Originally published as:

Li, S., Fukuda, J., Oncken, O. (2020): Geodetic Evidence of Time-Dependent Viscoelastic Interseismic Deformation Driven by Megathrust Locking in the Southwest Japan Subduction Zone. - *Geophysical Research Letters*, 47, 4.

<https://doi.org/10.1029/2019GL085551>

Geophysical Research Letters

RESEARCH LETTER

10.1029/2019GL085551

Key Points:

- Leveling and global navigation satellite system (GNSS) data from the southwest Japan subduction zone indicate interseismic viscous mantle flow due to megathrust locking
- A steady-state continental mantle viscosity of $\sim 10^{19}$ Pa-s is required to explain both the leveling and GNSS data
- The GNSS-derived velocity field represents a snapshot of time-varying interseismic deformation

Supporting Information:

- Supporting Information S1

Correspondence to:

S. Li,
shaoyangli@eri.u-tokyo.ac.jp

Citation:

Li, S., Fukuda, J., & Oncken, O.. (2020). Geodetic evidence of time-dependent viscoelastic interseismic deformation driven by megathrust locking in the southwest Japan subduction zone. *Geophysical Research Letters*, 47, e2019GL085551. <https://doi.org/10.1029/2019GL085551>

Received 25 SEP 2019

Accepted 6 FEB 2020

Accepted article online 10 FEB 2020

Geodetic Evidence of Time-Dependent Viscoelastic Interseismic Deformation Driven by Megathrust Locking in the Southwest Japan Subduction Zone

Shaoyang Li¹ , Jun'ichi Fukuda¹ , and Onno Oncken²

¹Earthquake Research Institute, The University of Tokyo, Tokyo, Japan, ²Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, Potsdam, Germany

Abstract The time-variable features of interseismic deformation in subduction zones are poorly understood and commonly ignored. Here, by incorporating century-long leveling data and contemporary global navigation satellite systems (GNSS) velocities, we investigate the temporal evolution of interseismic deformation in southwest Japan using two-dimensional viscoelastic earthquake-cycle models. We find that a steady-state continental mantle viscosity of 10^{19} Pa-s is required to explain these two geodetic data sets. Our preferred model predicts significant variations in the surface velocity field throughout the entire interseismic period due to viscous mantle flow driven by ongoing megathrust locking, indicating that the multiyear GNSS-derived velocity field represents a snapshot of time-varying interseismic deformation. The locking depth and locking time exert significant influences on the horizontal and vertical deformation patterns. Our findings highlight the importance of the interseismically relaxing mantle and the necessity of considering such an effect in determining the current locking state along the Nankai subduction zone.

Plain Language Summary Interseismic viscoelastic relaxation due to megathrust fault locking is explored recently using a viscoelastic Earth model for the late-stage interseismic period in the Cascadia and Peru-North Chile subduction zones, where the last great earthquake occurred centuries ago, and the next event is expected in the near future. In southwest Japan, the last great earthquake occurred only several decades ago, providing a unique opportunity to study the viscoelastic relaxation in early-stage interseismic period. We use historical measurements of uplift rates that were acquired before and after the last great earthquake and modern geodetic measurements of the horizontal and vertical surface velocities to constrain our numerical models and investigate how and why the surface deformation varies throughout the long interseismic period. We find that the horizontal and vertical velocity field gradually evolves into a long-wavelength pattern and a rather flat pattern, respectively, before the next event, which is consistent with both the historical and recent observations. Therefore, the recent and short time geodetic measurements in southwest Japan represent a snapshot of the time-variable signal because the weak Earth mantle is flowing viscously, driven by persistent megathrust fault locking, and the flow has not achieved a steady state.

