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Coseismic displacement of the 2011 Tohoku-Oki earthquake detected by repeated multi-narrow beam bathymetric surveys

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After the 11 March 2011 Tohoku-Oki earthquake, we carried out bathymetric surveys using the R/V Kairei in the rupture zone across the Japan Trench. Some survey tracks were aligned along the tracks obtained before the earthquake, and we analyzed the difference in bathymetry before and after the earthquake. Although the results may incorporate errors of several meters in vertical displacement and ~20 m in horizontal displacement, the extraordinary coseismic displacement caused by the 2011 earthquake was detected by the bathymetric surveys.

Off the coast of Miyagi in the Tohoku district, the R/V Kairei surveys had been conducted in 1999 and 2004 [e.g. Tsuru et al., 2002 JGR; Ito et al., 2005 GRL; Miura et al., 2005 Tectonophys.]. For analysis, we used only the data obtained by beams within a 45^o swath width (3-6 km) because these inner beam soundings have higher accuracy and less effects of errors in water column sound velocity. Direct comparisons of absolute values of soundings were hampered by the differences of sound velocities used to calculate the depths and by the uncertainty of ship position. The apparent offsets were examined on the seaward side, because the seaward was thought to have suffered little change from the earthquake. For the 38^{o}N track, there were large relative differences landward extended up to the trench axis (~144^{o}00'E, water depth ~7600 m), suggesting the earthquake fault rupture reached the trench axis. The 2011 seafloor is shallower throughout the landward side. Notably, on the outermost landward slope, the 40 km wide area between the slope break (water depth 3700 m) and the trench axis, the difference between the 1999, 2004, and 2011 data shows the seafloor is ~11-16 m shallower on average. Furthermore, locally upward and downward changes in seafloor elevation of +/-50 m are evident at the axial seafloor. These changes are likely due to seafloor deformation at the place of the plate boundary fault reaching the seafloor. Comparison of the 1999 and 2004 data obtained before the 2011 earthquake indicated no clear difference between the two sides of the trench axis.

The observed seafloor elevation change on the outermost landward slope corresponds to a sum of vertical displacement and additional uplift for the sloping seafloor due to horizontal displacement. We estimated the horizontal displacement by calculating the offset distance to maximize the cross-correlation of bathymetry. The estimated displacement is ~50 m in the east-southeast toward the trench. After restoring the horizontal displacement, the average elevation change became ~7-10 m in comparison between the 1999, 2004, and 2011 data. We interpret these to represent vertical displacement, from the fault motion along the subducting plate and uplift from other unknown processes such as inelastic deformation.

For the 38.5^{o}N track, bathymetric data comparison shows the same trend, and there are relative differences landward extended up to the trench axis (~144^{o}05'E). Though, change in seafloor elevation along this track is smaller than that along the 38^{o}N track.

Combined with results of coseismic displacements determined at GPS/acoustic seafloor geodetic stations and other ocean-bottom instruments deployed off Miyagi [Ito et al., 2011 GRL; Kido et al., 2011 GRL; Sato et al., 2011 Science], our study demonstrates the coseismic displacement increasing toward the trench. This large horizontal displacement and the steeply sloping seafloor on the outermost landward slope having an average inclination of 5^o produced large additional uplift by ~4-6 m in addition to the vertical displacement. This uplift was likely an important factor contributing to the generation of the massive pulsating pattern of tsunami waves observed by cabled seafloor pressure gauge [e.g. Maeda et al., 2011 EPS].

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