Did Extensional Failure of "Pre-Stressed" Lithosphere Above a Subduction Zone Contribute to the Size of the Tohoku-Oki Earthquake and Tsunami?

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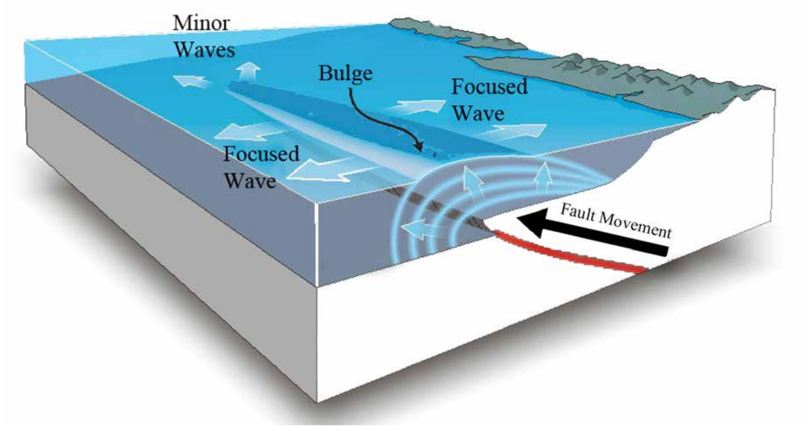


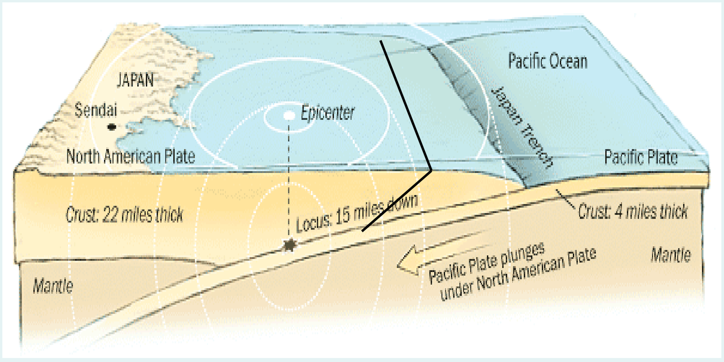
The Problem

Extensional fault offset during the Tohoku-oki Earthquake added to the size of the reulting tsunami.
Aftershocks over a 250 km wide region of the upper plate are primarily extensional.
Existing models do not explain such aftershocks unless normal faults have essentially no strength.

