Modeling the spatial and temporal evolution of normal faulting earthquakes in the upper plate of the Japan subduction zone after the 2011 Tohoku earthquake

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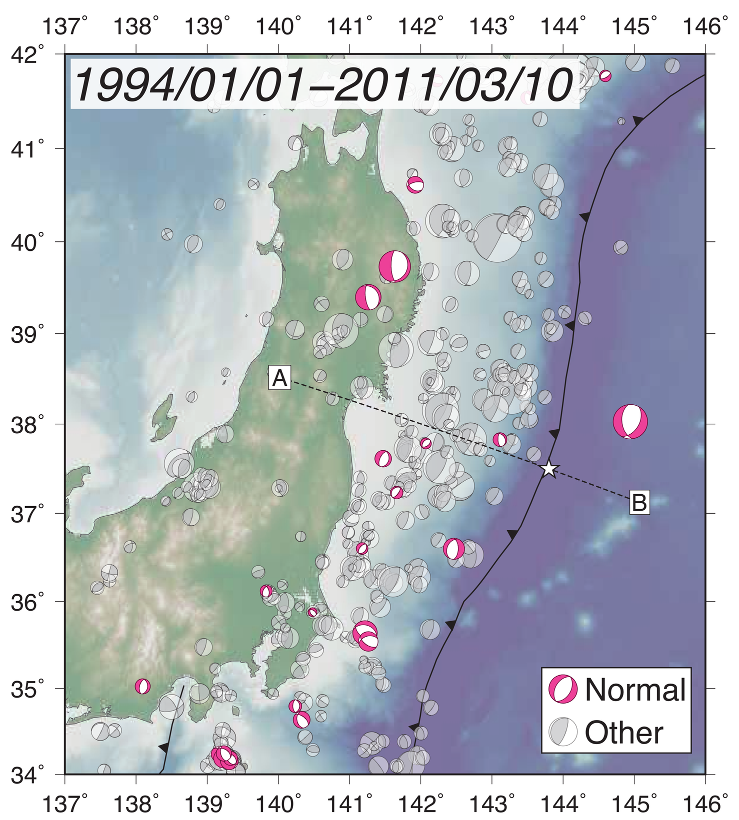
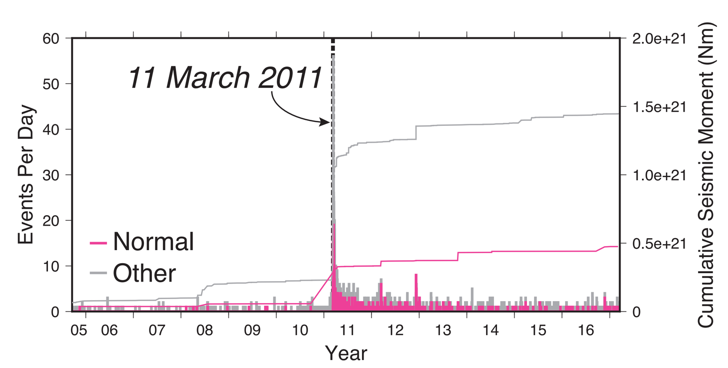
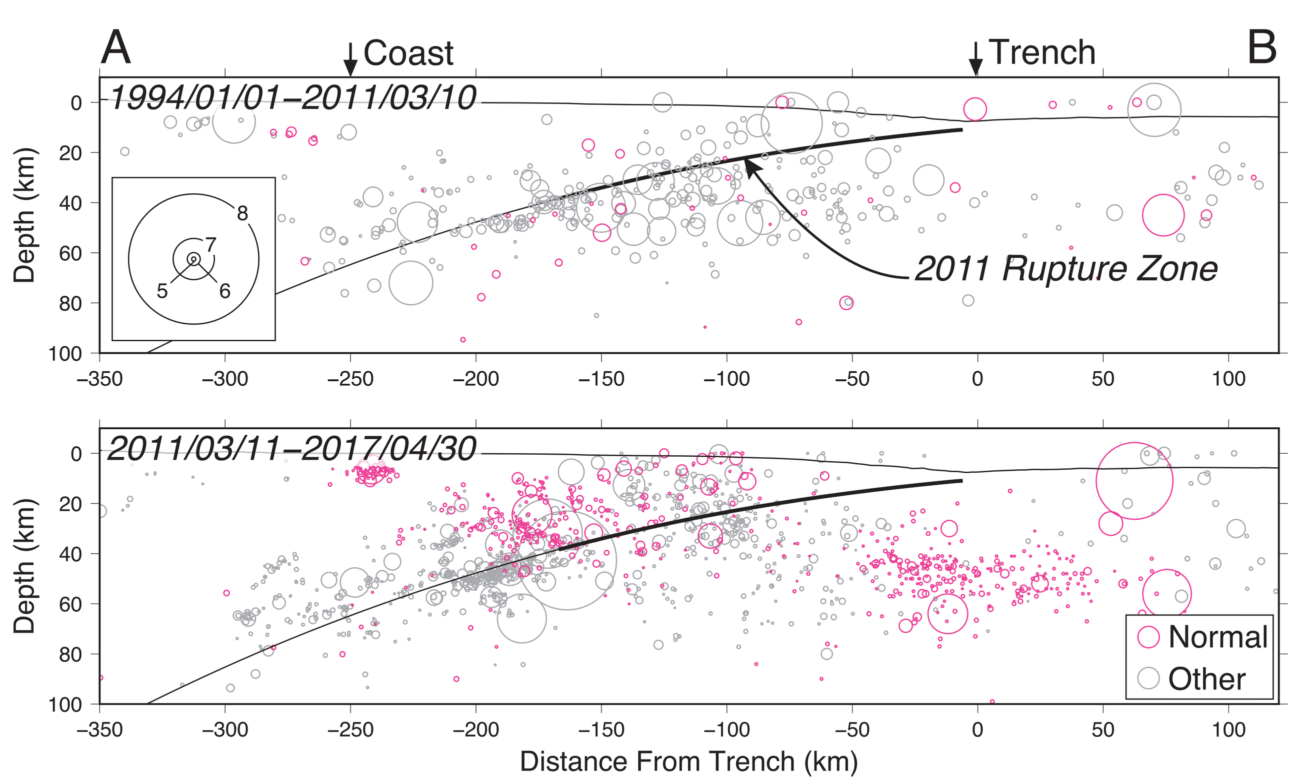
Seismicity in Japan

