A detailed view of the earthquake swarms triggered by the pore pressure change after the 2011 Tohoku-Oki earthquake: Rupture directivity and frictional strength variation on faults

*Keisuke Yoshida[1], Tatsuhiko Saito[3], Kentaro Emoto[2]

1. RCPEVE, Tohoku University, 2. Tohoku University, 3. National Research Institute for Earth Science and Disaster Resilience

Since earthquake nucleation and rupture processes are strongly controlled by the stress and frictional parameters on fault, it is important to study their relationship both from the observation and the computer simulation. It, however, is generally difficult to know the states of stress and strength at depth. In this study, we analyzed waveform records of the earthquake swarms in central Tohoku, which were estimated to be triggered by the reduction in frictional strength due to the pore pressure migration after the 2011 Tohoku-Oki earthquake, and investigated the relationship between the rupture directivity and the distribution of frictional strength on faults.

The directivity effects observed by a seismograph network contains information on rupture processes. We can estimate fault orientations and rupture direction by taking advantage of the directivity effect. It was generally difficult to obtain detailed information on rupture processes for moderate-sized and smaller earthquakes. However, as data quantity and quality have improved, directivity has been clearly observed for moderate-sized (e.g., Boatwright, 2007; McGuire, 2004; Seekins & Boatwright, 2010) and smaller (e.g., Chen, Jordan, & Zhao, 2010; Folesky et al., 2016; Tomic, Abercrombie, & Do, 2009; Yamada et al., 2005) earthquakes. This enables us to study the diversity of the rupture process on the identical tectonic setting.

Previous studies suggested that pore pressures migrated along existing planes from deep to shallow level after the 2011 Tohoku-Oki earthquake in the source regions of the earthquake swarms in central Tohoku (Yoshida & Hasegawa, 2018 and under review). Figure 1 shows the spatial distribution of relative moment rate functions of an earthquake in the swarm region in the Yamagata-Fukushima border based on the deconvolution (Ligorrfa & Ammon, 1999) of direct S-waves by those of the closest event. We can see a clear rupture directivity.

In order to obtain information of earthquake sources from waveform records, we first estimated the Q-1 structure and the site-effects in and around the source region based on the coda normalization method as Yoshida et al. (2017) did. We then determined source spectra for earthquakes at individual stations by using the Q-s1 structure and the site-effects. We focused on 135 earthquakes (M1.8-3.1) for which focal mechanisms were determined in the previous study (Yoshida et al., 2016) and the ones of their nodal planes are parallel to the hypocenter distribution (Yoshida & Hasegawa, under review). Their dominant frequencies show distinct spatial patterns, which are consistent with the result of the deconvolution analysis. Spatial patterns of dominant frequency are diverse, suggesting that the spatial patterns are

originated from earthquake sources.

We applied the unilateral directivity model of Ben-Menahem (1961) to the spatial distributions of dominant frequency. We focused on 119 earthquakes for which S/N is sufficient for all the frequency range at >10 different stations. 84 earthquakes show significant unilateral directivities, many of which are oriented to northwest. This direction is nearly opposite to that of the hypocenter migration. This observation is similar to that in induced seismicity (Folesky et al., 2016), and can be explained by the variation of frictional strength on the faults. We checked the robustness of the observed tendency by comparing the result with those based on different attenuation models.

For ~60 events of the 84 earthquakes, we could determine the fault planes based on the observed rupture directivity. Most of fault orientations are parallel to the macroscopic alignments of hypocenters. Fault planes of a few events are conjugate to the macroscopic planes, suggesting that theses earthquake occurred by using the smaller scale fault structures.

Keywords: rupture directivity, earthquake swarm, pore pressure