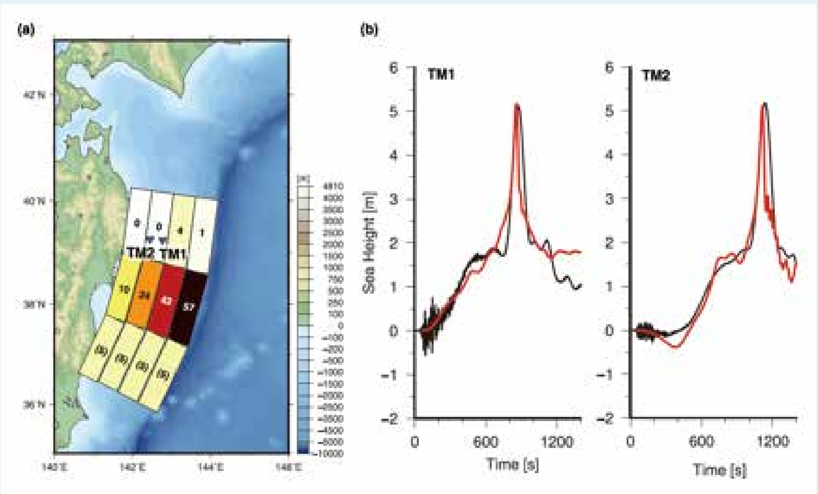
Abstract

The Tohoku-oki earthquake was not only the costliest natural disaster in history it was the best monitored. A major surprise was that this subduction earthquake produced up to 80 meters of lateral motion of the sloping seafloor near the trench and this significantly increased the size of the resulting tsunami. This was also the first time extensional aftershocks were seen in the upper plate above a subduction zone earthquake and for Tohoku they occurred over a 250 km-wide region. Inspired by the Tohoku data, researchers re-analyzed data and found upper plate extensional aftershocks associated with several other subduction earthquakes that produced large tsunami. Whether upper plate extension causes near-trench motion and large tsunami is controversial, but the extensional aftershocks are not easily explained in terms of standard models of subduction earthquakes. Most such models assume that the dip of the subducting plate (or slab) is constant in time. Here a set of idealized numerical models show that a reduction in the dip of a slab can cause upper plate extensional faulting even if the subduction interface has no long-term strength. Extensional faulting will not occur during an 'inter-seismic' period when the interface is strong and so 'locked', even as the plate bends more. The relief of compressional stresses during dynamic weakening of the interface triggers a release of bending-related extensional strain energy, adding significantly to the co-seismic radiated seismic energy and seafloor deformation. This mechanism is analogous to the breaking of a pre-stressed concrete beam supporting a bending moment when the compressional pre-stress is removed. The changes in slab dip required for this model are consistent with the observed westward migration of the volcanic arc across Honshu in the last several million years.

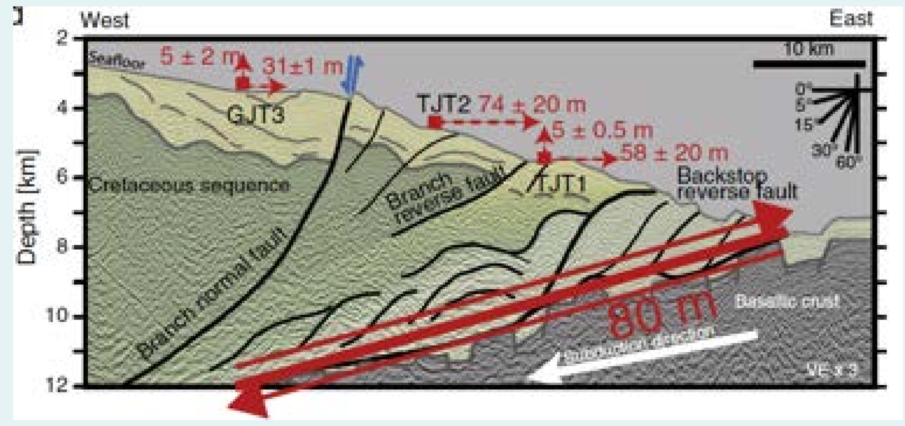
Surprising New Observations



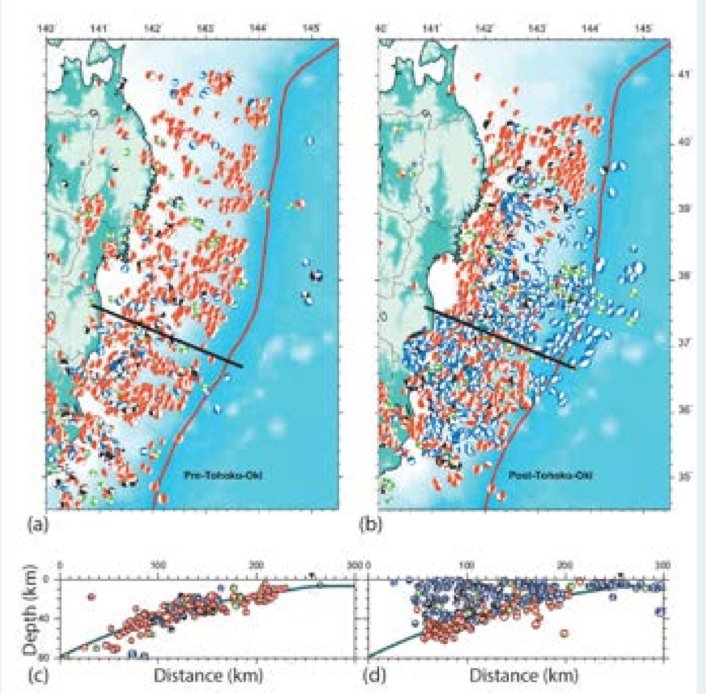
Seafloor motion during the Tohoku-oki earthquake was greatest seaward of a large normal fault.



