Causes of extensional deformation in subduction zones following megathrust earthquakes

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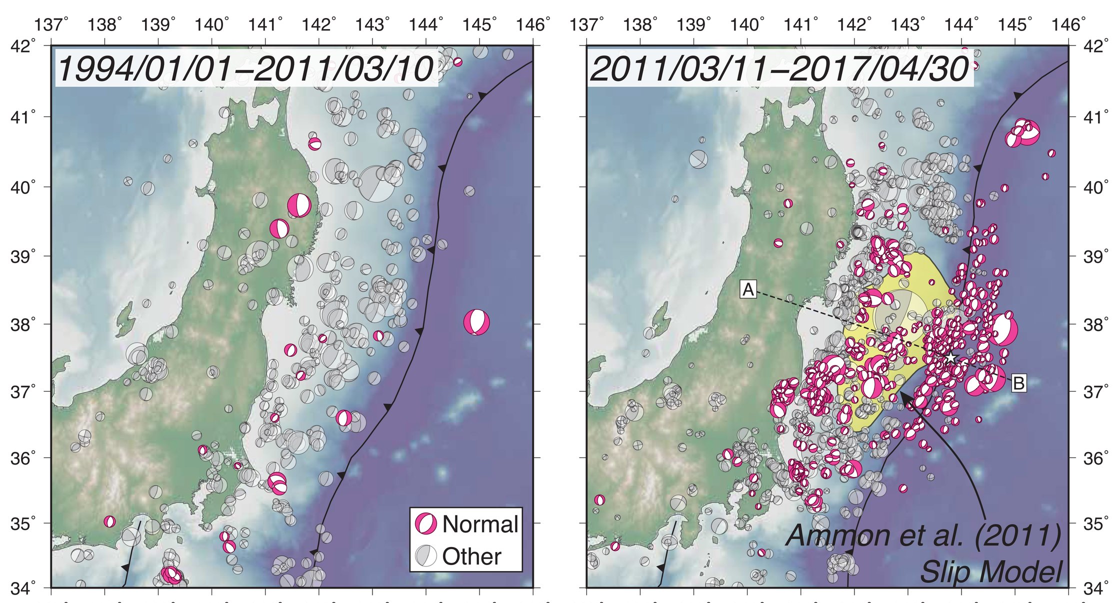
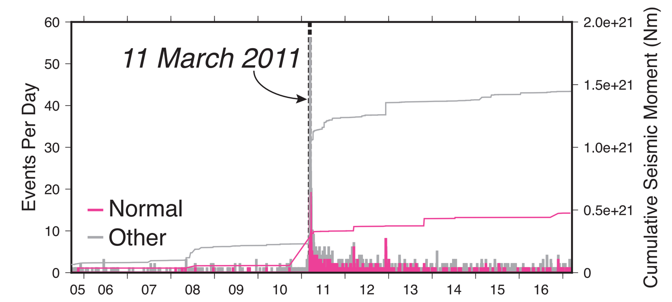
Extension and the Earthquake Cycle in Subduction Zones

Normal faulting seismicity in subduction zones can increase abruptly after a large earthquake on the megathrust. For example, the aftershock sequence of the 2011 Mw 9.0 Tohoku, Japan, earthquake included hundreds of normal faulting events, despite rare extensional seismicity before 2011.

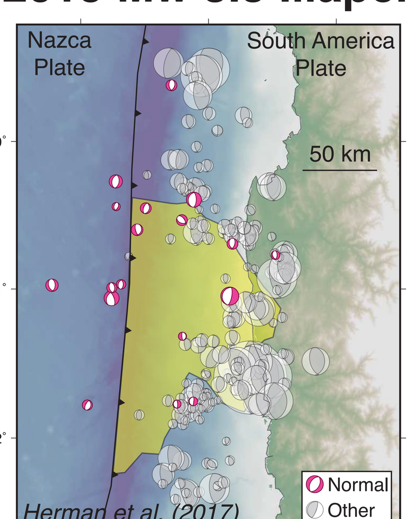




The rate of normal faulting seismicity has decreased since 2011, but remains elevated compared to pre-mainshock rates.

