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Illuminating 3-D rheology of weak volcanic arc of NE Japan from postseismic deformation of the 2011 Tohoku-oki earthquake

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1. Introduction

Past geodetic studies in the 2000s have indicated localized concentrations of high crustal strain rate along the volcanic front of NE Japan (Miura et al., 2004). These local anomalies of strain rate are often correlated to low viscosity zone (LVZ) beneath the Quaternary volcanoes along the volcanic front of NE Japan. The LVZ refers to the small-scale bodies of weak mantle material in the lower crust-upper mantle. Following the 2011 Mw9.0 Tohoku-oki earthquake, InSAR observations and GNSS analysis detected local ground subsidence in and around the five Quaternary volcanoes of NE Japan: Mt. Akitakoma, Mt. Kurikoma, Mt. Zhao, Mt. Azuma, and Mt. Nasu (Takada & Fukushima, 2013; Muto et al., 2016). Although several studies hypothesized the LVZ causes these local ground deformations beneath Quaternary volcanoes, the dimension and rheology of such LVZ are still poorly understood. Here, we analyzed the GNSS observations after the 2011 Tohoku-oki earthquake and identified localized areas of postseismic strain around the five volcanoes. To explain such localized postseismic strain, we investigated the three-dimensional structure and rheology of LVZs related to the five volcanoes (Dhar et al., 2025).

2. Localization of postseismic strain rate

To understand the spatial distribution of the postseismic strain rate in NE Japan after the 2011 Tohoku-oki earthquake, we extracted the short-wavelength strain rate from the GNSS measurements (2012-2014) provided by GEONET stations. We applied a moving average filter (Meneses-Gutierrez & Sagiya, 2016) to the postseismic GNSS velocity field to remove their long-wavelength components. Then, we used the remaining short-wavelength components to calculate the strain rate field by the method of Shen et al. (1996). The spatial distribution of postseismic strain rate (short-wavelength) illustrates the localization of (dimension of 80 km in both arc-parallel and arc-normal direction) postseismic contraction near five Quaternary volcanoes, embedded in the background of extension (areas marked in blue side of colormap, Figure 1, Dhar et al., 2025). This localization of strain contraction is due to the faster relaxation of coseismic stress changes than the surrounding areas. Such anomaly in stress relaxation rate indicates the presence of low viscous material (as in LVZ), which has a shorter relaxation timescale.

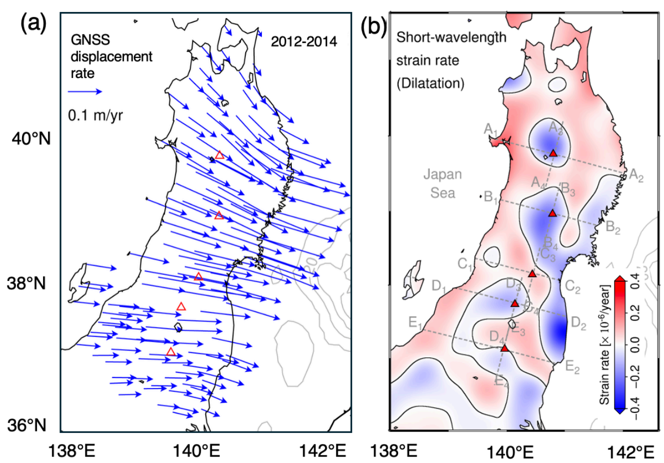

Figure 1: (a) GNSS observations after the 2011 Tohoku-oki earthquake (b) Short-wavelength postseimic strain rate (after Dhar et al., 2025).

3. Three-dimensional LVZ model

To explain the localized postseismic strain near the five Quaternary volcanoes, we constructed the three-dimensional rheological model of LVZ near the five volcanoes (Figure 2). We discretized the LVZ into cuboid elements to calculate the earthquake-induced deformation strain based on the semi-analytical Green's functions (see details in Dhar et al., 2022 and references therein). We consider the LVZ to be a viscoelastic material whose deformation behavior is defined by power-law Burgers rheology. Using the postseismic strain rate as a constrain, we explored the dimension, shape, locations, and effective viscosity of LVZs beneath the five volcanoes. The key findings of our study are as follow: (1) Our results suggest that most LVZs are located at depths of 15 to 55 km in the lower crust-upper mantle. These LVZs may represent viscoelastic heterogeneities which is a deeper extension of shallow elastic heterogeneities (< 5 km) inferred by previous studies (Takada & Fukushima, 2013). (2) Most LVZ models exhibit narrow tops (~20-40 km width) and wider roots (~100 km width). Such arc-normal shape of LVZ is also inferred by past seismological studies (Nakajima et al., 2013). Furthermore, the LVZ shapes vary from volcano to volcano and the LVZ dimensions are limited to ~80 km in arc-parallel direction. Therefore, our result infers an arc-parallel heterogeneity in subsurface rheology along the volcanic front of NE Japan. (3) The effective viscosity of LVZ is estimated to be ~10^{17} Pa·s and ~10^{18} Pa·s in the transient and steady-state postseismic deformation, respectively. The effective viscosity of LVZ (~10^{18} Pa·s) is one order of magnitude lower than the average viscosity of the lower crust-upper mantle.

