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Plastic deformation and seafloor uplift in geomechanically constrained dynamic rupture models of subduction zone earthquakes

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Numerical models that capture the complex interplay of the earthquake rupture, the emitted seismic waves, and the resulting displacement at the Earth's surface shed light on the complex processes governing the generation of tsunamis. Physics-based dynamic rupture models can account for complex fault geometry and meets constraints from a variety of data sets. However, parameterization of the complex rheologies and geometries of subduction zones such as on- and off-fault stress and strength, rock cohesion, and friction, is not trivial, yet greatly influences earthquake dynamics and tsunami interaction. For example, the vast majority of seafloor uplift during tsunami genesis occurs within the accretionary wedge, which consists of unconsolidated sediments. Capturing sedimentary constitutive response in order to account for this critical deformation, as well as the non-linear effects of such material on rupture dynamics requires realistically constrained dynamic earthquake models that account for off-fault plastic deformation.

We present an innovative coupling approach that constrains the complex initial conditions of elasto-plastic dynamic rupture models for earthquakes in subduction zones by a long-term seismo-thermo-mechanical model (STM, e.g. van Dinther et al., 2014, GRL). The STM model provides geometries for the slab, the accretionary wedge, and the spontaneously developing megathrust, which are all self-consistent with the stress field and rock strength. Such models evolve over millions to hundreds of years according to accretion and thrusting of ocean floor sediments, slab dehydration and fluid percolation, and cycles of megathrust and splay-fault slip episodes. We extract the STM model state prior the onset of slip and use it for the initial conditions in the earthquake model. Dynamic rupture at coseismic timescales coupled to seismic wave propagation is modelled with the software package SeisSol (www.seissol.org) using unstructured tetrahedral computational meshes optimally suited for the complex geometries of subduction zones. Our approach allows to investigate the importance of plasticity and dynamic wave-mediated stresses for tsunami genesis and wedge deformation and helps to evaluate the corresponding tsunami hazard.

The across-models ported initial state prior earthquake rupture indicates that the uppermost part of the accretionary wedge is close to plastic failure. Energy dissipation due to the occurrence of co-seismic, off-fault plastic deformation halts rupture propagation at the transition to a shallow velocity-strengthening region while the comparable, but purely elastic simulation ruptures through this region. The corresponding vertical coseismic seafloor uplift is considerably increased by the occurrence of plastic strain within the accretionary wedge and its effect on the fault dynamics.
The coupled, complex initial stress conditions and the heterogeneous material properties along the megathrust lead to pronounced rupture pulses that are smeared out when accounting for off-fault plasticity. The distribution of plastic strain after one dynamic rupture simulation resembles steeply dipping splay faults evolving over many seismic cycles within the wedge in STM models, suggesting high dynamic stress concentrations during co-seismic rupture.