1. Introduction

Understanding the time dependence of surface deformation associated with subduction zone earthquakes and megathrust locking is fundamental to validating hypotheses of Earth rheology (e.g., Bürgmann & Dresen, 2008; Christensen, 1982) and earthquake-cycle models (e.g., Govers et al., 2018; Sobolev & Muldashev, 2017; Wang et al., 2012). During the interseismic period, wholesale landward motion is observed by geodetic instruments on the continental side of the subduction zone, which is unambiguously delineated as the interseismic deformation pattern caused by megathrust locking, in contrast to the wholesale (or predominant) seaward motion during the coseismic and postseismic periods driven by megathrust earthquakes (Wang et al., 2012). The deformation rate measured in a few years of interseismic period is commonly assumed to be constant and is modeled with a time-independent elastic solution (e.g., Okada, 1985) due to megathrust fault locking between the downgoing oceanic plate and overriding continental plate (e.g., Bürgmann et al., 2005; Chlieh et al., 2008; Mazzotti et al., 2000; McCaffrey et al., 2007; Métois et al., 2012; Moreno et al., 2011; Wallace et al., 2004). In a viscoelastic Earth, stresses slowly built up due to megathrust fault locking are relaxed concurrently and drive slow viscous flow in the asthenosphere during the interseismic period (time scale of centuries) (Wang et al., 2012). As a result, the viscoelastic asthenosphere offers less

resistance to deformation from megathrust locking than an elastic Earth, forming a long-wavelength deformation pattern. To explain this widespread viscoelastic signal, elastic Earth models need to either deepen the downdip extent of the locked zone to a physically unreasonable depth or attribute the far-field signals to long-term geological deformation (Li et al., 2015). In the Peru-North Chile and Cascadia subduction zones, where the last great- to giant-magnitude ($>M8.5$) megathrust earthquakes occurred centuries ago, the interseismic viscoelastic relaxation has been found to be nearly in a steady state (i.e., the deformation rate does not change significantly with time), reflecting the deformation pattern in the late-stage interseismic period (Li et al., 2015, 2018). Yet, the temporal variability in surface deformation during the early-stage (when the postseismic transient has almost vanished) to late-stage (when the next event is about to occur) interseismic period is largely unexplored in these and other subduction zones with proper geodetic constraints.

The southwest Japan subduction zone provides an unparalleled opportunity to understand the time evolution of interseismic deformation caused by megathrust locking, owing to a globally unique geodetic data set available in this region. Here, the Philippine Sea Plate subducts beneath the Amurian Plate at the Nankai Trough (Figure 1), repeatedly producing great-magnitude ($>M8$) megathrust earthquakes (Ando, 1975; Ishibashi, 2004), with the most recent events being the 1944 Mw 8.1 Tonankai and 1946 Mw 8.3 Nankai earthquakes. A leveling survey was first conducted across Shikoku Island during the 4 decades leading up to the 1944/1946 earthquakes, followed by two repeat surveys in the decades after these two events (Thatcher, 1984). These three surveys have revealed distinct patterns of vertical deformation during the late-stage interseismic and postseismic periods. Because of these observations, the southwest Japan is the only region in the world with an instrumental geodetic record that spans the time scale of a full earthquake cycle. Furthermore, this region is covered by a dense and continuous global navigation satellite system (GNSS) network that has been in operation since the mid-1990s (Sagiya et al., 2000). Postseismic viscoelastic relaxation driven by the last events, which endured for approximately 5 decades following the 1944/1946 earthquakes (Johnson & Tebo, 2018), was likely fully vanished by the time the GNSS network was installed, as all of the GNSS stations have been recording landward motions to date, representing an early-stage interseismic deformation of the subduction zone. Therefore, these two data sets together provide globally unique constraints on the temporal evolution of surface deformation during the entire interseismic period.

