Modeling the hydromechanical effects of seamount subduction on megathrust stress and slip in southern Japan Trench

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The large trench-breaching rupture of the 2011 M=9 Tohoku-Oki earthquake was confined to the central segment of the Japan Trench subduction zone (off Miyagi). Numerous studies have shown that southward propagation of the rupture stopped offshore of Ibaraki upon reaching an area of seamount subduction. The observed rupture termination is consistent with the notion that extremely rugged subducting seafloor tends to stop large earthquakes but promote fault creep (Wang and Bilek, 2011; 2014). It is considered to be a consequence of stress and structural heterogeneity associated with the severe damage of the upper plate caused by the subducting seamount, which hinders shear localization along the plate interface.

Rapidly improved offshore geophysical observations over the past decade help constrain the creeping state of the megathrust in the southern seamount region in the Japan Trench. High-resolution seismic monitoring (including S-net) suggests that: (1) small earthquakes (up to M ~7) cluster at the downdip leading edge of a subducted seamount previously studied by Mochizuki et al. (2008); and (2) low-frequency tremors are localized at shallower depths (<10 km below seafloor) on top of the same seamount (Nishikawa et al., 2019). Seafloor GNSS measurements of postseismic deformation at an increasing number of sites show rapid trenchward motion (at 10s of cm yr^{-1}) in the seamount region, in contrast with the landward motion of the trench area in the main rupture zone (Tomita et al., 2017). These data are most consistent with shallow aseismic afterslip that likely extends to the trench in the southern seamount region, along-strike of the main rupture (Sun et al., 2018).

To quantitatively investigate key mechanical and hydrological processes underlying the observed megathrust slip behavior and its association with seamount subduction, we employ a two-dimensional Lagrangian-Eulerian finite element model to simulate coupled deformation and fluid flow. Our numerical approach describes the interplay between sediment consolidation, development of faults, and the evolution of stress and pore fluid pressure driven by ongoing plate convergence and the subduction of seamounts. Using laboratory and field observations as constraints, we define relations between key physical parameters (e.g., porosity, permeability, effective stress) associated with mechanical loading and fluid drainage during sediment subduction and accretion. To incorporate the role of fault damage zones as permeable pathways for fluid migration, we include a simple description of permeability enhancement along fault zones with increasing modeled shear strain. Our models show that, compared with the case of a smooth plate interface, seamount subduction leads to more severe damage of the upper plate with more densely developed off-megathrust splay faults. Our results also show that subducting seamounts can drive large spatial variations in tectonic loading, the degree of sediment consolidation, and the distributions of pore pressure and megathrust stress. Above the downdip leading flank of a subducting seamount, enhanced tectonic compression and drainage lead to amplified compressive stress normal to the megathrust (twice the magnitude for a smooth interface) and over-consolidated wall rocks (porosity lowered by 50% compared with a smooth-interface case). The enhanced stress and consolidation are accompanied by an opposite “stress shadow” behind the trailing flank (in the wake) of the subducting seamount, where reduced lateral compression leads to abnormally high sediment porosity and low stress normal to the megathrust. These variations help explain the observed patterns of megathrust slip distribution in southern Japan Trench and a number of other margins, with earthquakes and microseismicity favored by increased megathrust-normal stress and strengthened hanging wall at the downdip edge of the subducting seamount, and aseismic slow slip or afterslip in the stress shadow.

Keywords: seamount subduction, megathrust, shallow aseismic slip, fluid drainage, sediment consolidation, Lagrangian-Eulerian finite element model

