博士論文

Heterogeneous Subduction Zone Rheology Inferred from Postseismic Deformation of the 2011 Tohoku-oki Earthquake

(2011 年東北沖地震の余効変動から推定する沈み込み帯の不均質レオロジー構造)

Dhar SAMBUDDHA

令和 4 年

Abstract:

The dense and widespread geodetic network around northeastern (NE) Japan made an unprecedented recording of crustal deformation following the 2011 Tohoku-oki earthquake [1]–[3]. Most inland GNSS stations display a wholesale seaward motion in the direction of coseismic displacements[3]–[5]. In contrast, a few seafloor GNSS stations above the main rupture area show landward motion[1],[2],[6]. A more complex pattern has been observed in the vertical motion such as subsidence at the volcanic front, subsidence of seafloor, and rapid uplift along the Pacific coast of NE Japan[3],[5],[7]. This heterogeneous crustal deformation has been explained by several postseismic models that combined stress relaxation of viscoelastic earth (viscoelastic relaxation)[8] and continuous aseismic slip (afterslip) of plate boundary fault. Using geodetic observations, most postseismic models explored the rheological properties of viscoelastic mantle and plate boundary fault [1],[4],[5],[7],[9]–[17]. These models often conclude that the postseismic vertical observations are the key to infer the heterogeneous rheology of the lower crust–upper mantle[5],[7].

Previous studies have indicated that the forearc mantle wedge plays a crucial role in the heterogeneous surface deformation[18] due to its unique rheological structure, encompassing a stagnant and non-stagnant part within it[18],[19]. However, forearc rheology is yet to be resolved in three-dimension, which I considered the main objective of this study. Motivated by the two-dimensional postseismic model incorporating across-arc rheological heterogeneity[13], I explored the along-arc rheological heterogeneities of the forearc mantle wedge in NE Japan[16]. I developed a numerical model incorporating a three-dimensional rheological structure (Fig. 1a) and deployed power-law Burgers rheology for viscoelastic relaxation in the lower-crust/upper mantle and rate-strengthening friction law for afterslip on the plate boundary fault (Muto et al. [13] and reference therein). For geodetic constraints, I used the observations from newly deployed GNSS stations, operated by Tohoku university, along the Fukushima-Niigata transect[16], in addition to other networks including GEONET, seafloor GNSS-A sites[2],[20],[21], and a pre-existing similar network in the Miyagi-Yamagata transect[7],[13]. I demonstrated that my modeled surface displacement along the Miyagi-Yamagata and Fukushima-Niigata transect agrees well with the geodetic observations both in horizontal and vertical components. By comparing the rheology between the Miyagi and Fukushima forearc, I inferred an along-arc heterogeneity in the steady-state viscosity. In particular, my result suggests a variation in the cold-nose geometry along the arc i.e., narrower for the Miyagi and wider for the Fukushima transects[16]. Figs 1b and 1c shows illustrates the cold nose, regions with no or low cumulative strain by viscoelastic relaxation calculated over the ~5 years of postseismic deformation. My results can be evaluated by other geophysical observations such as deepening of D90-depth[22], depressed heat flow and thermal gradient[23] around Fukushima prefecture.

Furthermore, I investigated the relative contribution of viscoelastic relaxation and afterslip across NE Japan using my stress-dependent model. My results concluded the larger contribution of viscoelastic relaxation than afterslip for the inland GNSS stations in horizontal motion even shortly after the earthquake. For the vertical motion, viscoelastic relaxation dominates regions from the backarc to the volcanic front where afterslip dominates along the Pacific coast of NE Japan. I discussed the consistency of my results in light of previous stress-dependent models[13]–[16]. I extended my modeled displacements for forecasting long-term postseismic deformation, and I found that most Pacific coastal regions may regain their pre-earthquake ground elevation within approximately twenty years after the earthquake (Fig. 2). In the last decade, many port-piers in the coastal region are reconstructed after experiencing a substantial submersion during the coseismic period. Since then, as reported in 2016[24], port piers are raised way above the present sea level due to the rapid postseismic uplift, which has serious consequences on transshipment business. Hence my results can help provide scientific guidance to rebuild the port piers again.