Recent studies of interseismic deformation in southwest Japan generally incorporated only the GNSS observations and assumed that these observations were time-independent using either a purely elastic Earth model (e.g., Liu et al., 2010; Loveless & Meade, 2016; Nishimura et al., 2018; Yoshioka & Matsuoka, 2013) or a steady-state viscoelastic Earth model with a fully relaxed mantle (e.g., Noda et al., 2018). Conversely, our study aims to reconcile the leveling and GNSS data using viscoelastic earthquake-cycle models to better understand the underlying mechanism of time-dependent interseismic deformation in southwest Japan and potentially other subduction zones. We investigate how megathrust locking and associated viscous mantle flow influence the time-dependent patterns of interseismic deformation by comparing the models with both the leveling and GNSS data. Our models highlight that the GNSS-derived velocity field in southwest Japan, as reported in previous studies, only represents a snapshot of time-variable interseismic deformation due to a viscoelastically relaxing mantle that is driven by ongoing megathrust locking.

2. Geodetic Data

We consider a representative 100-km-wide margin-normal swath profile across the Nankai subduction zone to explore the viscoelastic deformation in southwest Japan (Figure 1). This profile is chosen because it passes through the main source area of the 1946 Nankai Earthquake (Sagiya & Thatcher, 1999) and overlaps a (quasi-margin-normal) route of historical leveling measurements across Shikoku Island (Figure 1). These measurements were made from the 1890s to 1970s, spanning almost an entire earthquake cycle. Thatcher (1984) used these measurements to derive the vertical displacements along the leveling route for the three time spans of interseismic and postseismic periods: the 5 decades prior to the 1946 event (i.e., 1896–1935, late-stage interseismic period), the 2 decades after the event (i.e., 1947–1964, postseismic period), and more than 2 decades after the event (i.e., 1964–1979, late-stage postseismic or early-stage interseismic period). Here we incorporate the smoothed uplift rates for each time span that were obtained by Wang and Tréhu (2016) (Figure 2d), which were derived from these vertical displacements. These curves are subject to an arbitrary vertical shift because the leveling measurements represent relative elevation changes (Wang &

Figure 1. Tectonic setting of the Nankai subduction zone. The inset at lower left shows the location of the study area (red rectangle) in southwest Japan. In the main figure, black vectors represent the horizontal GNSS velocities relative to the stable Eurasian Plate (Nishimura et al., 2018). Red and blue squares indicate uplift and subsidence rates, respectively. The purple curve shows the location of the historic leveling route (Thatcher, 1984). Yellow shading indicates the source regions of the 1946 Nankai and 1944 Tonankai megathrust earthquakes (Sagiya & Thatcher, 1999). Green shading represents possible regions of short-term slow slip events during 1996–2012 (Nishimura et al., 2013), and green dots indicate tremors observed during 2006–2009 (Obara et al., 2010). Black dashed lines denote the location of the swath profile. The gray dashed lines are depth contours of the plate interface at 10-km intervals, from Slab 2.0 (Hayes et al., 2018), and the solid black line shows the location of the slab geometry for the finite-element models.

Tréhu, 2016); therefore, we primarily use them to evaluate the first-order performance of our viscoelastic models. Nevertheless, these uplift rates clearly show distinct time-variable features (Figure 2d), including a high rate of uplift immediately after the 1946 Nankai Earthquake, with steep slopes on both sides of the crest of the uplift rate curve across Shikoku Island (blue curve); a decreasing uplift rate that exhibits a rather flat pattern more than 2 decades after the event (green curve); and an even flatter uplift rate curve in the late-stage interseismic period prior to the 1946 Nankai Earthquake (red curve).

Since the mid-1990s, GNSS data have successfully captured the linear trend of surface displacement, as well as the subtle deformation due to slow slip events, in southwest Japan (e.g., Nishimura et al., 2013). Here we use the inland velocity field reported by Nishimura et al. (2018), which was derived from the GNSS network (Figure 1), to quantitatively constrain our models. These velocities are estimated from the 2005–2009 period