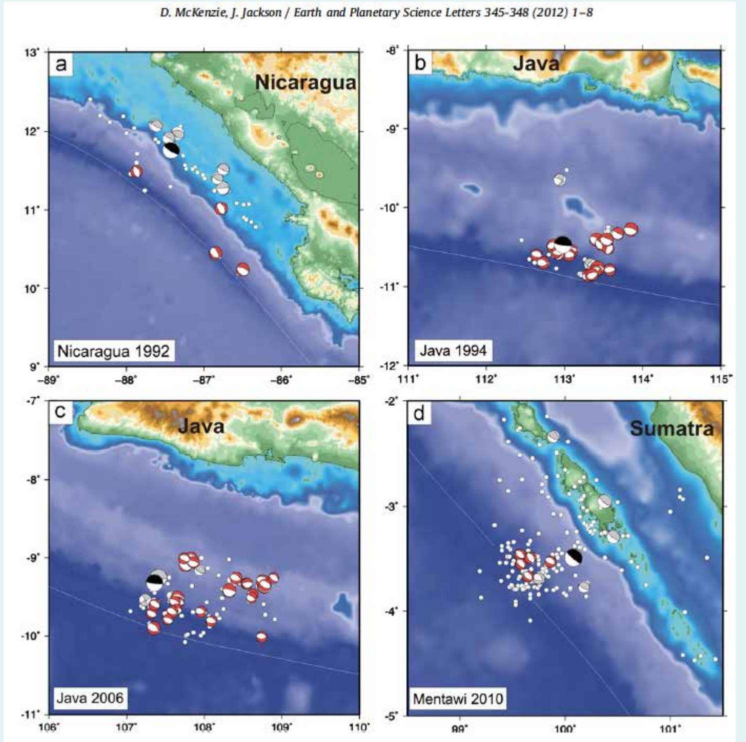
Estimated slip on the subduction interface in meters based on Tsunami sea surface height measuermemts from seafloor instrument records shown in (b) from Maeda et al. (2011).



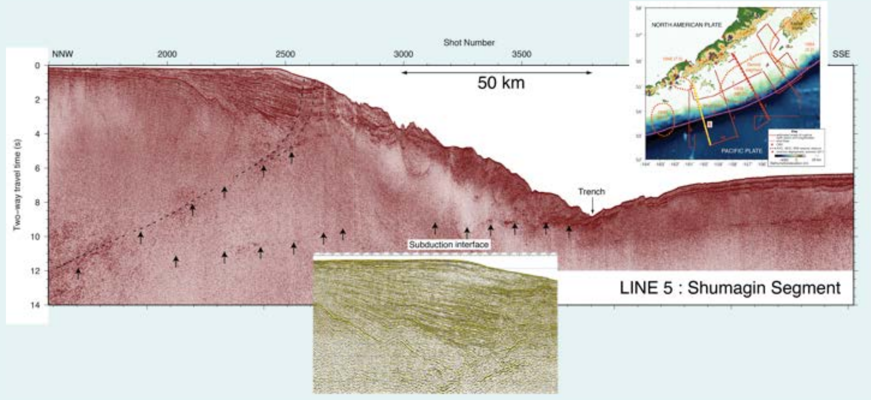
Direct observations of deformation for the frontal wedge near the 2011 Tohoku-Oki earthquake source from Tajima et al. (2013) who overlayed deformation estimates on a seismic cross section of the Northern Japan Trench taken from Tsuji et al. (2011).



Aftershocks abovethe megathrust were extensional over a 250 wide region. From Hasegawa et al (2012).

