Sequential activation of reverse and normal faulting in the upper plate during the 2011 Tohoku earthquake

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The Japan Trench was generally thought to belong to the erosive margin category, on which various mechanisms have been proposed to explain its fore-arc evolution over geological time scales. On the other hand, the occurrence of the 2011 Tohoku earthquake has challenged many aspects of existing subduction zone models. In particular, recent seismic survey (Boston et al., 2017) reveals that the upper plate above the large slip area of the 2011 Tohoku earthquake contains spatially mixed reverse and normal faults, which cannot be simply explained by a long-term segmentation of basal friction along the dip direction. Various other models, such as the subducting seamount model and the dynamic Coulomb wedge model, may allow alternating faulting regime in the upper plate as a response to fluctuations in basal conditions. However, they also have their own limitations: seafloor topography map does not seem to support recent seamount activity in the main slip region of the 2011 Tohoku earthquake, while the dynamic Coulomb wedge model was primarily constructed for margins hosting non-trench-breaking megathrust earthquakes. Therefore, we need to seek other solutions for understanding the coeval development of reverse and normal faults in the upper plate near the Japan Trench.

Here we propose that some reverse and normal faults in the upper plate were dynamically activated in sequence during two distinct stages of the up-dip rupture evolution of the Tohoku earthquake. The key concept emphasizes the temporal evolution of slip profiles during trench-breaking megathrust earthquakes, augmented with the free surface effects at different stages (Xu et al., 2016). At the earlier stage before a deeply nucleated rupture reaches the trench, its slip profile shows a half-elliptical shape with a negative gradient towards the trench, while the still locked portion of basal fault near the trench is strengthened by free-surface induced clamping (Oglesby et al., 1998). Both effects promote dynamic compression and thus reverse faulting in the upper plate. At the later stage after the rupture reaches the trench, its slip profile dramatically changes to a quarter-elliptical shape with an overall positive gradient towards the trench, while the already slipped portion of basal fault near the trench is weakened by free-surface induced unclamping. Both effects now favor extensional deformation and thus normal faulting in the upper plate. Since the same near-trench portion of the upper plate can sequentially experience dynamic compression followed by dynamic extension, it allows for a final state of mixed faulting structures. Due to the nature of dynamic loadings and a possible compensation between compression and extension, the spatial extent and the total displacement of each activated fault in the upper plate could be limited. From a viewpoint of stress wave evolution, the dynamic process proposed above shares a similar physics with rock failure during an impact and spalling test. In the latter case, mixed crack families dictating different principal stress orientations can emerge, due to an overprinting of incoming compressional stress wave and reflected tensile stress wave from the end free surface. Given the rough validation by the analog rock failure test, our proposed mechanism may provide a clue for understanding the upper plate faulting structure near the Japan Trench, contributed by past megathrust earthquakes of the type similar to the 2011 Tohoku. Since this mechanism is expected to hold for any rupture that energetically reaches the trench, its validity can be further investigated in other regions known to host trench-breaking ruptures.

References:

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