Seismicity in Japan
Normal faulting seismicity has been relatively uncommon in the subduction offshore Japan prior to 2011. However, the aftershock sequence of the 2011 Mw 9.0 Tohoku earthquake has had numerous normal faulting events. The majority of extensional moment release occurred between the east coast of Honshu and the outside of the subducting Pacific plate.

The Mw 9.0 Earthquake
Aftershocks occurred between the east coast of Honshu and the outside of the subducting Pacific plate. The stress changes resulting from the earthquake are likely to have occurred over several years.

What are the physical mechanisms operating during the earthquake cycle that drive these normal faulting aftershocks? How long will they continue?
We use a numerical modeling approach to address these questions, including the geometry of the Japan subduction zone and 3-D elasticity.

Model Setup
The modeling approach is similar to that of Govers et al. (2018). In this study, we use a slab with a more realistic geometry based on a transect through the Japan subduction zone at the location of the 2011 Tohoku earthquake. The slab geometry is from the USGS Slati model (Hayes et al., 2018). The subducting plate moves at 90 km/hr relative to the fixed backstop of the upper plate (Argus et al., 2011). The upper plate consists of an elastic layer on top of a linear visco-elastic layer (relaxation time = 8 years).

Normal faulting seismicity has decreased since 2011, but the rate of extensional earthquakes and moment release still remain elevated compared to the pre-Tohoku rates.

The late-interseismic stage (T = 40 years)
After reaching steady state, we use a 400-km-long region of the seismic zone to produce a Mw 9.0 earthquake. This produces a distribution of fault slip and surface motion compatible with observations of the 2011 Tohoku earthquake.

We simulate primary aftershock by relocking the seismic zone and unlocking the down-dip interface. Although our models simulate this stage as occurring instantaneously, it likely occurs over several years.

The co-seismic stress changes promote normal faulting above the rupture zone and between the downdip edge of the rupture and the coast. Stress changes are largest near the downdip tip of the rupture and have highly variable orientations in this region.

The primary aftershock further promotes normal faulting throughout the upper plate as it extends more. In this stage, the subducting plate also extends more.

Normal faulting aftershocks in the upper plate largely occurred in the regions predicted by our model (above the downdip edge of the slip region). Similarly, normal aftershocks occurred in favorably stressed parts of the subducting plate.

Long-term Stress Evolution
Despite the significant kinematic imprint of fault viscous relaxation of deeper, warmer regions, this process does not strongly affect the stress field in the shallower, cooler, elastic regions. The stress field in the elastic region remains favorable to normal faulting earthquakes until continued convergence recovers the initial elastic stress state.

Preliminary Conclusions
Normal faulting aftershocks following the 2011 Tohoku earthquake are consistent with the stress changes caused by shallow co-seismic fault slip and afterslip on the deeper plate interface. Although viscous relaxation rapidly reduces the stress level in deeper regions, the elastic parts remain in a state of relative extension.