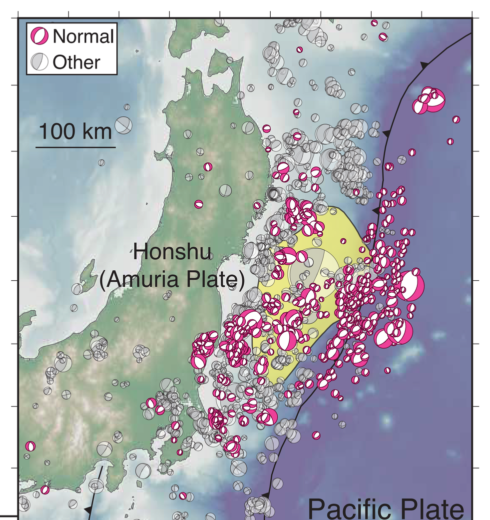
Increased normal faulting activity has also been seen after other large megathrust earthquakes. The aftershock sequences of 13 recent Mw 8.0+ megathrust earthquakes highlight how the locations of normal faulting aftershocks (i.e., in the slab or in the upper plate) depend systematically on the mainshock centroid depth and magnitude.

2015 Mw 8.3 Illapel

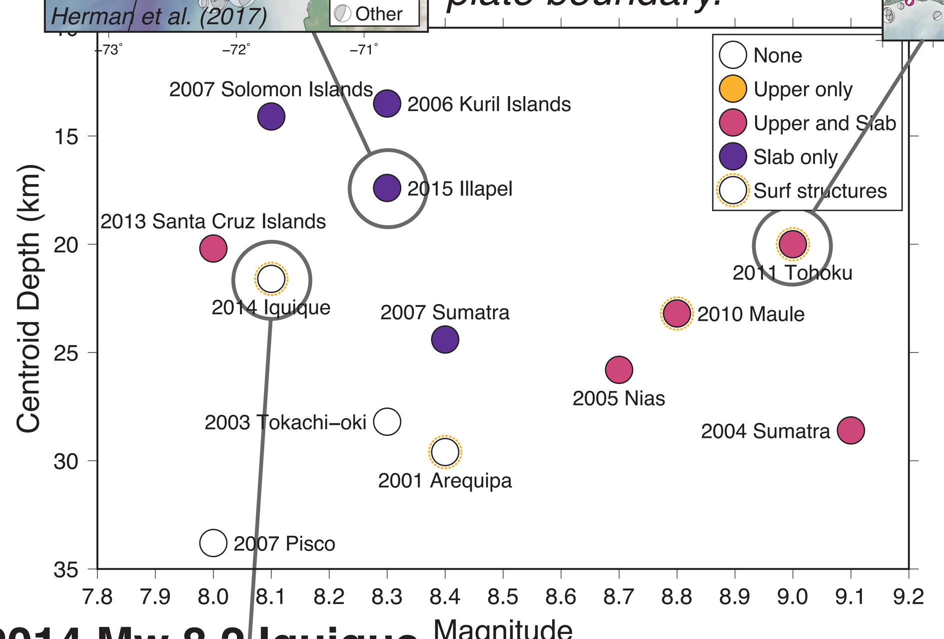


Events that rupture close to the trench trigger many outer rise and intraslab extensional aftershocks. Small normal faulting aftershocks may also occur above the plate boundary.