(i.e., 59–63 years after the 1946 Nankai Earthquake) with seasonal signals removed and defined with respect to a stable Eurasian Plate reference frame (Nishimura et al., 2018). This time period is chosen because it is free of large earthquakes (especially the 2011 Mw 9.0 Tohoku-oki earthquake) and transient events. The velocity field is therefore considered a representative snapshot of the interseismic period and shows systematic spatial patterns in the horizontal and vertical components (Figure 1). All of the stations capture northwestward (landward) horizontal motions, and their velocities gradually decrease away from the trench, with the profile-parallel horizontal velocity decreasing from ~50 mm/year near the Pacific coast to ~4 mm/year near the Sea of Japan coast (top panel of Figure 2b). The stations exhibit significant subsidence in the coastal area closest to the trench (6 mm/year maximum), prevalent uplift across most of Shikoku Island (6 mm/year maximum), and gentle subsidence across most of Honshu Island (1–2 mm/year), forming a long-wavelength flexure pattern in the trench-normal direction (bottom panel of Figure 2b).

3. Viscoelastic Earthquake-Cycle Models

We construct our two-dimensional viscoelastic earthquake-cycle models using the open-source finite-element code *PyLith* (Aagaard et al., 2013). Unlike previous viscoelastic earthquake-cycle models (e.g., Ito & Hashimoto, 2004; Matsu'ura & Sato, 1989; Pollitz et al., 2010; Savage & Thatcher, 1992; Thatcher & Rundle, 1984), which assumed an elastic layer over a (layered) Maxwell viscoelastic substrate, our models include an elastic slab that penetrates into the Maxwell viscoelastic mantle asthenosphere, with the modeled subduction system consisting of four domains (Supporting Information Figure S1): the elastic continental plate, the elastic oceanic plate, the viscoelastic continental mantle (including mantle wedge), and the viscoelastic oceanic mantle. By doing so, our models incorporate a first-order control of the slab on the viscous mantle flow during the earthquake cycle, such that the viscous flow in the mantle wedge is anchored by the stiff slab (i.e., the viscous flow cannot penetrate the slab) and surface deformation on the continental plate is retarded against more extensive motion during the interseismic and postseismic periods (e.g., Li et al., 2015; Melosh & Fleitout, 1982; Miyashita, 1987; Pollitz et al., 2008; Sun & Wang, 2015; Trubienko et al., 2013).

The rigidity values of the elastic plates and mantle are assumed to be 48 and 64 GPa, respectively, and the Poisson ratio is assumed to be 0.25 throughout the model domain, following Wang et al. (2012). We explore the continental mantle viscosity within the reasonable 10^{18} – 10^{20} Pa-s range (Walcott, 1973) because inland surface deformation is sensitive to the continental mantle rheology. The oceanic mantle viscosity has a smaller impact on inland deformation and is therefore fixed at 10^{20} Pa-s, following Wang et al. (2012). Our model domain is set 2,000 km wide and 500 km deep (Figure S1). The thicknesses of the oceanic and continental plates are both set to 30 km, following the estimates of Yoshioka and Ito (2001) and Kudo et al. (2001) in the vicinity of the swath profile (Figure 1). The slab geometry is retrieved from the Slab 2.0 model (Hayes et al., 2018). The displacements that are perpendicular to the lateral and bottom model boundaries are fixed to zero, and the displacements that are parallel to these boundaries are not constrained. The top boundary is set as a free boundary. We tested these boundary conditions and found no biasing influence on the model results.

To model the first-order deformation processes of viscoelastic earthquake cycles, we simulate megathrust locking and periodic earthquakes in a kinematic fashion in the viscoelastic Earth. Megathrust locking is assumed to be constant throughout all the earthquake cycles and is simulated using the backslip method (Savage, 1983). We simplify the problem and focus on the first-order control of megathrust locking on inland deformation by using only one free parameter (i.e., the full locking depth, hereafter termed the “locking depth” for simplicity) to characterize the locking ratio distribution on the megathrust interface. Specifically, the locking ratio is assumed to have a value of 1 from the surface to the locking depth and transitions to 0 within 10 km in the downdip direction, following Wang et al. (2003) (e.g., Figure S2). Megathrust locking for a given locking depth is then simulated by kinematically imposing a backslip rate distribution that is equal to the locking ratio distribution multiplied by the profile-parallel convergence rate (63.3 mm/year; Nishimura et al., 2018). The stress changes due to megathrust locking deform the Earth in vicinity of the megathrust fault and drive interseismic viscoelastic relaxation (viscous flow) in the mantle (Li et al., 2015; Wang et al., 2012). Figure S3 shows an example of model predictions of viscoelastic surface deformation due to only the locking of megathrust fault.

