Detailed view of earthquake swarms in northeastern Japan triggered by fluid migration associated with the 2011 Tohoku-Oki earthquake

Keisuke Yoshida
Research Center for Prediction of Earthquakes and Volcanic Eruptions, Graduate School of Science, Tohoku University, Aoba-ku, Sendai 980-8578, Japan.

The phenomenon of earthquakes induced by the injection of fluids has been recognized for many decades (e.g., Healy et al., 1968). The mechanism for inducing earthquakes has been understood to be increasing pore pressure reducing the effective normal stress acting across preexisting fault surfaces (Raleigh et al., 1976; Segall & Liu, 2015). The occurrence of earthquake swarms are sometimes explained by a mechanism similar to fluid-injection-induced-seismicity, that is, the reduction in frictional strength due to migrating fluids. Since the migration behavior of hypocenters, which is frequently seen in earthquake swarms, is similar to that observed in fluid-injection-induced-seismicity (e.g., Julian et al., 2010; Parotidis et al., 2005), those earthquake swarms are interpreted as being associated with pore pressure diffusion (e.g., Shapiro et al., 1997)

The 2011 M9 Tohoku-Oki earthquake induced many earthquakes around its source area. A great number of aftershocks took place even in inland Japan, which is densely covered by a nationwide seismic network. Previous studies revealed that migrating earthquake swarms are included in those aftershocks (Kosuga, 2014; Okada et al., 2015; Yoshida et al., 2016, 2017, 2018). This provides a unique opportunity to study the mechanism of remote aftershock triggering.

In this presentation, I will introduce the following distinctive characteristics of the earthquake swarms triggered by the 2011 Tohoku-Oki earthquake:

(1) These swarms are triggered in the stress shadow of the 2011 Tohoku-Oki earthquake. Namely, Coulomb stresses decreased by the static stress change of the earthquake.
(2) Initiations of the swarm activities are delayed for a few days to months from the earthquake. Their focal regions are distributed near the ancient calderas and along the tectonic lines.
(3) Hypocenters moved from deeper to shallower level along several sharply defined planar structures.
(4) Source parameters of earthquakes changes with time. In particular, focal mechanisms with unfavorably-oriented fault planes tend to occur during initial stages, while most of earthquakes have favorably-oriented fault planes during later stages. Stress drops tend to be small (~1MPa) during the initial stages while they have higer values (~ 3MPa) during the later stages. Similar observations are reported in cases of fluid-injection induced seismicity (Kwiatek et al., 2014; Martínez-Garzón et al., 2014; Staszek et al., 2017).
(5) Seismicity characteristics changed with time. In particular, b-value is high (~2) during the initial stages while it gradually decrease during the later periods. Similar observations are reported in cases of fluid-injection induced seismicity (Wyss, 1973; Bachmann et al., 2011, 2012). The timing of earthquake occurrences is almost random during the initial stages, but it gradually becomes temporally clustered in later periods, with the number of events decaying aftershock-like after relatively large events.

These observations suggest that the generation mechanism of the present earthquake swarms is essentially similar to fluid-injection-induced seismicity, that is, the reduction in frictional strength due to the pore pressure evolution. The pore pressure evolution is probalby caused by the 2011 M9 Tohoku-Oki earthquake under the conditions of permeability heterogeniety. The obseved temporal variations of source parameters and seismicity characteristics are possibly explained by varying frictional strength due to the pore pressure evolution.