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Stable forearc stressed by a weak megathrust: Geodynamic implications of a stress reversal caused by the M=9 Tohoku-oki earthquake

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The rupture-zone averaged static stress drop in the 2011 M=9 Tohoku-oki earthquake was less than 5 MPa according to all published slip models, but it caused a reversal of the state of stress in most of the offshore forearc, from predominantly compressive to predominantly extensional. In this work, we demonstrate that this stress reversal has the following important geodynamic implications. (1) The reversal unequivocally indicates a very weak subduction megathrust. In order to reproduce this reversal in a finite element model of force balance that quantifies the effects of gravity and megathrust friction, the effective coefficient of friction of the megathrust has to be about 0.032. A lower value would make the forearc too extensional before the earthquake, and a higher value would make it too compressive after the earthquake. (2) The very weak megathrust results in very low differential stresses in the upper plate, consistent with previously reported sensitivity of the state of stress to small perturbations. Applying the dynamic Coulomb wedge model, we demonstrate that the inner wedge, and by inference the nearshore-onshore forearc, is in a stable state throughout subduction earthquake cycles, far from failure. (3) The outer wedge is normally in a stable state but may reach an extensionally or compressively critical state during an earthquake, depending on the behavior of the shallow megathrust. Gravitational collapse of the outer wedge is prevented by a finite strength of the underlying shallow megathrust. Therefore, complete stress drop (i.e., effective coefficient of friction decreases to zero) is unlikely to have happened over the main part of the shallow megathrust except for limited local areas. (4) The presence of permanent deformation such as earthquakes and active faulting in the overall stable forearc can be explained by structural and stress heterogeneities. We propose that for the most part, the upper plate near a subduction zone is much below its yield stress and is an elastic body, but permanent deformation can locally occur in areas of low strength, high stress, or high fluid pressure. (5) The concept of dynamic Coulomb wedge (Wang and Hu, 2006, JGR) needs to be expanded to address timescales much beyond subduction earthquake cycles. The strength of the megathrust varies over geological timescales, affecting the stability of the outer wedge and its response to earthquake rupture.