faults, but also needs to transfer large spatial and temporal modeling scales such that short seismic events are resolved.

We deploy a continuum mechanic numerical method that involves a plane-strain finite-difference scheme with marker-in-cell technique to solve the conservation of momentum, mass, and energy for a visco-elasto-plastic rheology. The simulated laboratory setup constitutes a triangular, visco-elastic crustal wedge that is underlain by a restricted, velocity-weakening zone. Both are driven toward a backstop by a subducting, straight slab. We benchmark our geodynamic numerical approach to a novel gelatin lab experiment that shows a cyclic seismic pattern.

Our results demonstrate that the fluid-dynamic, viscous-elasto-plastic code simulates a series of regular rapid, short, elastic seismic events if velocity-weakening friction is incorporated. During the inter-seismic period the seismogenic zone subducts with the slab, thus focusing stresses near its down-dip end. Once material strength is exceeded, the seismogenic zone fails and ruptures predominantly in up-dip direction, thereby causing a short, rapid reversal of wedge displacements and acceleration of reversed velocities. After this stress release, healing (increase of friction coefficient) is essential to build up stresses for generating the next earthquake. Velocity strengthening in aseismogenic regions assists a) to limit the rupture up- and down-dip of the seismogenic zone, b) to move peak-velocity locations to just below the up-dip extent of the seismogenic zone, and c) to decrease the frequency of a rupture breaking up to the trench. Timing of events, spatial earthquake source parameters, and magnitudes are mainly affected by two material parameters: shear modulus (inversely related to the inter-seismic duration) and dynamic friction drop (affecting several source parameters through a differential stress drop). Within the range of material parameters constrained in the lab, we accomplish a first-order match between numerical and analogue models for the most important earthquake source properties. Therefore, we conclude that inertia and a non-steady-state state component in the friction formulation are not essential in the numerical study. After this promising benchmark we will apply our visco-elasto-plastic code with velocity-dependent friction to a more realistic subduction setup and regional subduction cases.