Most often, stress-dependent postseismic models produce systematic errors in their modeled displacements, owes to the limitations of model parameters and governing deformation mechanisms [5],[16].

As a result, their modeled displacements do not always provide a robust understanding of the relative contributions of their deformation sources. I took an alternative approach by decomposing individual GNSS time series into their two contributing components: viscoelastic relaxation and afterslip. I designed an analytical expression (hereafter, function model) based on laboratory-derived constitutive properties of rocks that have been used in recent stress-dependent postseismic models[13],[25]. My function model can predict north-south, east-west, and up-down components of the postseismic GNSS time series at most GEONET stations (F5 solution of daily coordinates) across NE Japan (Fig. 3a–c). For each time series, I empirically fitted the function model to the observed time series for two years and predict the time series over the remaining eight years of postseismic deformation[26],[27]. My modeled displacements yield an average residual of ~2 cm compared to total ten years of observations after the earthquake. Therefore, our function model may help predict the postseismic GNSS time series in the coming decades. I ensured the robustness of my function model by deploying Bayesian optimization[15] with GP-UCB (Gaussian process upper confidence bound) sampling method[28]. Similar to previous stress-dependent models, my results suggest a larger contribution of viscoelastic relaxation rather than afterslip in the short-term horizontal motion[13]–[16] (Figs 2d). The viscoelastic relaxation seems to dominate the short-term vertical deformations in the areas from volcanic front to backarc, whereas afterslip dominates the rapid postseismic uplift along the Pacific coast of NE Japan[5],[9],[13],[15],[16] (Fig. 3e). My results also infer the decadal persistence of coastal uplift by afterslip, which is recently reported by several previous studies. Hence, my proposed function model not only benefits in long-term prediction of postseismic deformation but also helps to understand the complex interplay of viscoelastic relaxation and afterslip with much greater ease.