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



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.





Transects through the subduction zone show that normal faulting aftershocks dominantly occurred in two regions: (a) within the upper plate between the coast and the trench, and (b) within the subducting plate under and oceanward of the trench. There is limited overlap between regions of normal faulting and other styles of seismicity, except in the upper plate above the rupture zone.

The unusual occurrence of these extensional faulting events at a convergent plate boundary prompts the questions:

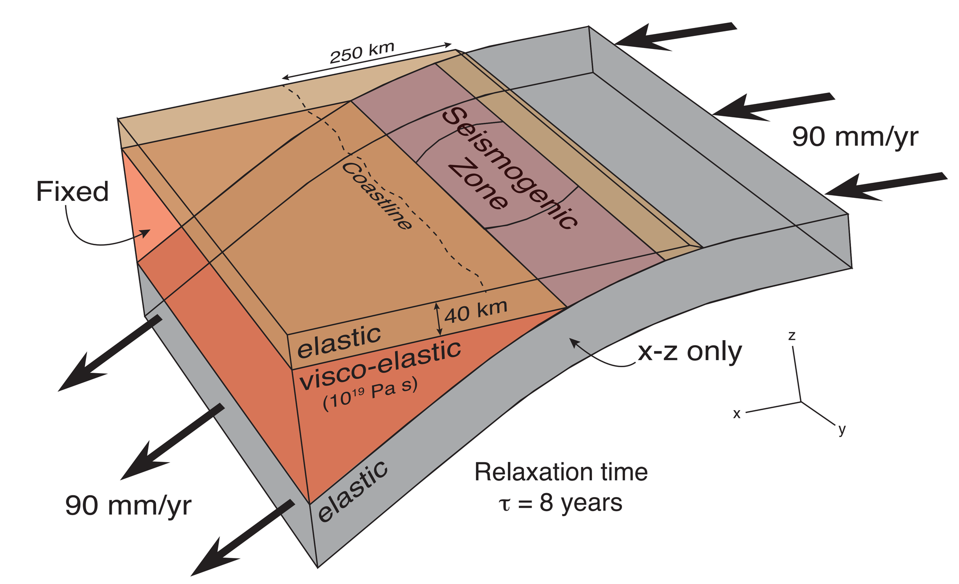
What are the physical mechanisms operating during the earthquake cycle that drive these normal faulting aftershocks?

