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The large aftershocks triggered by the 2011 Mw 9.0 Tohoku-Oki earthquake, Japan

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ABSTRACT

The Mw 9.0 Tohoku-Oki earthquake that occurred off the Pacific coast of Japan on March 11, 2011, was followed by thousands of aftershocks, both near the plate interface and in the crust of inland eastern Japan. In this paper, we report on two large, shallow crustal earthquakes that occurred near the Ibaraki-Fukushima prefecture border, where the background seismicity was low prior to the 2011 Tohoku-Oki earthquake. Using densely spaced geodetic observations (GPS and InSAR datasets), we found that two large aftershocks in the Iwaki and Kita-Ibarake regions (hereafter referred to as the Iwaki earthquake and the Kita-Ibarake earthquake) produced 2.1 m and 0.44 m of motion in the line-of-sight (LOS), respectively. The azimuth-offset method was used to obtain the preliminary location of the fault traces. The InSAR-based maximum offset and trace of the faults that produced the Iwaki earthquake are consistent with field observations. The fault location and geometry of these two earthquakes are constrained by a rectangular dislocation model in a multilayered elastic half-space, which indicates that the maximum slips for the two earthquakes are 3.28 m and 0.98 m, respectively. The Coulomb stress changes were calculated for the faults following the 2011 Mw 9.0 Tohoku-Oki earthquake based on the modeled slip along the fault planes. The resulting Coulomb stress changes indicate that the stresses on the faults increased by up to 1.1 MPa and 0.7 MPa in the Iwaki and Kita-Ibarake regions, respectively, suggesting that the Tohoku-Oki earthquake triggered the two aftershocks, supporting the results of seismic tomography.

1. Introduction

The Mw 9.0 Tohoku-Oki earthquake (USGS 38.322°N, 142.369°E) occurred on March 11, 2011, in the Pacific Ocean east of Japan (Fig. 1a), where the Pacific plate subducts beneath Honshu at a rate of ~9 cm/yr (Imanishi et al., 2012). Due to the release of long-term accumulated stress, it generated a tsunami that caused significant damage locally in Sendai. Several estimates of the fault slip distribution have been published (e.g., Fujii et al., 2011; Loveless and Meade, 2011; Yoshida et al., 2012), indicating a coseismic slip exceeding 30 m over a wide region.

The Tohoku-Oki earthquake has caused large variations in the stress field both near the source and far from the epicenter, causing a significant increase in seismic activity in the crust of the overriding plate west of the source area (Okada et al., 2011). Thousands of aftershocks occurred in the first few months following the Tohoku-Oki earthquake. Two major aftershocks were the Iwaki earthquake (Mj 7.0), which occurred in a previous seismic gap on April 11, 2011, and was the strongest on-land aftershock, and the Kita-Ibarake earthquake (Mj 6.0), which occurred on March 19, 2011 (note: Mj is the quick response magnitude and CMT is the centroid-moment tensor calculated by the Japan Meteorological Agency (JMA); both are reported by the NEID (http://www.fnet.bosai.go.jp/event/search.php?LANG=en)). We aimed to answer two main questions regarding these large aftershocks. First, what were the focal mechanisms of the earthquakes? Other than the CMT solution from the NEID, there is little published information about the slip distributions. Kobayashi et al. (2012) used InSAR data to detect the Iwaki earthquake. Second, were the two events triggered by the Tohoku-Oki earthquake? Using earthquake catalog data from the JMA (2004), the Coulomb stress changes on the fault planes of the Iwaki and Kita-Ibarake earthquakes have been calculated in some studies (e.g., Okada et al., 2011; Toda et al., 2011; Imanishi et al., 2012).

In this study, we used geodetic data (GPS and InSAR) to constrain the location, geometry and slip distribution of the two earthquakes. Then, we tested whether these earthquakes were caused by the Tohoku-Oki earthquake.

