# Rupture Processes and Geophysical Background of the 2011 and 2016 Northern Ibaraki Prefecture Earthquakes

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Large earthquakes often enhance seismicity not only in vicinity of the rupture area, but also distant areas by dynamic and static stress changes (e.g., Hill, et al., 1993;Kilb, et al., 2000). At the time of the 2011 Tohoku-oki earthquake, the sudden change in seismicity rate was observed in many areas in Japan (Toda, et al., 2011). One of such areas is the Fukushima Hamadori and northern Ibaraki prefecture area (see Figure). Before the Tohoku-oki earthquake, the seismicity was very low with normal faulting earthquakes (Imanishi, et al., 2012). The strong east-west coseismic extension excited the seismicity. One month after the Tohoku-oki earthquake, the 2011 Iwaki earthquake ($M_j$ 7.0, $M_w$ 6.6) struck this area. In the northern Ibaraki prefecture area, an $M_j$ 6.3 ($M_w$ 5.9) earthquake took place on December 28, 2016 (hereafter referred to as "Event 2016"). In the vicinity, two earthquakes with similar size occurred just 8 minutes after the origin time of the Tohoku-oki earthquake ("Event 2011a") and 8 days after that ("Event 2011b"), respectively. The In-SAR analysis (Kobayashi, et al., 2011;Nakai, et al., 2017;Fukushima, et al., 2018) suggested the surface ruptures at the same locations. It is unusual that M ~ 6 earthquakes occurred in the same fault in 6 years. For now, it is important to know if these earthquakes ruptured the same fault based on seismological analyses.

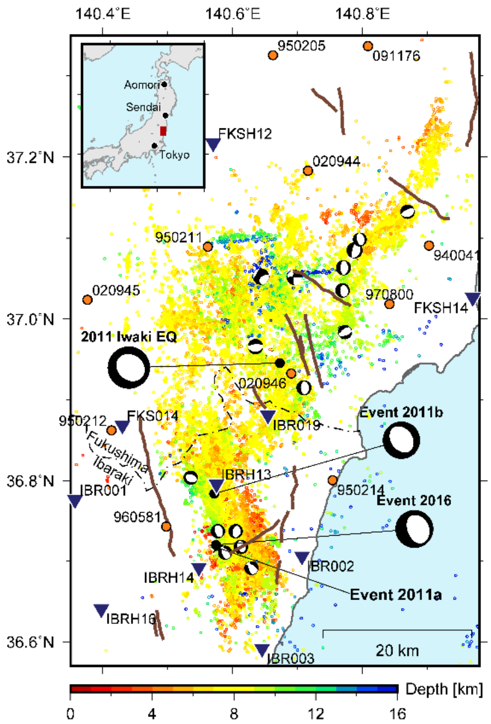


**Figure.** Map of the study area. Colored dots show hypocenters of earthquakes. The blue triangles and the orange circles indicate the locations of seismic stations and GEONET stations, respectively.

We relocated the seismicity since 2011 using hypoDD code (Waldhauser and Ellsworth, 2000), and the result implies that almost all faults ruptured by Event 2016 was also ruptured in 2011. The main fault was southwest dipping.

On the other hand, the seismograms from those events look different. We performed slip inversion analyses (Uchide and Ide, 2007) and found that the slip areas of the 2011 events (Events 2011a and 2011b) and Event 2016 were half overlapped. As for the 2011 events, Events 2011a ruptured shallower part than Event 2011b, therefore it is likely that Event 2011a ruptured the ground surface rather than Event 2011b.

The stress drop distributions inferred from the estimated finite-fault model were more distinct. The stress drop distribution of Event 2016 penetrated between those of Events 2011a and 2011b. The slip occurred wider area than the stress drop areas, and as a result we observed the overlap of the slip areas.

Our model suggests that these three events ruptured on the same fault, and, however, consumed the strain energy in different portion of the fault. Therefore, a stress accumulation since 2011 equivalent to the stress drop of the 2011 events is not required for the occurrence of Event 2016. The ground surface strain inferred from the GNSS data suggests an increase in the east-west extensional strain, which may be enough to make Event 2016 happen.

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We used JMA Unified Earthquake Catalog, seismic data from KiK-net, K-NET, and F-net (Okada, et al., 2004) maintained by NIED, the Daily Coordinate of GEONET maintained by GSI. We also used hypoDD code (Waldhauser and Ellsworth, 2000) and gpsgridder code (Sandwell and Wessel, 2016).

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