How long will they continue?

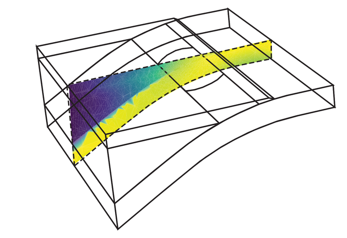
We use a numerical modeling approach to address these questions, including the geometry of the Japan subduction zone and 3-D deformation.

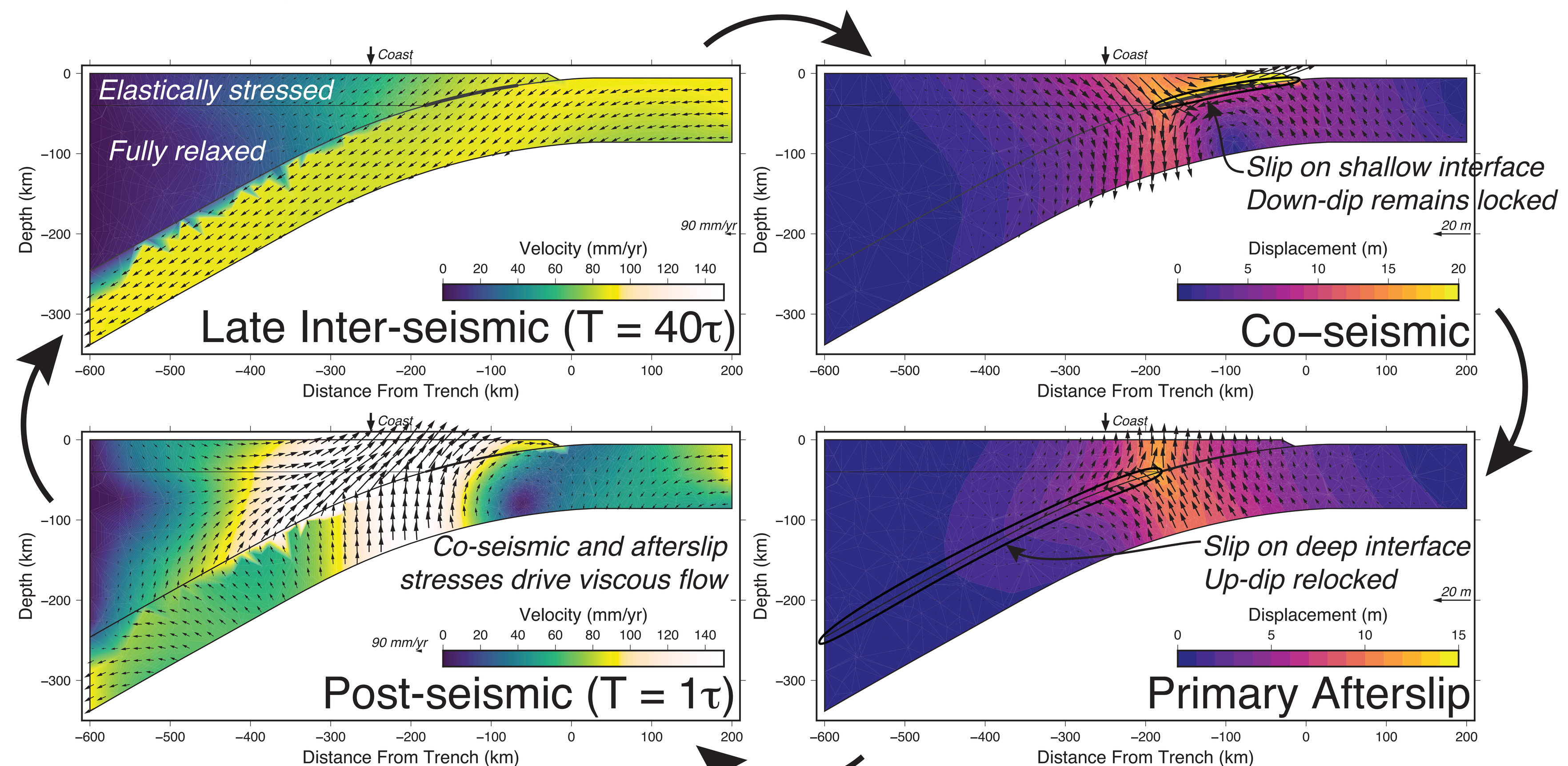
Model Setup

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 Slab2 model (Hayes et al., 2018). The subducting plate moves at 90 mm/yr 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).