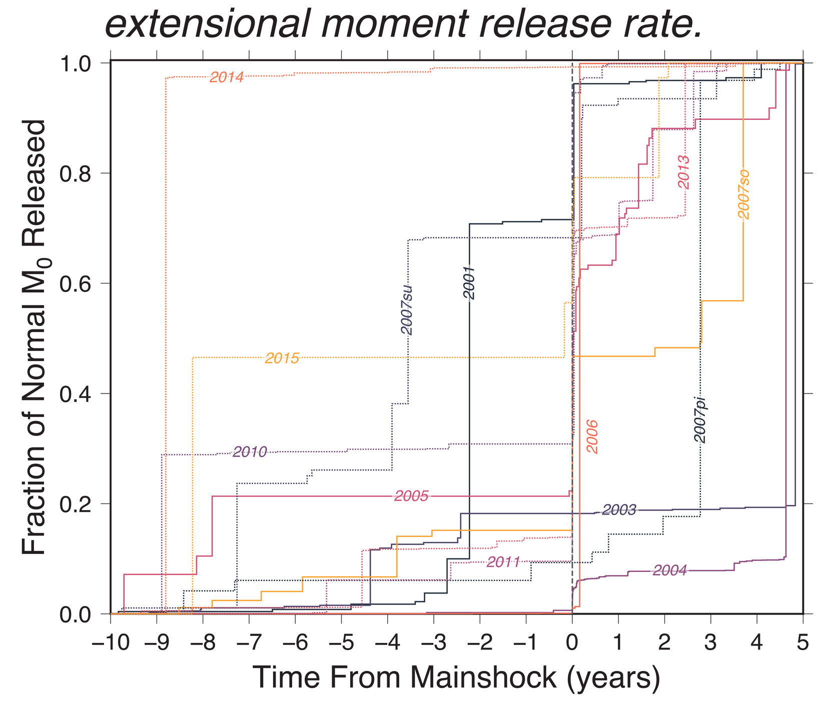
2011 Mw 9.0 Tohoku



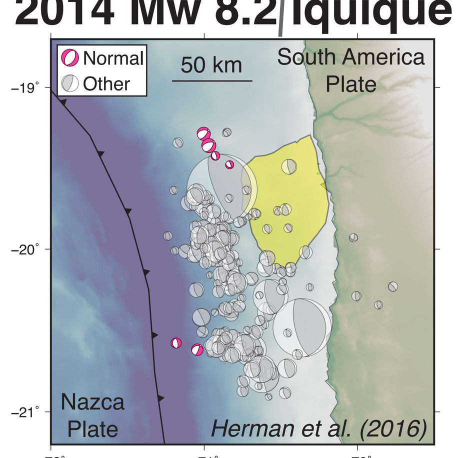
When an earthquake ruptures the full seismogenic width, vigorous intraslab and upper plate normal faulting aftershock activity occurs along the length of the rupture zone.



Normal faulting moment release over time (relative to the mainshock) spikes at the time of 9 mainshocks. This can be followed by years of increased extensional moment release rate.



2014 Mw 8.2 Iquique



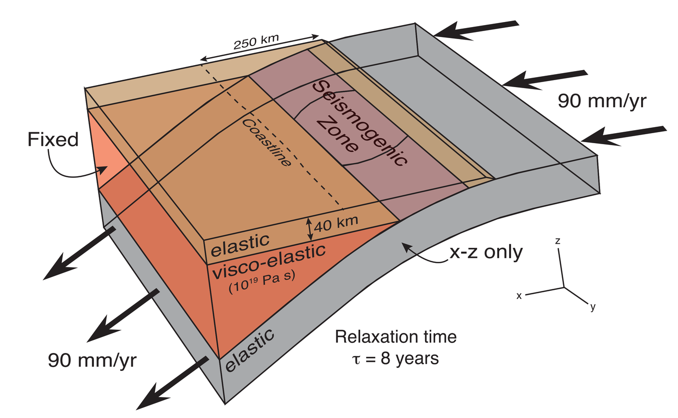
Deeper events trigger little extensional seismicity in either plate. Small normal faulting aftershocks may occur near the plate interface and tension cracking can occur at the surface.