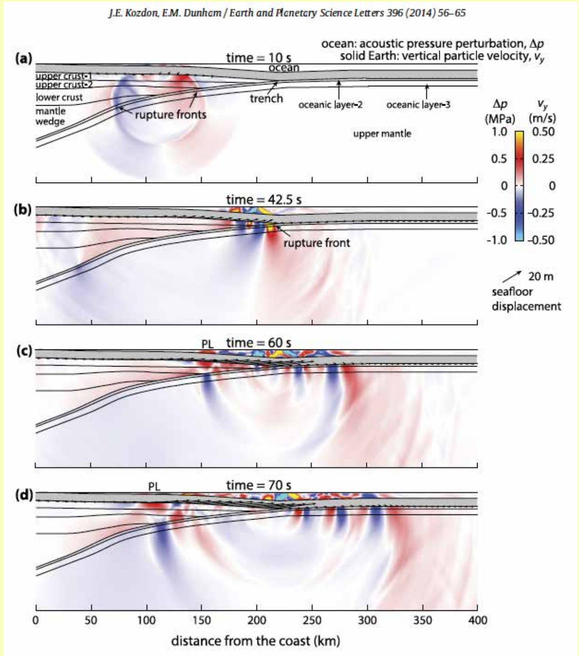


Map showing upper plate normal faulting afterschocks for 4 subduction earthquakes that produced large Tsunami. Relocation of events done after the Tohoku-oki event by McKenzie and Jackson. (2012).

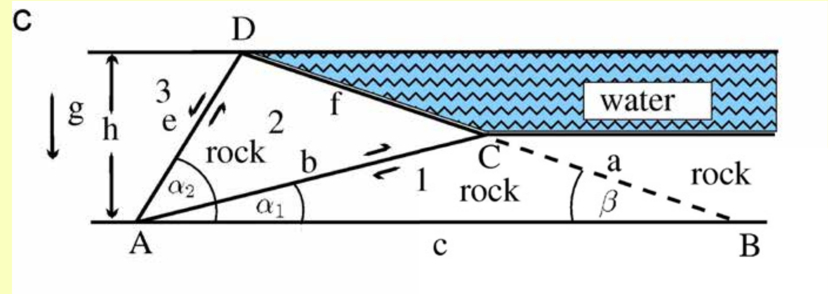


Large normal faults on the backside of accretionary prisms are seen for several subduction zones including the Shumagan Gap section of the Alaskan margin. The lower insert shows a close up of the seismic cross-section showing offset layers near the seafloor indicating that the normal fault has recently been active. Unpublished figure provided by Anne Becel.

Existing Models Require No Strength on Aftershock Normal Faults

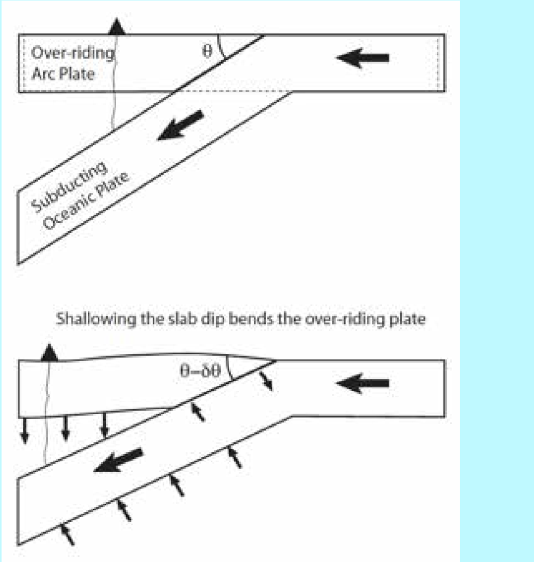


Dynamic Overshoot model of Kozdon and Dunham (2013) should produce ~ 10 MPa change in upper plate stress while >100 MPa of relative extensional stress is needed to have normal fault slip.

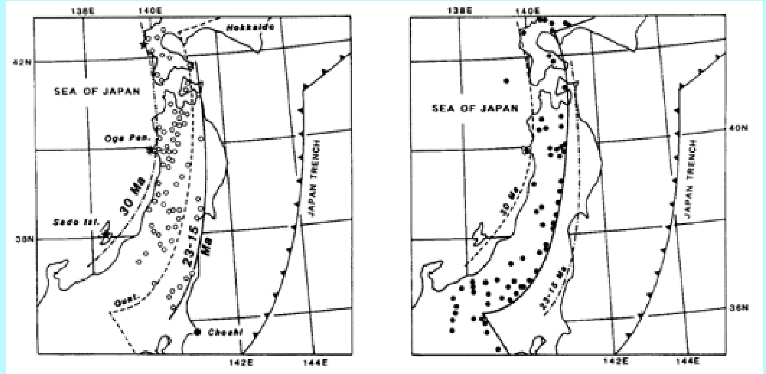


Gravitational collapse model of McKenzie and Jackson (2012). Also produces small stress change in upper plate and so would not produce normal faults unless friction is nearly zero.