All of the accumulated slip deficit is modeled to be suddenly released in an ensuing earthquake at a fixed recurrence interval of 150 years, with this interval based on the quasi-periodic occurrence of great

Figure 2. (a)–(c) Model-predicted time-dependent surface velocities (colored curves) for a locking depth of 30 km and continental mantle viscosities of (a) 10^{18} , (b) 10^{19} , and (c) 10^{20} Pa-s, compared with the GNSS-derived velocities (black dots with error bars). The colored curves are plotted at 5-year intervals, with the colors representing the elapsed time since the last earthquake. (d) Smoothed uplift rates derived from historic leveling data across Shikoku Island during the color-coded survey time spans (adapted from figure 7b of Wang & Tréhu, 2016).

earthquakes every ~150 years in the southwest Japan subduction zone (Ando, 1975; Ishibashi, 2004). The megathrust earthquake (stretching the continental mantle) drives transient seaward postseismic viscous flow in the mantle in the opposite sense of landward interseismic viscous flow driven by megathrust locking (compressing the continental mantle). Postseismic viscous flow decays with time as the coseismic stress perturbation is relaxed, and its duration depends on the earthquake size (Wang et al., 2012), which is about 5 decades for Nankai case (Johnson & Tebo, 2018). The postseismic deformation is then overwhelmed by the viscoelastic interseismic deformation as the locking process continues, forming one complete cycle of earthquake deformation. Therefore, viscous flows driven by coseismic ruptures and megathrust locking are both included in our earthquake-cycle models. By running a number of earthquake cycles, the temporal evolution of the surface velocity field within each cycle reaches to a cycle-independent stable fashion (Hetland & Hager, 2006) (Figure S4). We use the fully stabilized modeling results in the eleventh earthquake cycle for comparison with the geodetic observations.

In the following section, we first construct viscoelastic earthquake-cycle models with a fixed and physically reasonable locking depth (i.e., 30 km) and different continental mantle viscosities to initially investigate the time dependence of the surface velocity field. We then vary the locking depth using a fixed and physically preferred continental mantle viscosity (i.e., 10^{19} Pa-s) to explore the influences of locking depth and megathrust locking duration on both the horizontal and vertical model-predicted surface deformation patterns and to determine the best fit to the GNSS velocities.

4. Results

4.1. Influence of Viscoelastic Continental Mantle on the Time Dependence of Surface Velocity Field

We first investigate the temporal evolution of the surface velocity field predicted by the viscoelastic earthquake-cycle models using different values of continental mantle viscosity (10^{18} , 10^{19} , and 10^{20} Pa-s) and a fixed locking depth and compare the model predictions with both the leveling and GNSS data (Figure 2). Given the young age of the subducting plate and the warm thermal regime of the southwest Japan subduction zone (Hyndman et al., 1995), we employ a typical and physically reasonable locking depth of 30 km. The modeling results show that the two orders of magnitude variation in the continental mantle viscosity yields significant differences in the time dependence of the interseismic surface deformation rates in both the horizontal and vertical directions, such that the weaker (stronger) continental mantle yields a faster (slower) temporal variation in deformation rate (Figures 2a–2c). The weak continental mantle (10^{18} Pa-s) also leads to fast temporal stabilization (~50 years after the earthquake) of surface deformation into a long-wavelength pattern (Figure 2a); the strong continental mantle (10^{20} Pa-s), in contrast, results in