This systematic, global behavior of extension associated with megathrust earthquakes suggests a common geodynamic process, so in this study we investigate:

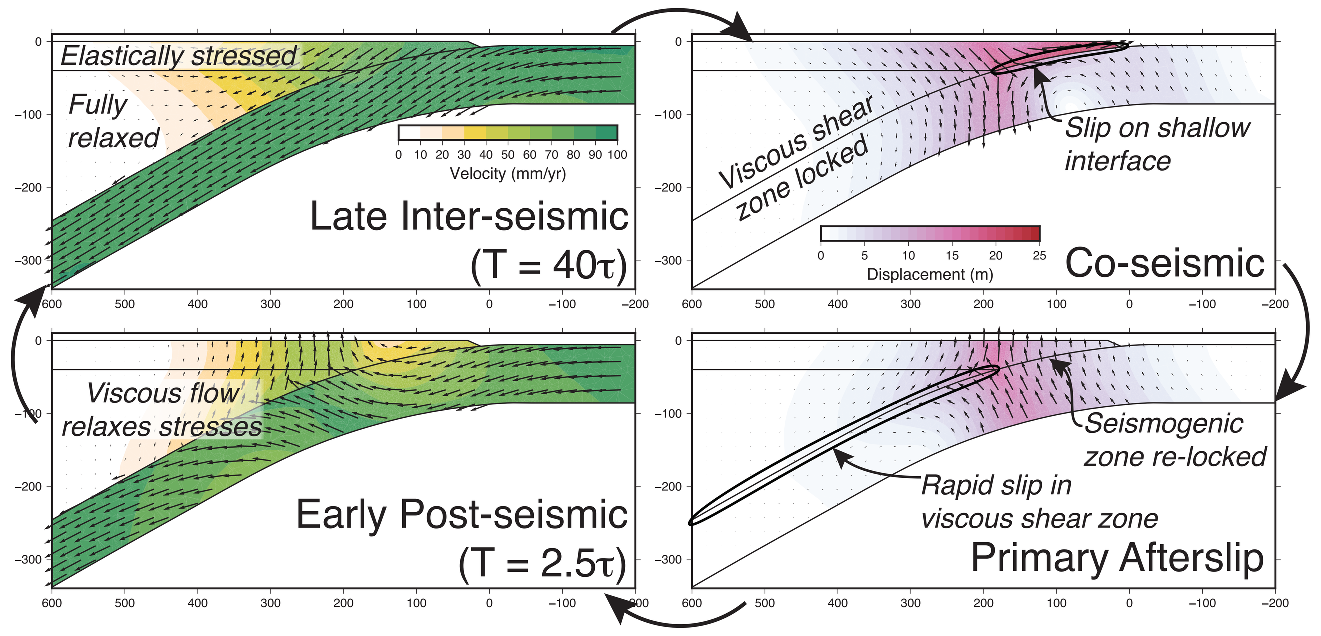
What aspects of the megathrust earthquake cycle facilitate the occurrence of normal faulting aftershocks?

Model Setup

The modeling approach is based on that of Govers et al. (2018). We have a curved slab based on a transect through the Japan subduction zone (from Slab2; 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 mantle wedge (relaxation time = 8 years).

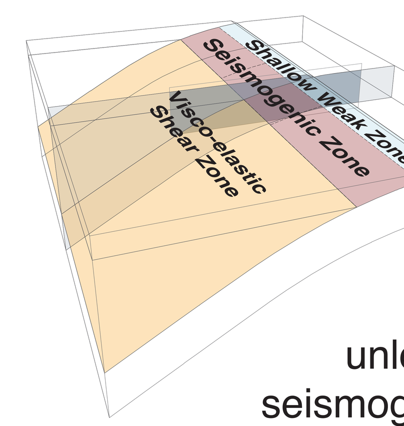


The model is driven into steady state over 10+ earthquake cycles. After this spin-up period, then each cycle is identical to the previous. Previously, we focused on the geodetic imprint of the earthquake cycle and its implications for the first-order earthquake cycle deformation processes in the subduction system. Four main stages can be recognized:

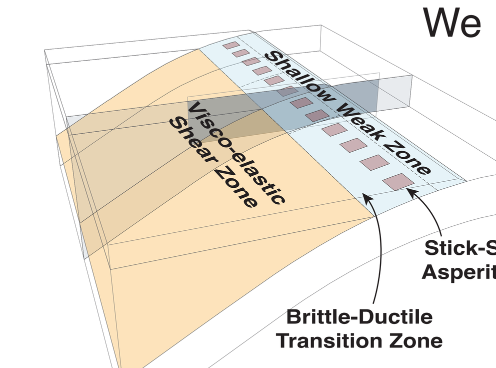


Earthquake Cycle Stresses

In this study, we focus on the stresses throughout the model, which are inferred to promote or inhibit intraplate fault slip. Specifically, we investigate how the plate interface slip configuration affects these stresses. The kinematic evolution of these models is similar.

