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Seismo-thermo-mechanical modeling of subduction zone seismicity

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Recent megathrust earthquakes, e.g., the 2011 M9.0 Tohoku and the 2004 M9.2 Sumatra events, illustrated both their disastrous human and economic impact and our limited physical understanding of their spatial occurrence. To improve long-term seismic hazard assessment by overcoming the restricted direct observations in time and space, we developed a new numerical seismo-thermo-mechanical (STM) modeling approach.

This approach may help to shed light onto the interaction between long-term subduction dynamics and deformation and associated short-term seismicity. Additional advantages of this STM approach include the physically consistent emergence of rupture paths, both on- and off-megathrust, and the inclusion of three key ingredients for seismic cycling –rate-dependent friction, slow tectonic loading, and visco-elastic relaxation–. The validation of this approach was accomplished through a comparison with a laboratory seismic cycle model (van Dinther et al., JGR, 2013a). A more realistic geometry and physical setup of the Southern Chilean margin showed that results also agree with a range of seismological, geodetic, and geological observations, albeit at lower coseismic speeds (van Dinther et al., JGR, 2013b). This setup also suggests that a) $\sim$5% of cyclic deformation is being stored on the long-term, b) a self-consistent downdip transition zone between 350°C and 450°C arises from temperature-dependent viscosity, and c) megathrusts are weak (i.e. pore fluid pressures of $\sim$75% to 99% of that of solid pressures).

After introducing the main features of this innovative approach, this study focuses on analyzing the spontaneous unstable rupturing of off-megathrust events. Shallow off-megathrust subduction events are important in terms of hazard assessment and coseismic energy budget. The characteristics of simulated normal events within the outer-rise and splay and normal antithetic events within the wedge resemble seismic and seismological observations in terms of location, geometry, and timing. Their occurrence agrees reasonably well with both long-term analytical predictions based on dynamic Coulomb wedge theory and short-term quasi-static stress changes resulting from the typically triggering megathrust event. The impact of off-megathrust faulting on the megathrust cycle is distinct, as more shallower and slower megathrust events arise due to occasional off-megathrust triggering and increased updip locking. This also enhances tsunami hazards, which are amplified due to the steeply dipping fault planes of especially outer-rise events.