Mechanism of vertical displacement on the Northeast Japan fore-arc region through gigantic earthquake cycles

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Fore-arc region in the middle (38-39.5°N) Northeast Japan (NEJP) exhibited fast subsidence (up to 3-4 mm/yr) in the interseismic period during ~100 years before the 2011 Tohoku earthquake (M_W9) (e.g., Nishimura, 2014). At the 2011 Tohoku earthquake, the fore-arc region also subsided by 0.4-1.2 m (Nishimura, 2014). On the other hand, long-term vertical displacement rate on the fore-arc region indicates very slow uplift (0.1-0.2 mm/yr) (Tajikara, 2004). Therefore, when and how the vertical displacement on the fore-arc region balances and satisfies the long-term displacement through the gigantic earthquake cycle has been argued as the vertical displacement paradox and is still controversial (e.g., Ikeda, 2014; Nishimura, 2014; Sagiya, 2015; Hashima and Sato, 2017). This study attempted to elucidate the mechanism of the vertical displacement on the NEJP fore-arc region through the gigantic earthquake cycle and solve the vertical displacement paradox via a numerical modeling.

This study modeled the crustal deformation through the gigantic earthquake cycles using finite element method (Shibazaki *et al.*, 2007) considering heterogeneous rheological structure. The interplate coupling and the earthquake slip on the asperity of the gigantic earthquake were modeled via the slip-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 and connects to the viscoelastic mantle wedge.

The modeling result indicated that interseismic subsidence rate in the fore-arc region increased with the duration of locking of the asperity of the 2011 Tohoku earthquake. It was caused by increasing slip deficit rate on the deeper portion of the plate interface caused by continuous locking of the asperity during several hundreds 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 modeling result indicated that large postseismic uplift occurred on the fore-arc region during ~50 years after the gigantic earthquake caused by large afterslip (up to ~10 m) with long duration, which was controlled by postseismic viscoelastic shear deformation in the ductile shear zone. The result predicts that the coseismic fore-arc subsidence will almost recover 40-50 years after the 2011 Tohoku earthquake mainly due to this long duration afterslip. The sum of the large postseismic uplift (~0.4-1.4 m/50 yr) caused by the long-duration afterslip and subsequent uplift in the earlier interseismic period (~0.6-0.8 m/150 yr) will balance to the sum of the fast subsidence in the later period of the gigantic earthquake cycle (~0.6-0.8 m/300 yr) and the coseismic subsidence (~0.4-1.4 m). This is the possible mechanism to solve the vertical displacement paradox in the NEJP fore-arc region.

Similar fast interseismic subsidence also has been observed in the East Hokkaido fore-arc region (western Kuril subduction zone), 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 yr) 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 hundreds years, i.e., at least ~30 m of the slip deficit has been cumulated on the asperities of the 17th century event.

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