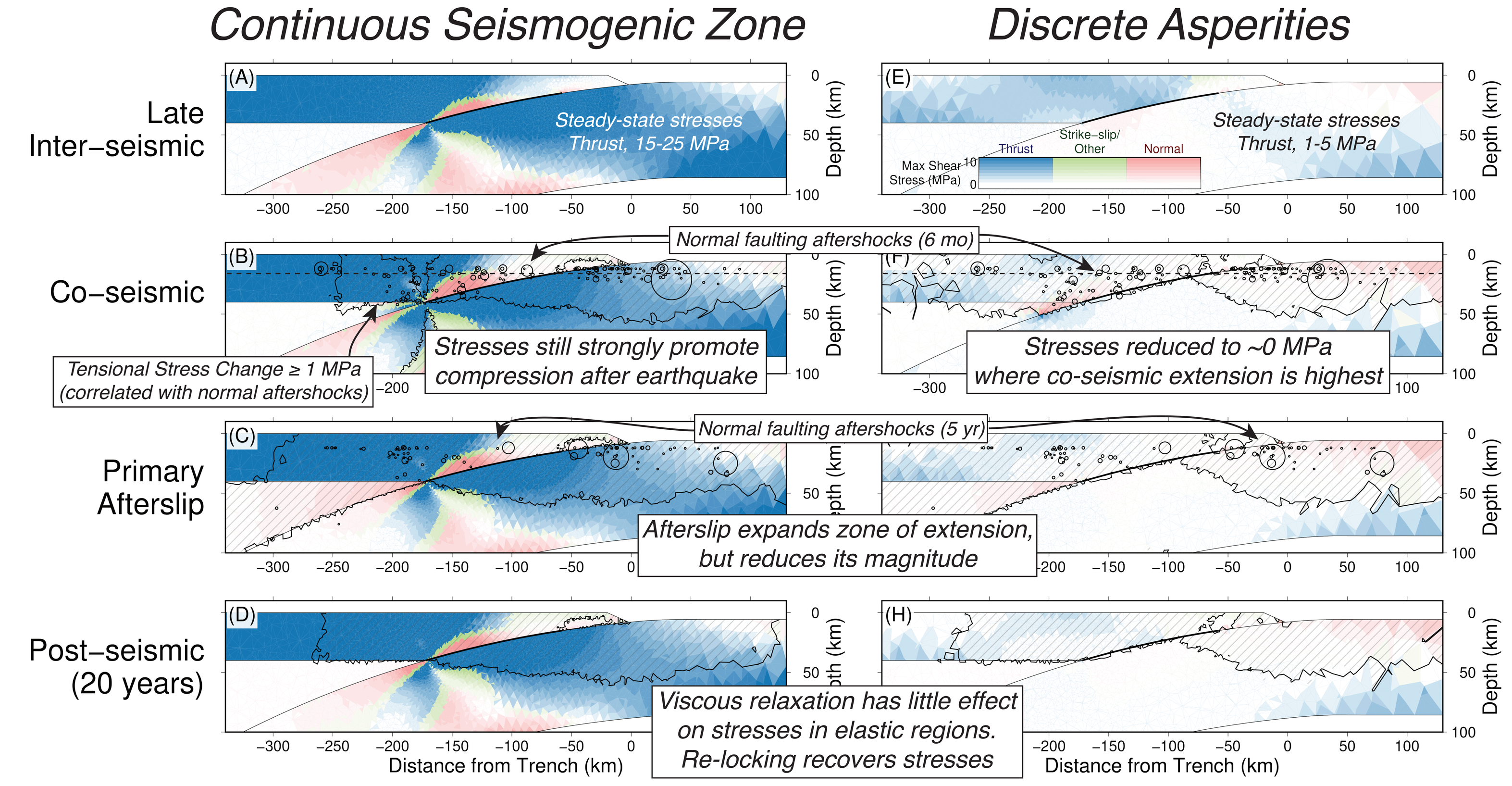


We first run a laterally uniform (i.e., plane strain) model in which the entire ***seismogenic zone*** is locked during inter-seismic loading and unlocked during the co-seismic stage. Down-dip of the seismogenic zone is a ***visco-elastic shear zone*** that is locked (elastic) during the earthquake and otherwise unlocked. The shallow interface up-dip of the seismogenic zone is weak, and always unlocked.



We test the effect of having a plate interface with discrete ***stick-slip asperities*** embedded in a region that is always unlocked. We also keep the ***brittle-ductile transition*** down-dip of the asperities unlocked. The asperities are 40 km to a side (Mw ~7.0-7.5 earthquake), separated by 40 km. This is compatible with the dimensions and distributions inferred from coupling inversions.