New Model



Schematic showing how a reduction in the dip of a subducting slab could result in bending of the over-riding plate.



Distribution of arc volcanic rocks in Northeast Japan in the Oligocene (stars on left panel), in the Miocene (circles on left) and in the Quaternary (filled circles on right) from Tatsumi et al (1989). The authors conclude that the arc has migrated landward since Miocene time.

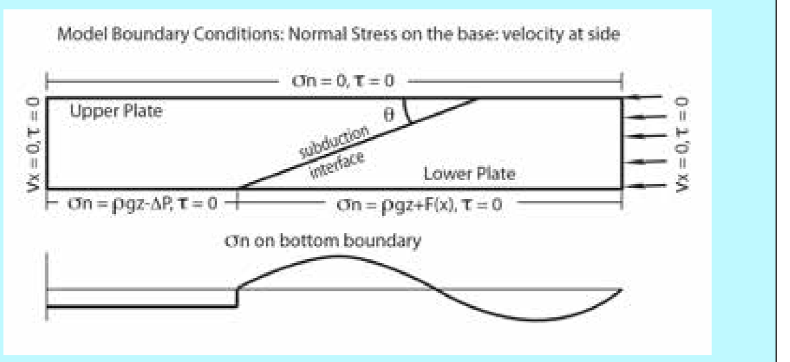
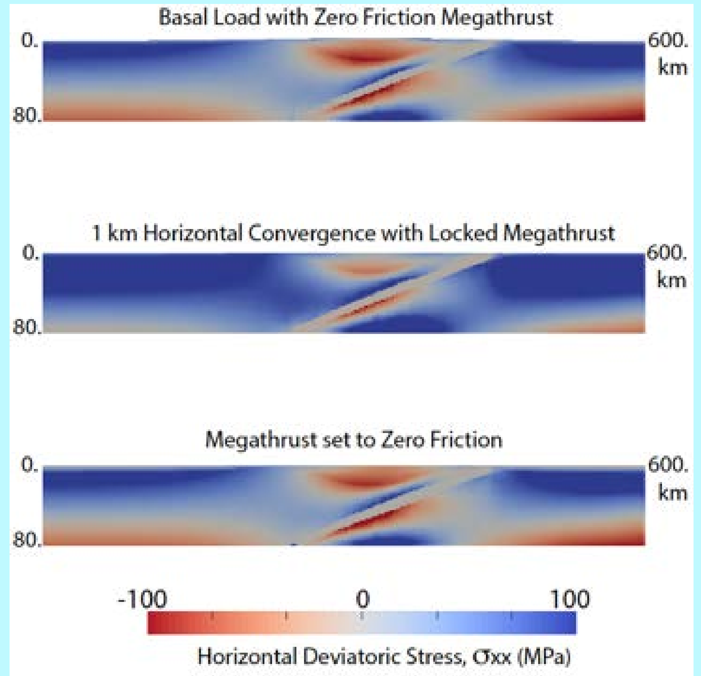
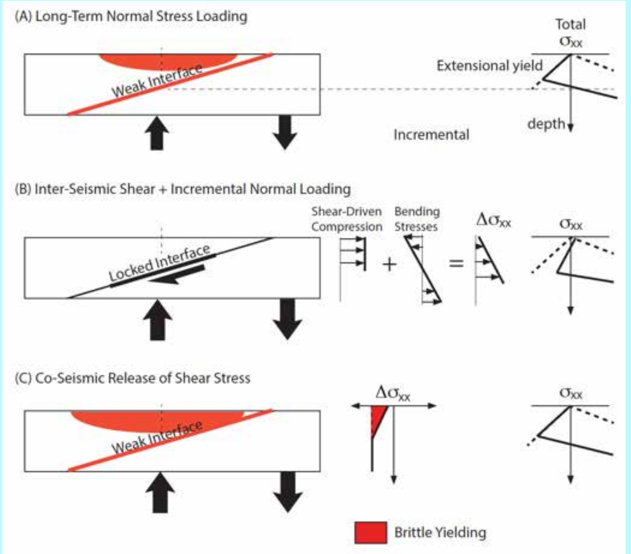