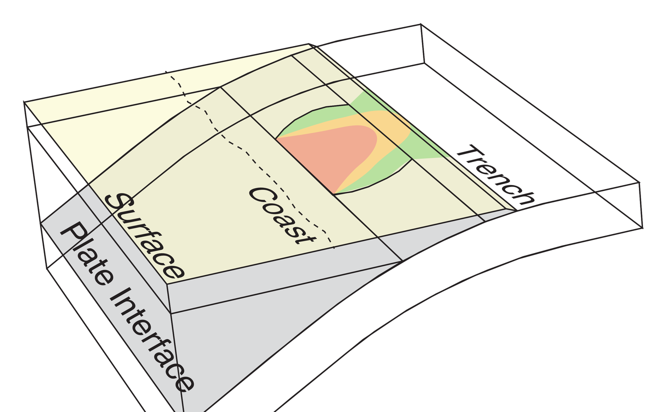


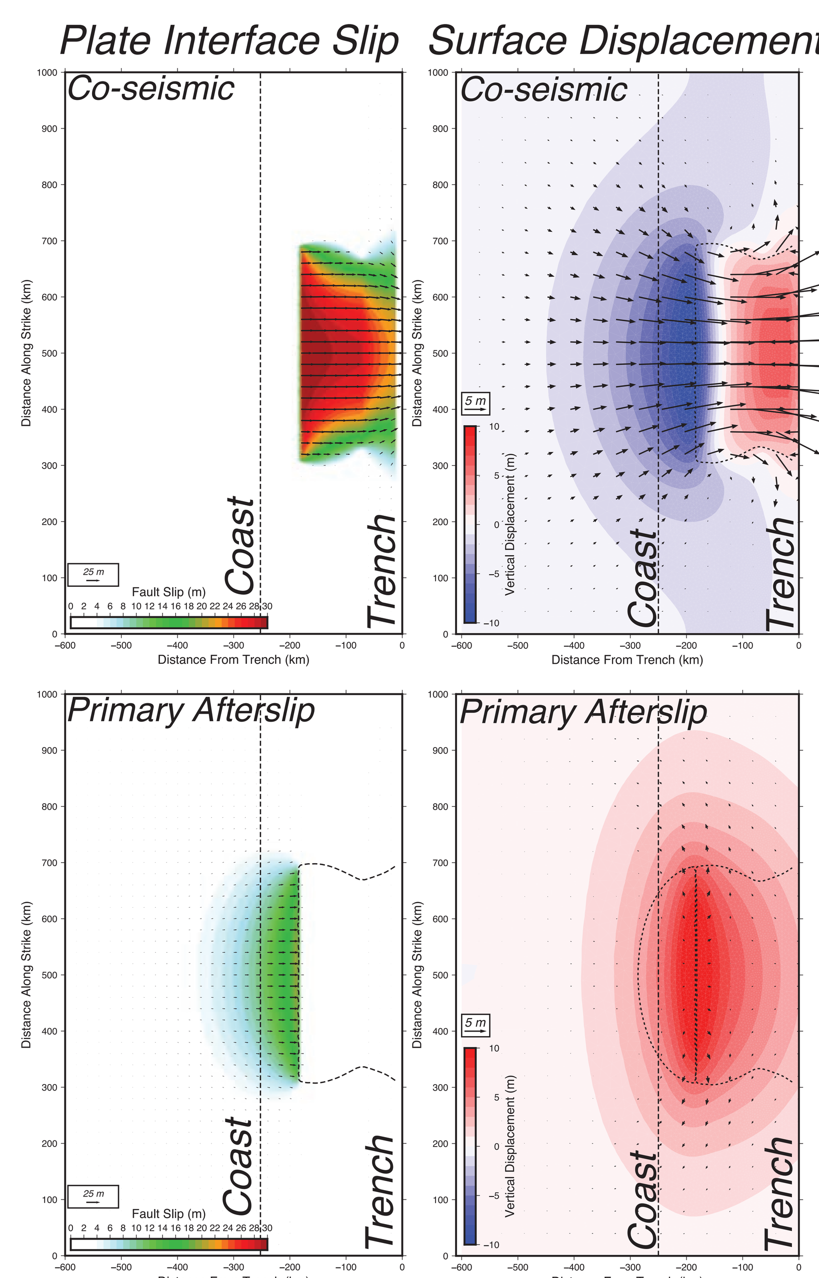
First, the model is consistently driven into steady state over 20 earthquake cycles. Each cycle involves locking/unlocking the entire along-strike extent of the seismogenic zone. After this spinup process, four distinct stages of the earthquake cycle repeat (Govers et al. 2018):

