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The relationship between earthquake cycle processes and normal faulting earthquakes in subduction zones: A case study of the 2011 Tohoku earthquake

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After the 2011 Mw 9.0 Tohoku earthquake ruptured the subduction megathrust offshore Japan, many normal faulting earthquakes were observed in regions that previously hosted dominantly thrust faulting events. The rate of normal faulting seismicity has decreased since 2011, but is still significantly higher than before the Tohoku earthquake. Similar normal faulting earthquake sequences have been observed after other Mw 8.5+ megathrust events and in some cases appear to last for decades. In this study, we investigate whether the spatial distribution and temporal evolution of normal faulting seismicity in subduction zones can be explained by earthquake cycle deformation processes, particularly co-seismic and post-seismic stress changes. We develop a three-dimensional finite element model of the subduction zone offshore Honshu with an appropriate plate interface geometry and a rheology consisting of an elastic upper plate above a linear visco-elastic mantle wedge. We spin up the model using internally consistent earthquake cycles to generate pre-stresses; stresses build across the locked plate interface during the inter-seismic stage, driving co-seismic slip. Afterwards, the interface is re-locked as afterslip and bulk viscous relaxation occur, leading back into the subsequent inter-seismic stage. We incorporate the co-seismic slip from known megathrust earthquakes occurring before 2011 to better represent the slip deficit and state of stress at the time of the Tohoku earthquake.

The model results show that the immediate co-seismic effect of a great megathrust earthquake is to cause approximately trench-normal extension of the upper plate (relative to the pre-earthquake stress field). This extension occurs above and landward of the rupture zone in the regions that currently host significant normal faulting earthquakes. Early afterslip occurring on the subduction interface down-dip of the rupture results in further extension of both the upper and subducting plates, promoting normal faulting earthquakes in these regions. Although the upper plate continues to move trenchward as a consequence of the bulk viscous relaxation of the deeper visco-elastic regions, this does not have a significant effect on the stress field in the shallower, elastic regions. The dominant process responsible for reestablishing the pre-earthquake state of stress is the plate convergence after the re-locking of the subduction megathrust. We find good agreement between the predicted spatial and temporal pattern of tensile stresses and the post-seismic normal faulting earthquakes in Japan.