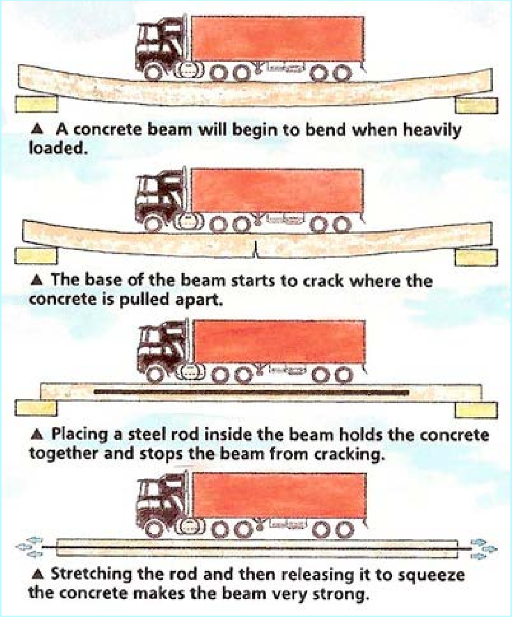
Illustration of boundary conditions used for a numerical model testing the interaction of a bending moment applied to the base of the upper lithospheric plate in a subduction system. The subduction interface is specified as a zone of high initial plastic strain..



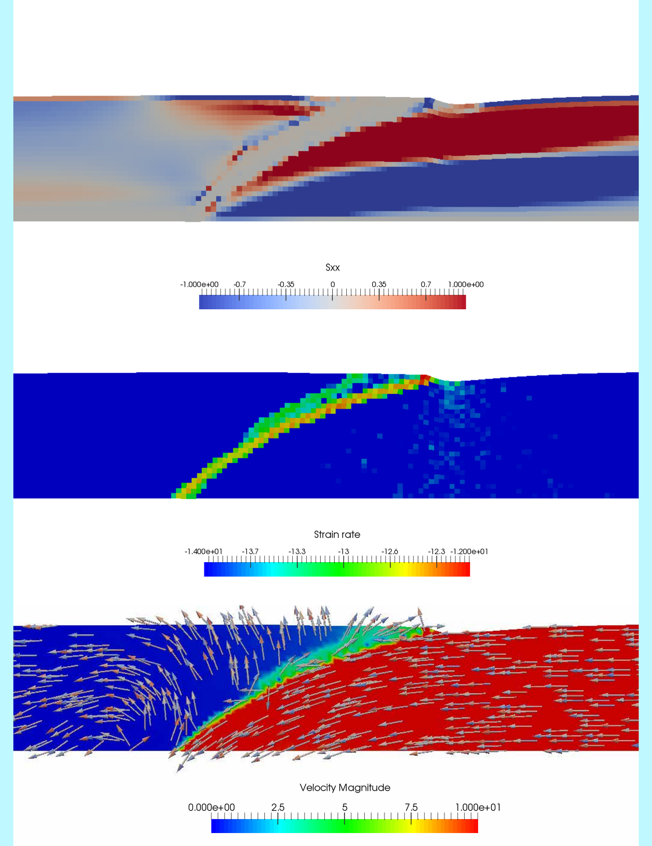
Results of a numerical model of the interaction of plate bending and convergence on the geologic (top), inter-seismic (middle) and co-seismic (bottom) time scales. The top panel is stress due to long term bending of upper plate with zero friction interface. The second panel shows how the stresses are changes by 1 km of horizontal convergence when the subduction interface is locked. The bottom shows the effect of reduction of the interface friction to zero that allows restoration of the extensional stress.



Cartoon illustrating the interaction of shear stresses and normal stresses causing deformation in a subduction system. (A) shows the long-term effect of loads transmitted by normal stress acting across a weak subduction interface. (B) A gradual build up of shear stress on the locked interface compresses the upper plate. A gradual increase of normal stress across the interface produces more bending of the upper plate. Because shear related compression is everywhere greater than bending related extension the upper plate no where fails in extension as it would without the compression. (C) The sudden drop in shear stress across the fault cause sudden extensional failure of the upper plate.



Cartoon illustrating how pre-stressing conrete can increase strength of a beam. The breaking of the tensioned steel rods in the bottom panel would cause an increase in tension and so failure of the beam, analogous to the failure of a megatrust with a bent upper plate.



