Estimation of rupture directivity, fault plane, and stress drop of small earthquakes in inland areas of Japan

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Dominant frequency or duration of seismic waves is considered to reflect the fault size. Some studies used the dominant frequency for the estimation of fault size and stress drop for small earthquakes assuming simple fault models (e.g., Brune, 1970; Sato & Hirasawa, 1973; Madariaga, 1976) without estimating heterogeneous slip distribution on the fault. Some of the simple source models are based on a symmetrical circular fault model (Madariaga & Ruiz, 2016). The assumption of the isotropic rupture evolution on a symmetrical circular fault can lead to a large estimation error of the fault size and thus the stress drops if the real source process is asymmetrical or exhibits a significant directivity effect (e.g., Kaneko & Shearer, 2015). We should carefully check if we can assume a symmetrical source model when we apply it in analyzing seismograms of small earthquakes.

We investigated the rupture directivities of small and moderate-sized earthquakes (M_JMA>2) in the Yamagata-Fukushima border earthquake swarm which was estimated to be triggered by the upward fluid movement after the 2011 Tohoku-Oki earthquake. We utilized the dense nationwide seismic network in Japan to estimate the rupture directivity. Apparent source time functions were calculated at each station for 1,782 earthquakes based on the waveform deconvolution technique with nearby (< 300 m) small earthquakes to remove the propagation- and site-effects. We found clear directional dependences of the peak amplitude and the pulse width in the apparent source time functions, suggesting the earthquake rupture directivity, for 904 of 1,782 events.

Based on the unilateral rupture model, we estimated the direction, duration, and velocity of rupture for each earthquake. Rupture directions of most earthquakes tend to be different from those of the hypocenter migration. This difference between the microscopic and macroscopic propagations of rupture might be explained by the spatial variation of the frictional strength; ruptures of each earthquake are hindered to develop toward shallower part due to higher frictional strength ahead of the pore-pressure front (shallower part) than behind (deeper part). It suggests the importance of the knowledge of frictional strength on fault to understand fracture dynamics of small earthquakes.

Besides, we estimated fault planes of small and moderate-sized earthquakes based on focal mechanism and rupture directivity (Fig.). Most of fault planes are parallel to the macroscopic planar structures, which suggests that they were triggered by fluid intrusions along those common planar structures. By taking the limitation of the resolution of hypocenter relocation, information from the rupture directivity can be unique data to reliably determine the fault planes of small and moderate-sized earthquakes.

By considering the estimated fault planes and areas of small earthquakes, we confirmed the temporal increase in stress drop reported by Yoshida et al. (2017, JGR). The systematic temporal changes in frictional strength, stress drop, background seismicity rate, b-values, the upward hypocenter migration along the planar structures, and the rupture directivity rather opposite to the hypocenter migration can be explained in a consistent manner by the effects of the upward fluid flow along several pre-existing planes after the 2011 M9 Tohoku-Oki earthquake.

Keywords: frictional strength, stress drop, hypocenter migration