Initiation of the M~9 earthquake cycle: the 2021 Miyagi-Oki Mw7.0 earthquake at the deep seismic/aseismic transition

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The 2011 M9 Tohoku-Oki earthquake provides a rare opportunity to investigate how the earthquake cycle of a great (M9) earthquake impacts the generation of smaller (M7-8) earthquakes on the same fault. Following the Tohoku-Oki earthquake, the interplate seismicity drastically increased in the downdip extension while it disappeared within the main rupture area. An Mw7.0 earthquake occurred in the downdip extension off Miyagi in March 2021, followed by an Mw6.7 earthquake in May 2021. To examine the initial evolution of the earthquake cycle after the Tohoku-oki earthquake, we investigated the regional seismicity around the two M~7 earthquakes and their source processes.

We first relocated earthquake hypocenters around the source regions of the 2021 March Mw7.0 and May Mw6.7 Miyagi-Oki mainshocks by using the Double-Difference method (Waldhauser & Ellsworth, 2000). We used 49070 P-wave and 47566 S-wave differential arrival time data from the JMA unified catalog and 175817 P-wave and 204395 S-wave differential arrival time data derived from the waveform correlation.

We obtained the relocated hypocenters of 2736 interplate events. A small number of interplate earthquakes occurred before the Tohoku-Oki earthquake in and around the source region of the March earthquake, but the number sharply increased after the Tohoku-Oki earthquake. The hypocenter of the March Mw7.0 earthquake is located very close to the hypocenters of four M5-6 earthquakes which occurred after the Tohoku-Oki earthquake. The inter-event distances of these four earthquakes were much shorter than the source sizes of the four earthquakes and the mainshock, even when considering the estimation error; they probably ruptured the same seismic patch. Inside these M5-6 repeating earthquake source regions, M2-3 repeating earthquakes also occurred, forming a hierarchical structure. Almost all of these repeating earthquakes occurred after the Tohoku-Oki earthquake, suggesting that the March mainshock was initiated in a conditionally stable region where the repeating earthquake sequence emerged after the Tohoku-Oki earthquake (Hatakeyama et al., 2017).

We then estimated the spatiotemporal distributions of the slips of the two mainshocks in the same manner, following Hartzel & Heaton (1983) by using the apparent moment rate functions (AMRFs). To estimate the AMRFs, we applied the iterative time-domain approach by Ligorría and Ammon (1999) after Kikuchi and Kanamori (1982) to the S-waves (transverse component) with a non-negative constraint. We used the acceleration waveform data from onland stations of NIED KiK-net and offshore stations of S-net.

The results show that the March Mw7.0 mainshock had two large-slip regions: several kilometers ESE (first rupture; t=4–7 s) and ~20 km south of the hypocenter (second rupture; t=8–12 s). The rupture area of the March mainshock showed a complementary relationship with the aftershock area located between the two large slip areas. The May Mw6.7 occurred ~15 kilometers southeast of the southern large slip patch of the March mainshock, where the shear stress increased by the March mainshock rupture. In the May mainshock, the maximum slip occurred a few kilometers southeast of the hypocenter, with the total slip area being longer in the north direction as a moderate slip propagated to the north.

The two M~7 mainshocks ruptured the westernmost part of seismic patches of the 1978 Mw7.5

Miyagi-Oki earthquake, which is the most recent typical earthquake in an ~40-year interval of M~7.5 earthquake sequence, and loaded the eastern shallow seismic patches for the sequence. The further updip area is a part of the main rupture area of the Tohoku-Oki earthquake and hosts almost no interplate seismicity after this earthquake. Assuming that the spatial pattern of interplate earthquakes along the Japan trench will be restored to a situation similar to that before the Tohoku-Oki earthquake in the future, the downdip seismically active area should gradually expand to the updip area. The initial ruptures propagated in the updip direction for the 2021 M~7 earthquakes, similarly to the smaller earthquakes after the Tohoku-Oki earthquake (Yoshida et al., 2020, JpGU). The March Mw7.0 earthquake was initiated from a conditionally stable patch, which is probably a transient feature in the postseismic period of the previous M9 earthquake. Therefore, the 2021 Miyagi-Oki Mw7.0 initiated at the deep plate boundary probably illuminates seismicity in the early stage of the great interplate earthquake cycle. Continued monitoring of interplate seismicity is essential to examine how plate-locking evolves during the M9 earthquake cycle.