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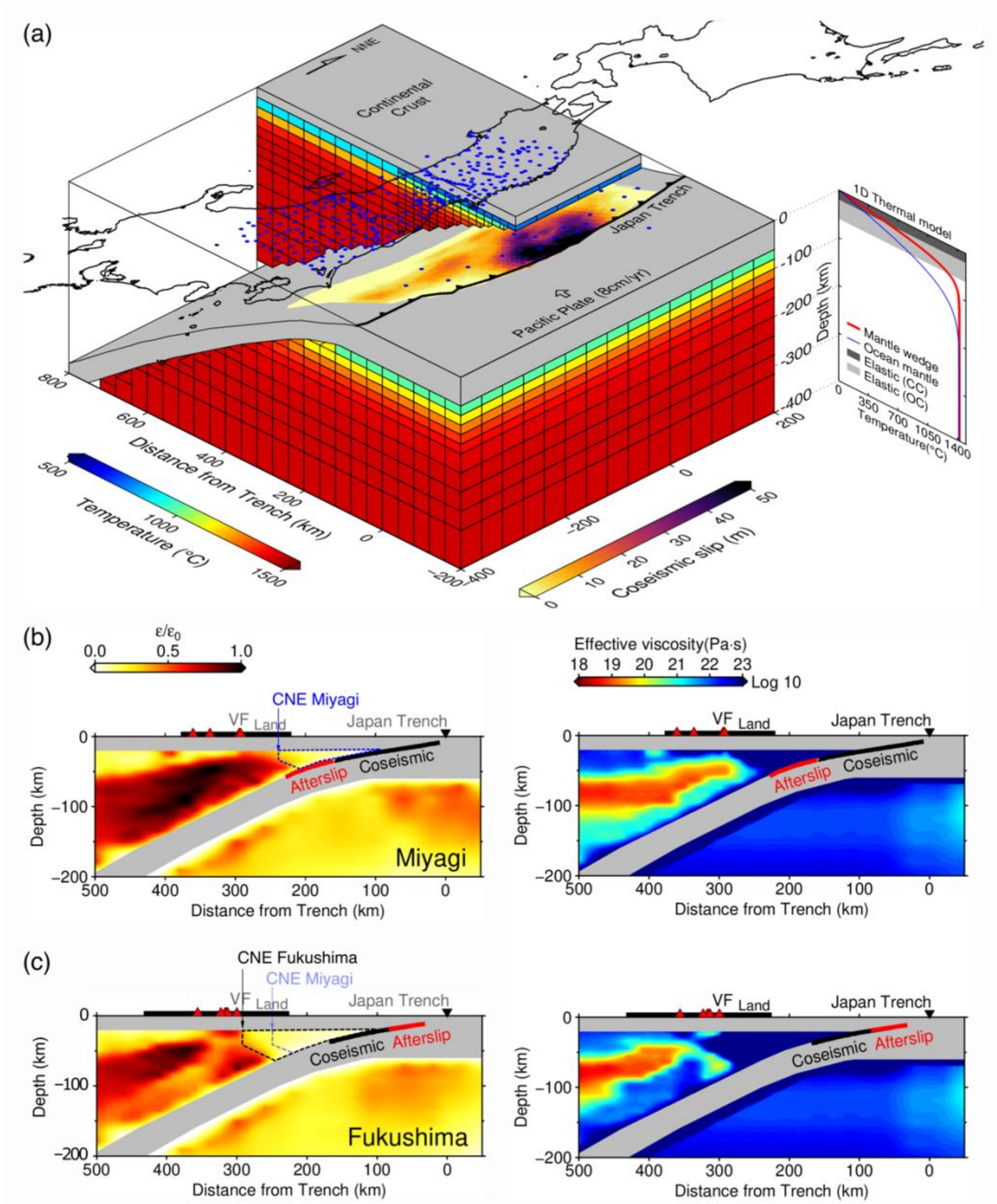

Figure 1. (a) 3-D numerical model with thermal profile (b) Total cumulative strain by viscoelastic relaxation, calculated over ~5 years of postseismic deformation and effective steady-state viscosity profile in the Miyagi-Yamagata transect and (c) the Fukushima-Niigata transect. The cumulative strain is normalized by coseismic stress perturbation.

