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The Impact of 3D Elastic Structure on Estimates of Megathrust Frictional Properties Derived from Earthquake Cycle Inversions of Pre- and Post-2011 Tohoku-oki Earthquake GNSS Observations

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The evolution of the shear traction at plate interfaces is a key input to seismic hazard assessments, as it relates rheological properties of the interface material to the slip history of the fault. However, at the relevant spatial scales, shear tractions can only be modelled indirectly, with kinematic coupling commonly used as a proxy for inferring any slip deficit that drives seismic hazard. When the 2011 Mw 9.1 Tohoku-oki earthquake ruptured the Northern Japanese megathrust, it did so in an area where simplified models estimated low-to-medium kinematic coupling (Uchida and Bürgmann, 2021).

The reliance on kinematic coupling for seismic hazard assessment could be reduced if instead the long-term slip budget (or equivalently, the shear stress history) could be estimated for a given fault zone. Such a method, in turn, would require the definition of specific constitutive laws in order to simulate multiple earthquake super-cycles, as well as an inversion independent of initial conditions. We have built such a scheme building on previous work (Kanda and Simons, 2010; Hetland and Simons, 2010; Kanda et al., 2013; Mallick et al., 2022; Köhne et al., in press). Our approach assumes that the plate interface is divided into fully-locked asperities surrounded by regions of the fault interface characterized by rate-dependent friction. We impose a historically realistic rupture timeline for each of the assumed asperities, but let the remaining fault interface evolve freely otherwise according to its mechanical properties, until it obtains cycle-invariance. After reaching the time period where GNSS observations of the region exist, we calculate the residuals to surface displacement timeseries, and use a Bayesian inference approach to estimate the best-fit frictional parameters. This inference is sensitive to our inherent ignorance of the elastic structure of the area around the plate interface. Therefore, we extend our framework to assess the impact of such heterogeneity.

We present results from our updated Northern Japanese subduction zone model, where we consider both pre- and post-2011 Tohoku-oki earthquake GNSS surface displacement observations. We first show, using a homogeneous halfspace model, how estimates of slip deficit and kinematic coupling differ. We also find that the product of the rate-dependent frictional

parameter (a-b) with effective normal stress generally decreases with depth. We then show how these conclusions change after considering the more realistic 3D elastic structure of Hashima et al. (2016), who have shown the importance for the coseismic fault slip and associated surface deformation (Hsu et al., 2011; Ragon and Simons, 2023). The structure includes depth-varying elastic moduli for the continental plate, down going slab, and mantle. Using PyLith, we calculate the relevant stress and displacement kernels for our earthquake simulation framework. Our model results provide important perspectives for future seismic hazard assessments and postseismic studies of rheological properties.