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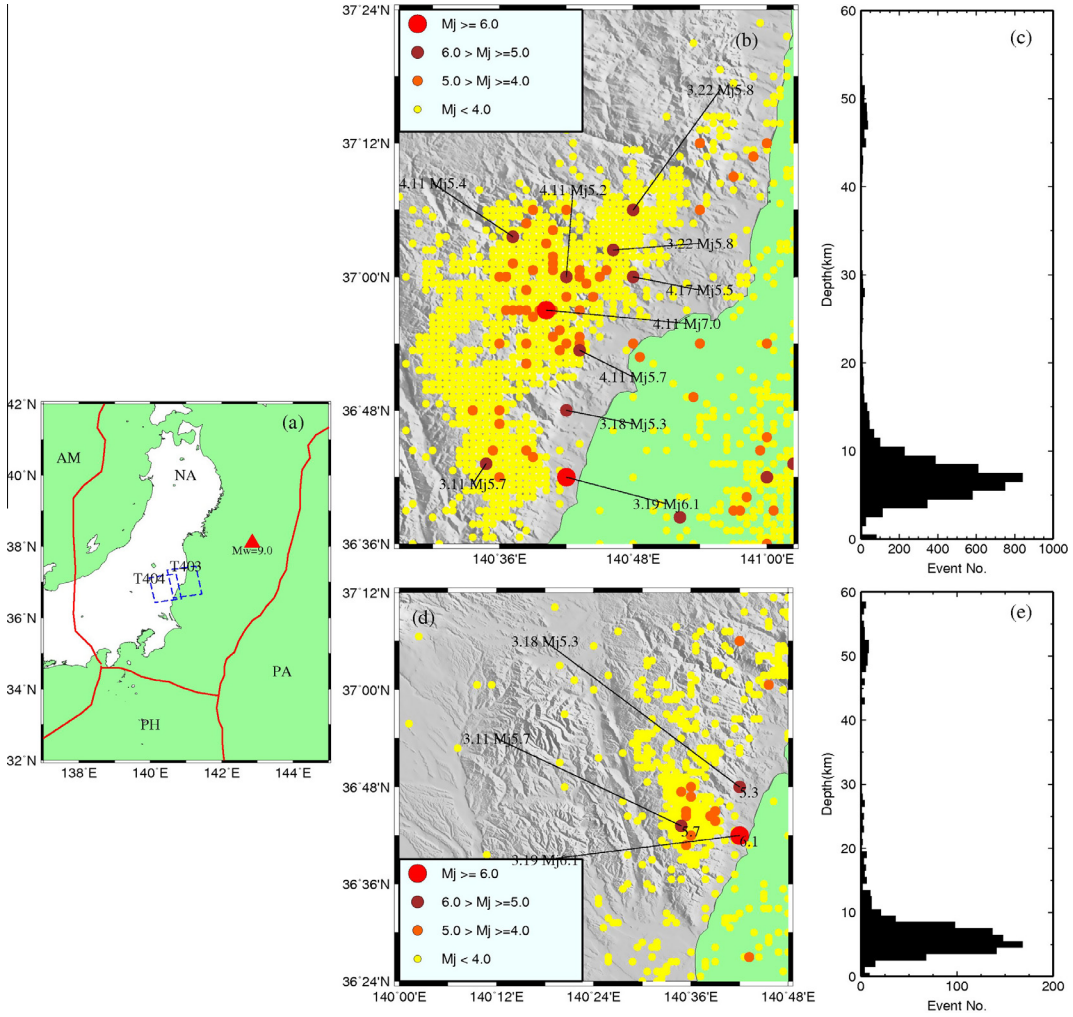

Fig. 1. Earthquakes that occurred in the study region during the PALSAR data acquisition period. (a) The location of overlapping PALSAR data, (b) the earthquakes that occurred between 2011/3/3 and 2011/4/18 in the Track 403 overlap region, (c) the focal depth statistics for the earthquakes in (b), (d) the earthquakes that occurred between 2011/2/2 and 2011/3/20 in the Track 404 overlap region, and (e) the focal depth statistics for the earthquakes in (d).

2. Geological background

As located at a plate boundary, earthquakes occur frequently in Japan. After The Mw 9.0 Tohoku-Oki earthquake there were several $M \geqslant 6$ earthquakes occurred inland and off Japan's western coast in the Japan Sea (Hirose et al., 2011). These aftershocks included an Mj 7.0 earthquake on April 11, 2011, and nine moderately sized earthquakes (Mj $\geqslant$ 5.0) after April 18, 2011. Based on seismic waveforms, the focal mechanism of the largest aftershock in the study region from the JMA indicates that these earthquakes were normal faulting events. The aftershock depths (Fig. 1c and e) indicate that most aftershocks occurred at depths shallower than 20 km. However, the area of the Iwaki and Kita-Ibarake earthquakes, in Fukushima prefecture, northeastern Japan, had lower background seismicity before the 2011 Tohoku-Oki earthquake (Imanishi et al., 2012).

The two aftershocks focused on in this study occurred in the western Iwaki city of Abukuma-sanchi. Metamorphic rocks and Cretaceous strata, granite and epidiorite are distributed throughout this area, as are forearc deposits with a Tertiary unconformity (Kubo et al., 2007). Previous field investigations indicate that there are active strike-slip and normal faults, including the Itozawa Fault and the Yunotake Fault, which have orientations of N10°W strike, 70°W dip and N60°W strike, 60°S dip, respectively (Active Fault and Earthquake Research Center, 2011). The Mj 7.0 Iwaki earthquake produced a 14-km-long westward normal-slip rupture on the Itozawa Fault and a 16-km-long southward normal-slip rupture on the Yunotake Fault. The northwestern end of the rupture on the Yunotake Fault is ~2.5 km from the northwestern end of the Itozawa Fault (Mizoguchi et al., 2012). Both faults have normal fault scarps with offsets of up to 2 m (e.g., Otsubo et al., 2012). The Yunotake Fault coincides with a ~200-m-high scarp, which is the result of geologically recent normal faulting or erosion that bounds the Neogene and pre-Neogene rocks (Kubo et al., 2007). The Itozawa Fault developed within the Gosaisho metamorphic rocks and is composed of three strands (Mizoguchi et al., 2012). Although both the Yunotake and Itozawa faults have been recognized as active (Nakata and Imaizumi, 2002), their paleoseismic histories are poorly understood. This normal faulting is inconsistent with the present-day regional stress field in northeastern Japan, which is characterized by a reverse-faulting regime with E–W compression (e.g., Zoback, 1992; Kubo et al., 2002; Townend and Zoback, 2006). In the northern Kita-Ibarake region, the seismicity changed drastically from a quiescent stage to an active stage, with no previously identified active faults.