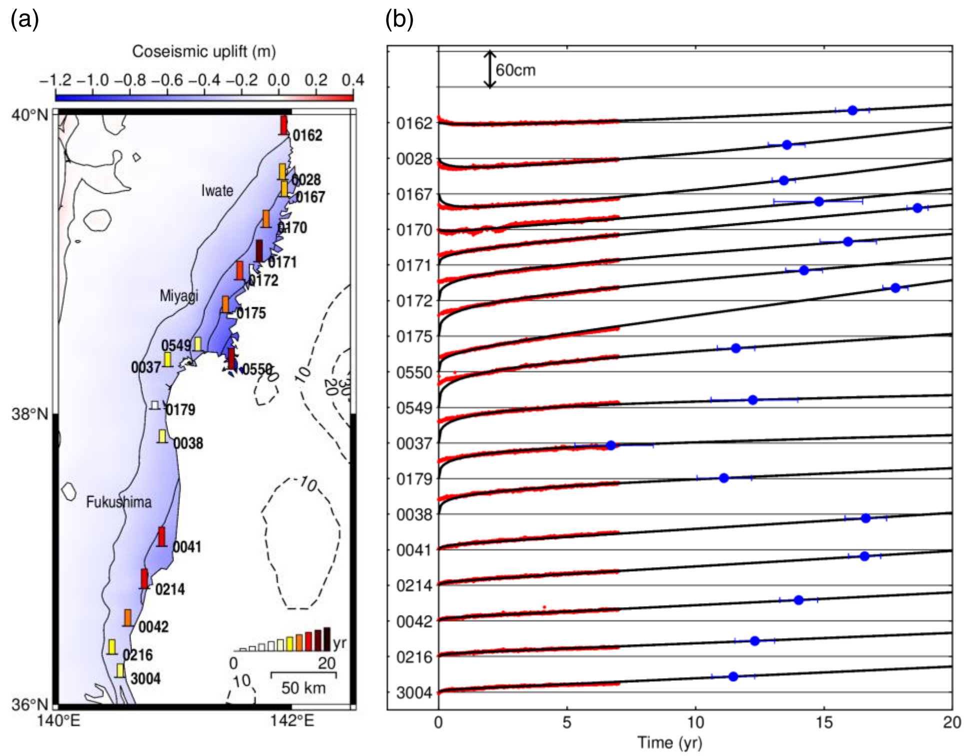

Figure 2: (a) The recovery time for coastal GNSS stations. (b) The observed and modeled time series for twenty years after the mainshock. The blue dot marks the time when coseismic subsidences at the GNSS stations are fully recovered by the postseismic uplift.

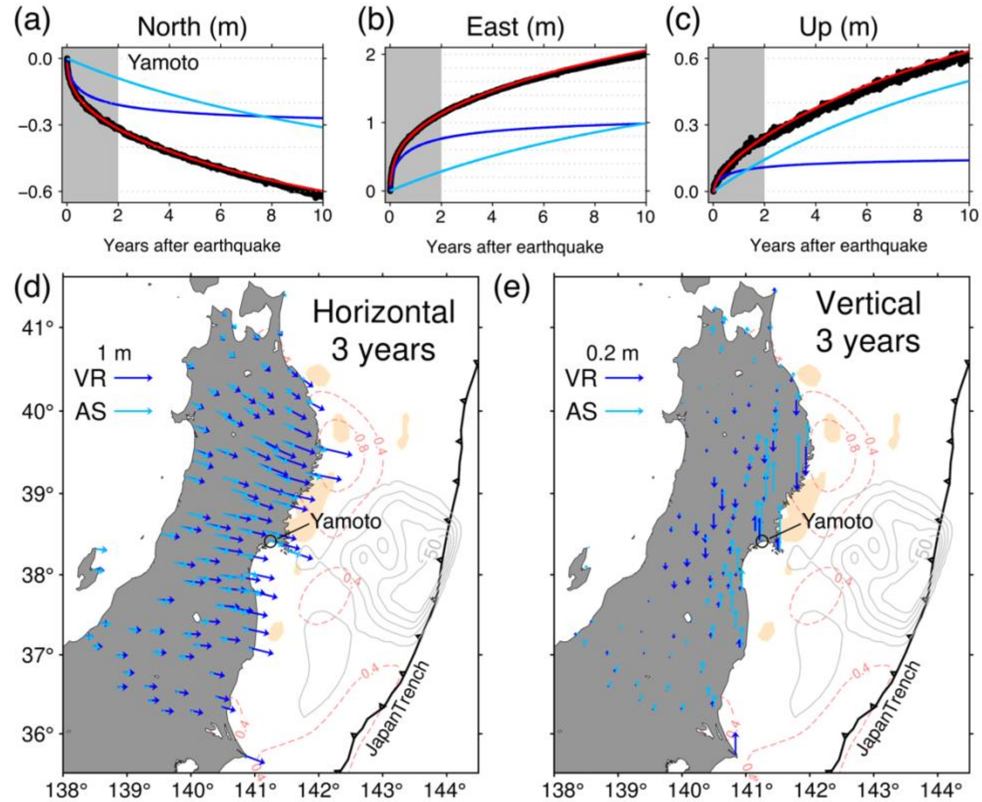

Figure 3: (a) The observed and modeled time series at Yamoto station. (b) The cumulative displacements due to VR and AS in spatial distribution in horizontal and (c) vertical components. The VR and AS represent viscoelastic relaxation (blue) and afterslip (cyan).