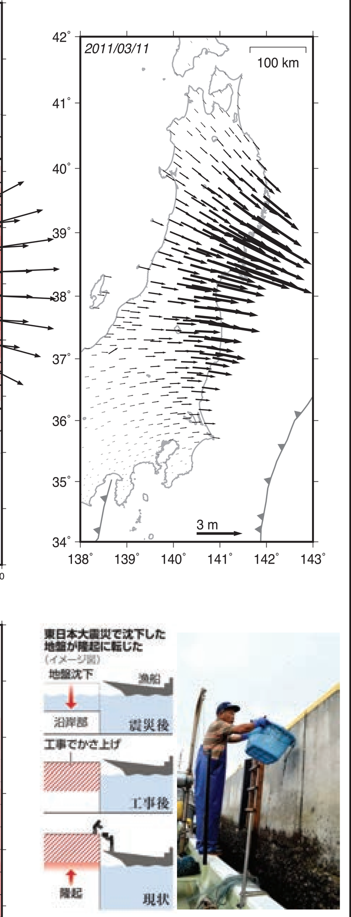




The Mw 9 Earthquake







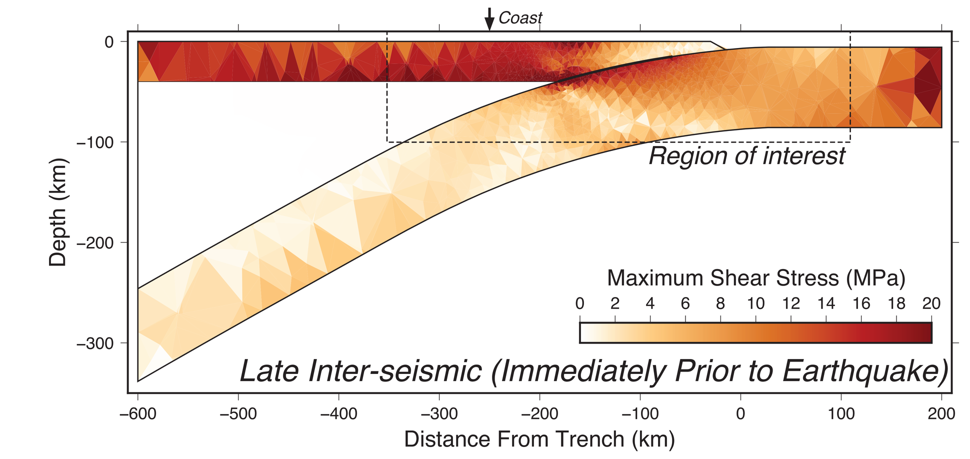
After reaching steady state, we unlock a 400-km long region of the seismogenic zone to produce a Mw 9.0 earthquake. This produces a distribution of fault slip and surface motion compatible with observations of the 2011 Tohoku earthquake.