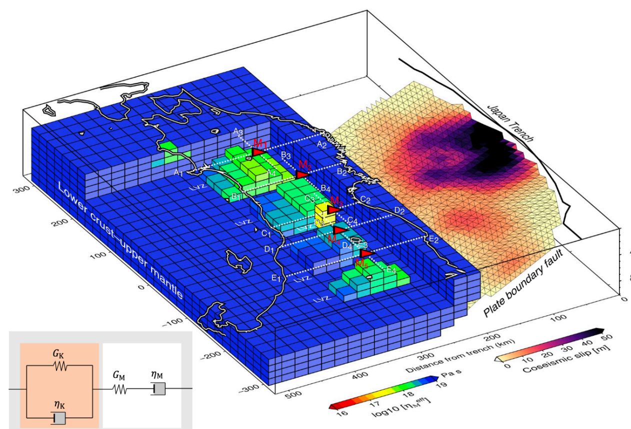

Figure 2: The 3-D rheological model of LVZ near five Quaternary volcanoes (after Dhar et al., 2025). Inset shows the spring-dashspot representation of power-law Burgers rheology model.

4. Conclusion

We found the localized postseismic strain rate near the five Quaternary volcanoes of NE Japan, utilizing the two years of GNSS observations after the 2011 Tohoku-oki earthquake. To explain such localized postseismic strain, we developed a 3-D rheological model of LVZ near those five volcanoes. Our results suggest that these LVZs have narrow tops, wider roots, and ~80-km arc-parallel dimension. They are located at the 15-55 km depth beneath the volcanoes. As their shape and viscosity vary among themselves, they highlight the arc-parallel rheological heterogeneities of the volcanic arc of NE Japan.

5. References

Dhar, S., Takada, Y., & Muto, J. (2025). Inferring 3-D Rheology of Low - Viscosity Zone Around Quaternary Volcanoes of NE Japan From Postseismic Deformation of the 2011 Tohoku - Oki Earthquake. Journal of Geophysical Research: Solid Earth, 130(4), e2024JB029939. https://doi.org/10.1029/2024JB029939

Dhar, S., Muto, J., Ito, Y., Miura, S., Moore, J. D. P., Ohta, Y., & Iinuma, T. (2022). Along-arc heterogeneous rheology inferred from post-seismic deformation of the 2011 Tohoku-oki earthquake. Geophysical Journal International, 230(1), 202–215. https://doi.org/10.1093/gji/ggac063.

Meneses-Gutierrez, A., & Sagiya, T. (2016). Persistent inelastic deformation in central Japan revealed by GPS observation before and after the Tohoku-oki earthquake. Earth and Planetary Science Letters, 450, 366–371. https://doi.org/10.1016/j.epsl.2016.06.055.

Miura, S., Sato, T., Hasegawa, A., Suwa, Y., Tachibana, K., & Yui, S. (2004). Strain concentration zone along the volcanic front derived by GPS observations in NE Japan arc. Earth, Planets and Space, 56(12), 1347–1355. https://doi.org/10.1186/BF03353360.

Muto, J., Shibazaki, B., Iinuma, T., Ito, Y., Ohta, Y., Miura, S., & Nakai, Y. (2016). Heterogeneous rheology controlled postseismic deformation of the 2011 Tohoku - Oki earthquake. Geophysical Research Letters, 43(10), 4971-4978. https://doi.org/10.1002/2016GL068113.

Nakajima, J., Hada, S., Hayami, E., Uchida, N., Hasegawa, A., Yoshioka, S., Matsuzawa, T., & Umino, N. (2013). Seismic attenuation beneath northeastern Japan: Constraints on mantle dynamics and arc magmatism. Journal of Geophysical Research: Solid Earth, 118(11), 5838–5855. https://doi.org/https://doi.org/10.1002/2013JB010388

Shen, Z., Jackson, D. D., & Ge, B. X. (1996). Crustal deformation across and beyond the Los Angeles basin from geodetic measurements. Journal of Geophysical Research: Solid Earth, 101(B12), 27957–27980. https://doi.org/10.1029/96JB02544.

Takada, Y., & Fukushima, Y. (2013). Volcanic subsidence triggered by the 2011 Tohoku earthquake in Japan. Nature Geoscience, 6(8), 637–641. https://doi.org/10.1038/ngeo1857.