Numerical modeling of crustal deformation and stress in the Northeast Japan island arc associated with the 2011 Tohoku earthquake

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Forearc region in the middle (38-39.5°N) Northeast Japan (NEJP) exhibited fast subsidence (up to 3-4 mm/year) in the interseismic period during ~100 years before the 2011 Tohoku earthquake (M_W9.1) (e.g., Nishimura, 2014). The forearc region also subsided by 0.4-1.2 m at the 2011 Tohoku earthquake, and it has been rapidly uplifted during the postseismic period (e.g., Nishimura, 2014). The mechanism of the forearc subsidence during the interseismic period has been studied and is still controversial (e.g., Ikeda, 2014; Nishimura, 2014; Sagiya, 2015; Hashima and Sato, 2017). To understand the mechanism of the forearc subsidence before the gigantic earthquake will help to assess the potential of a gigantic earthquake in subduction zones from geodetic observations. Therefore, this study attempted to elucidate the mechanism of the vertical displacement on the NEJP forearc region through the gigantic earthquake cycle via a numerical modeling.

This study modeled the crustal deformation through the gigantic earthquake cycle using finite element method considering heterogeneous rheological structure. We modeled the interplate coupling and the earthquake slip on the asperity of the gigantic earthquake via the split-node method (Melosh and Raefsky, 1981) based on the back-slip model (Savage, 1983). We modeled the fault creeping on the middle and deeper portions of the plate interface via a thin low-viscous layer (e.g., Hu et al., 2016). The model considered a ductile shear zone, which is extended from the deeper portion of the plate interface.

The modeling result indicates that interseismic subsidence rate in the forearc region increases with the duration of locking of the asperity of the 2011 Tohoku earthquake. It is caused by increasing slip deficit rate on the deeper portion of the plate interface owing to the continuous locking of the asperity during several hundred years with viscoelastic relaxation in the mantle wedge and the ductile shear zone. Therefore, the result implies that the observed fast subsidence during ~100 years before the 2011 Tohoku earthquake might occur only in the later period of the gigantic earthquake cycle. The fast interseismic subsidence in the forearc region was observed only in the region where is located above the deeper extended portion of the large coseismic slip area of the 2011 Tohoku earthquake. Our result, which the continuous locking of the asperity of the gigantic earthquake during several hundred years causes the fast interseismic subsidence in the forearc region, is consistent with this observation.

The modeling result indicates that large postseismic uplift occurs on the forearc region during ~50--100 years after the gigantic earthquake due to large afterslip (up to ~10 m) with long duration, which is controlled by postseismic viscoelastic shear deformation in the ductile shear zone. The result predicts that the coseismic forearc subsidence will almost recover ~35-40 years after the 2011 Tohoku earthquake mainly due to this long duration afterslip. The large postseismic uplift (~1.0-1.5 m/50 year) caused by the long-duration afterslip and subsequent uplift in the earlier interseismic period (~0.5 m/150 year) will balance to the sum of the fast subsidence in the later period of the gigantic earthquake cycle and the coseismic subsidence. This is the proposed mechanism of the vertical displacement in the NEJP forearc region during the gigantic earthquake cycle.

Similar fast interseismic subsidence also has been observed in the East Hokkaido forearc region (western Kuril subduction zone) (e.g., Suwa et al., 2006), where the gigantic earthquake occurred in the 17th century (e.g., Nanayama et al., 2003) and subsequent large postseismic uplift with long-duration (~1.5 m/60 year) was estimated (Sawai et al., 2004). Our result implies that this fast subsidence may also be caused by the continuous locking of the asperities of the gigantic earthquake during several hundred years, i.e., at least ~30 m of the slip deficit has been cumulated on the asperities of the 17th century event.