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

For more on surface expressions of the earthquake cycle, see T51C-07 on Friday morning:

Linking Paleogeodesy Observations with Geodynamic Models of Megathrust Earthquakes (Furlong, Herman, Govers)

Co-seismic and Early Afterslip Stress Changes

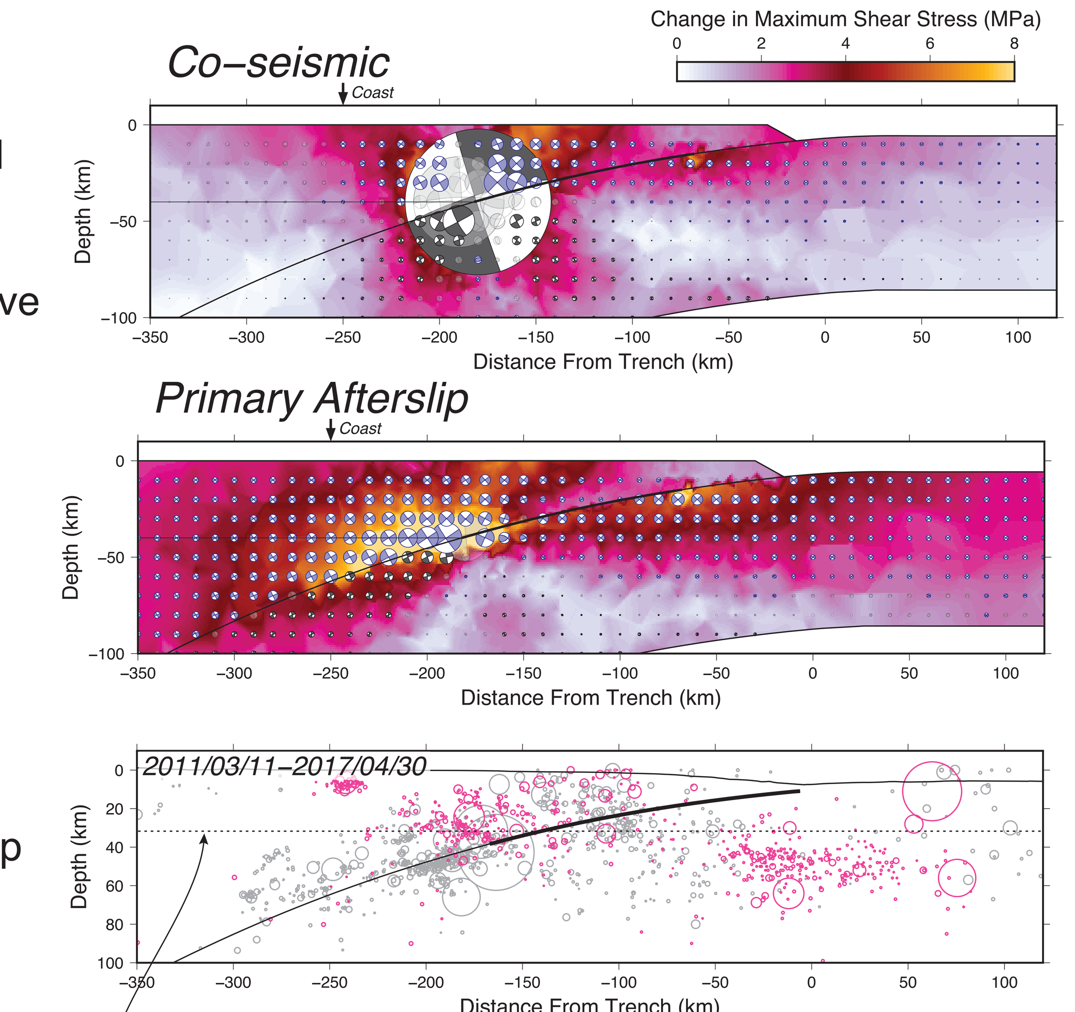


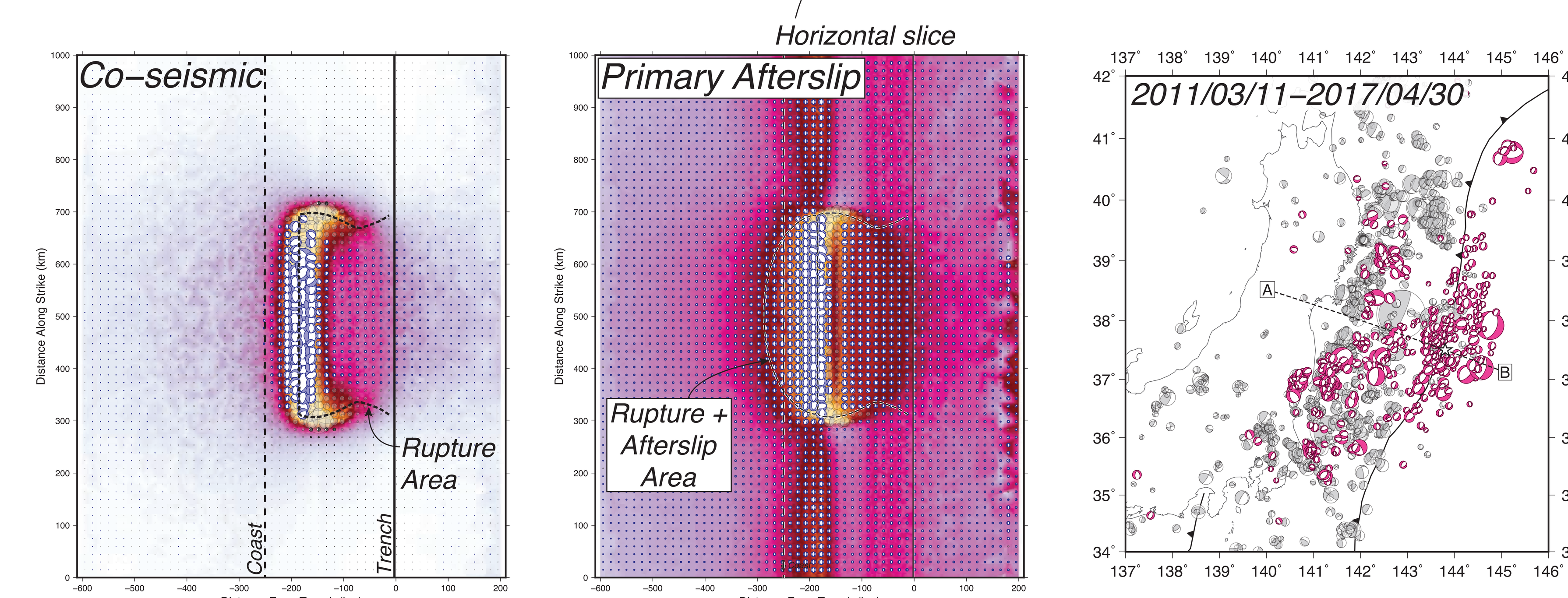
We use the steady state distribution of stress from immediately before the simulated earthquake as a reference state. The elastic region of the upper has accumulated significant stresses, whereas the visco-elastic region has deformed by flowing to reduce stresses caused by the previous earthquake. Stresses have also built in the elastic subducting slab.

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