Snapshots of stress, srain rates and velocity a numerical model of long term subduction with a reduction in the dip of the subduction interface. The weak material along the interface is pushed up in a wedge with a spontaneously formed normal fault.

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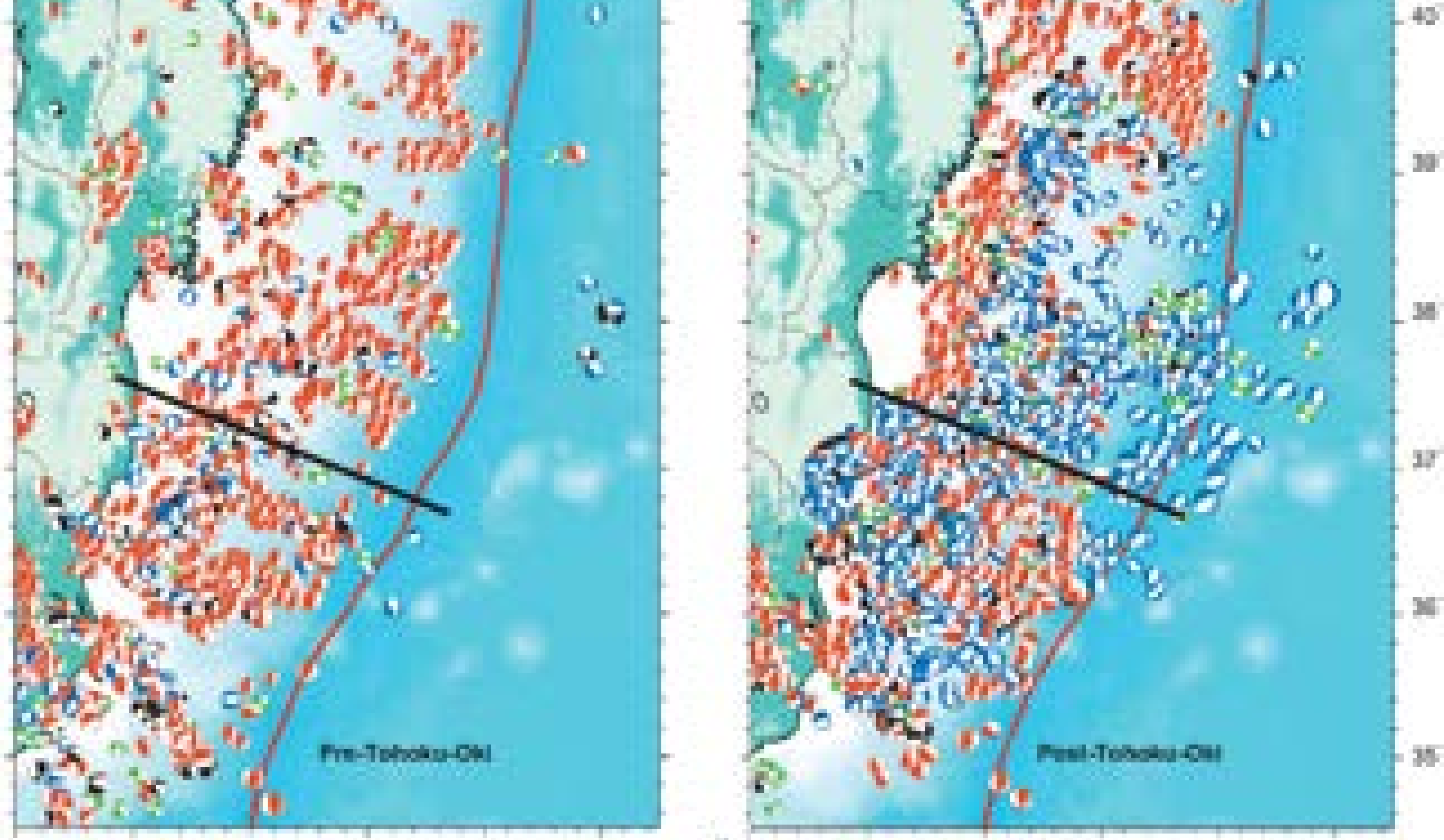

(a) (b)