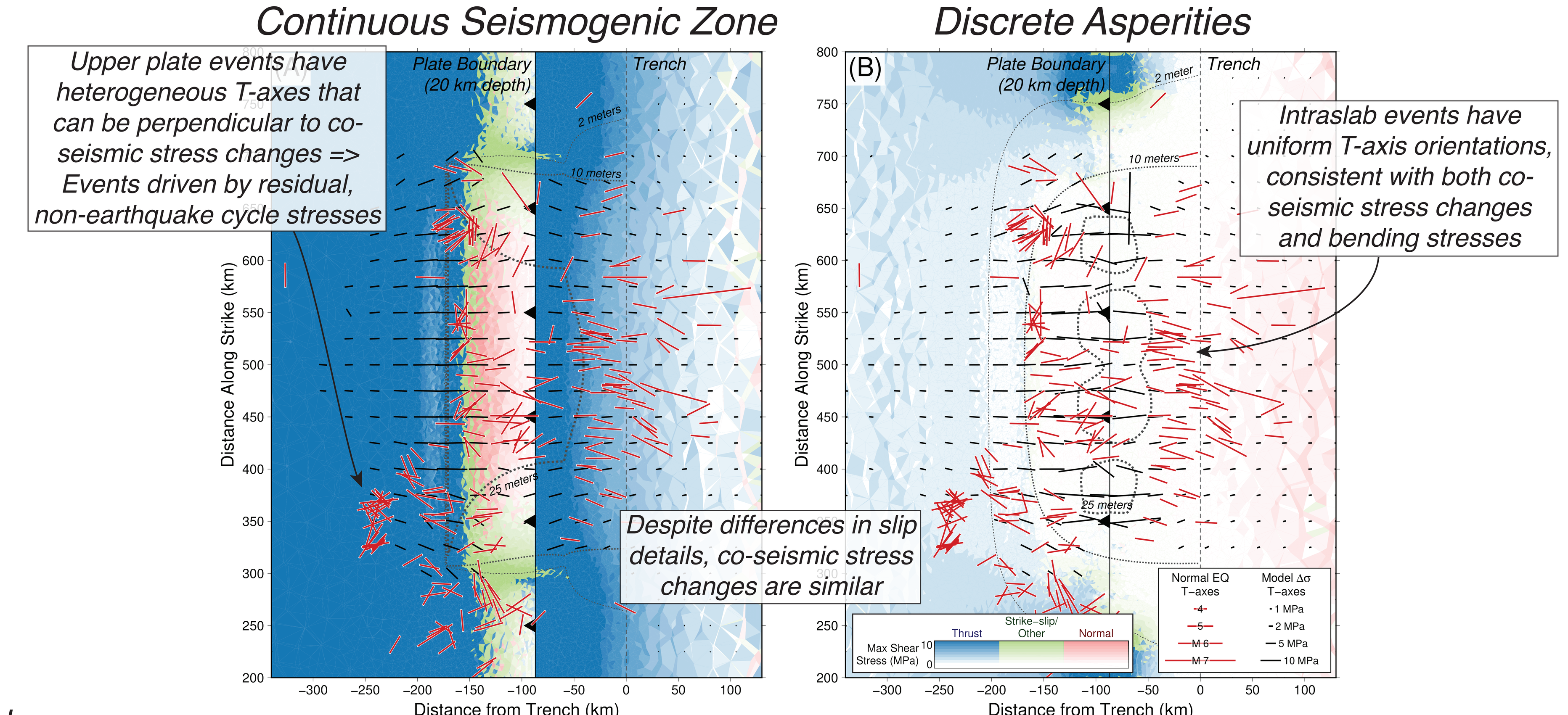
Stress Evolution Over Time



When the seismogenic zone is continuous and there is a sharp brittle-ductile transition, the steady- state stresses are 10-25 MPa and compressive. Despite tensional co- seismic stress changes up to 5 MPa, the steady-state earthquake cycle stresses always favor thrust faulting.

In the discrete asperity model, the steady-state stresses are < 5 MPa. The co-seismic stress changes reduce the stress levels to zero (or even promote extension) in the regions of maximum extension. The normal faulting aftershocks occur in these low-stress zones.

Co-seismic Stresses in Map View

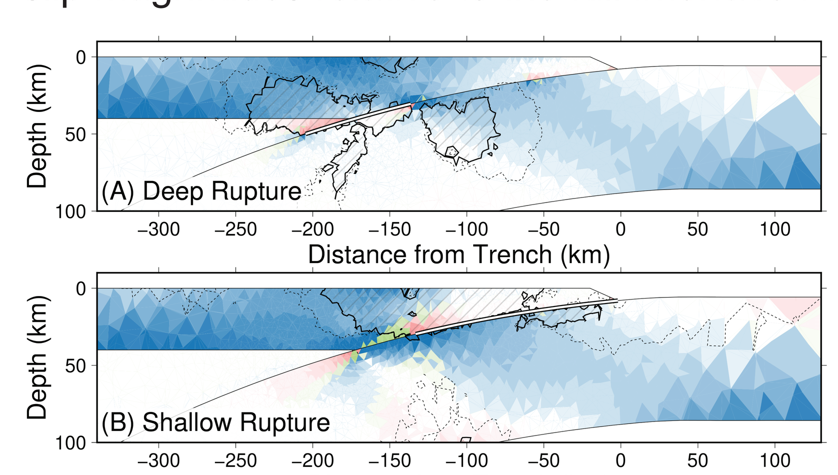


Extensional aftershocks occur in regions of tensional stress change > 1 MPa. However, in the continuous seismogenic zone model, the steady-state stresses always favor thrust faulting > 5 MPa, except near the rupture.

The distribution of co-seismic stress changes is similar in the discrete asperity model. The main difference is in the steady-state stresses; now the normal faulting aftershocks occur mostly in low (< 1 MPa) steady-state stress areas.

Deep vs. Shallow Megathrust Ruptures

To investigate the observed relationships between normal faulting aftershock locations and the depth of incomplete ruptures (i.e., events that do not rupture the whole seismogenic width), we run two additional co-seismic models: one in which only the deep interface slips and another in which only the shallow interface slips. Both earthquakes have reduced slip magnitudes relative to the full interface rupture.



*The **deep rupture** generates lobes of tensional stress change, but these do not extend far into either the upper plate or the slab. The stresses still favor mainly thrust faulting, except very near the plate interface.*

*The **shallow rupture** causes tensional stress changes >1 MPa throughout the upper plate above the rupture, and >0.5 MPa into the outer rise.*

Conclusions

- "Patchy" stick-slip asperities produce lower magnitude (< 5 MPa) inter-seismic compressive stresses
- In discrete asperity model, co-seismic stress changes reduce inter-seismic stresses to ~0 MPa
- Normal faulting kinematics controlled by residual (non-earthquake) stress field
- Stress changes of incomplete (Mw < ~8.5) define extensional earthquake locations