The primary afterslip 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 down-dip edge of the slip region). Similarly, normal aftershocks occurred in favorably stressed parts of the subducting plate.





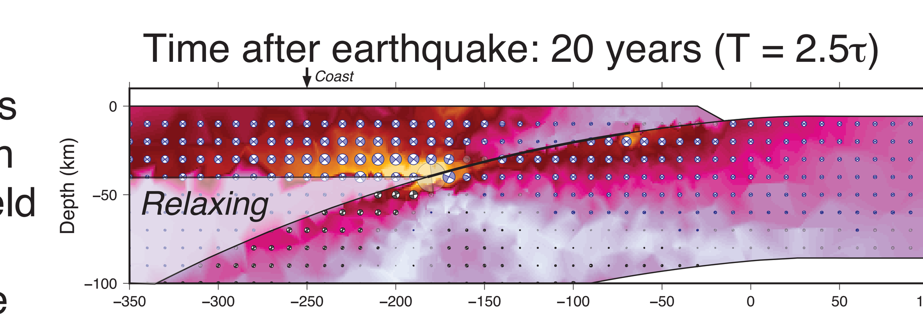
Co-seismic stress changes favor normal faulting above the downdip edge of the rupture between the coast and the trench.

Afterslip extends the large stresses promoting normal faulting earthquakes into the subducting plate and along strike.

The normal faulting aftershocks that occurred offshore Honshu generally lie in the same regions predicted by our model.

Long-term Stress Evolution

Despite the significant kinematic imprint of bulk viscous relaxation of deeper, warmer regions, this process does not strongly affect the stress field in the shallow, 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.