Figure 3. (a) Model misfit map as a function of full locking depth and locking time. The black contour represents the upper root mean square error (RMSE) bound (3 mm/year). The gray curve indicates the nonlinear trend of the model parameter tradeoff. (b, c) Five specific examples (white squares with coordinates shown in Figure 3a) of the simulated surface velocities (curves), which are compared with the GNSS observations (black dots with error bars) in both the (b) horizontal and (c) vertical directions. In the legend, D and T stand for locking depth and locking time, respectively, and numbers denote the two parameter values for each simulation.

insignificant variation of surface deformation during the entire postseismic and interseismic periods (Figure 2c). Only the model with a continental mantle viscosity of 10^{19} Pa·s produces a first-order similarity between the model-predicted temporal variation of vertical velocities and leveling observations (Figures 2b and 2d). Furthermore, both the horizontal and vertical GNSS velocity patterns are best reproduced by the model prediction for ~60 years after the simulated earthquake (greenish to yellowish curves in Figure 2b), with this timing being similar to the elapsed time between the 1946 Nankai Earthquake and GNSS measurements (59–63 years).

Hereafter, we describe the time-dependent features of our preferred model with a continental mantle viscosity of 10^{19} Pa·s (Figure 2b). Within a few decades after the earthquake, the coastal and inland areas show landward and seaward motions in the horizontal component (blue curves in the top panel of Figure 2b) due to contributions from both plate reloading and postseismic viscoelastic relaxation (Wang et al., 2012). The dividing boundary of landward and seaward motion (i.e., the intersection point of the velocity curve and the horizontal axis in the top panel of Figure 2b) then migrates to the far-field area at an accelerating rate (Figure S5). Around 6 decades after the earthquake, the wholesale motion is primarily landward and comparable to the GNSS velocities, indicating the dominance of interseismic locking processes and the completion of the postseismic transient. This preferred model further predicts that the horizontal velocity continues to increase due to ongoing interseismic viscous flow that amplifies the deformation rates, particularly in the far field, until the occurrence of the next great event (i.e., yellowish and reddish curves in the top panel of Figure 2b).

The vertical velocity field predicted by this model shows a rapid uplift rate across Shikoku Island (150–250 km from the trench) and slow subsidence rate across Honshu Island (300–400 km from the trench) in the first few decades after the earthquake (blue curves in the bottom panel of Figure 2b). The vertical rate then decays gradually, reproducing the contemporary GNSS measurements at 6 to 7 decades after the event quite well. The vertical rate continues to evolve into a rather flat and stabilized pattern during the late-interseismic period (i.e., reddish curves in the bottom panel of Figure 2b). Such a temporal evolution of the model-predicted vertical rates is consistent with the three snapshots of the uplift rate patterns derived from the century-scale leveling measurements over the deformation cycle of the 1946 Nankai Earthquake (Figure 2d).

4.2. Influences of Locking Depth and Locking Time on the Pattern of Surface Deformation

We then explore the influences of the locking depth and locking time (i.e., the duration of interseismic viscoelastic relaxation due to megathrust locking, or, equivalently, the time since the last earthquake), on both the horizontal and vertical components of the model-predicted surface deformation patterns by fixing the continental mantle viscosity to 10^{19} Pa·s based on the fit to the GNSS data (Figure 3). We place equal weights on the horizontal and vertical components and calculate the misfit between the observed and model-predicted velocities in terms of their root mean square errors, which clearly indicates a tradeoff between these two parameters (gray curve in Figure 3a), such that the model with a relatively shallow locking depth and longer locking time fits the data similarly well to the model with a relatively deep locking depth and

shorter locking time. Even though, the optimal parameter space for the locking depth and locking time is identified as the models that explain the GNSS velocities with low root mean square errors. For simplicity, we consider an upper bound root mean square error of 3 mm/year (black contour in Figure 3a) as the threshold for determining the optimal parameter space. This upper bound yields optimal locking depth and locking time ranges of 25–30 km and 60–80 years, respectively.

We further present five examples to illustrate the model sensitivity of the locking depth and locking time to the shapes of both the horizontal and vertical components of the predicted surface velocity curves (Figures 3b and 3c), including the optimal model (65-year locking time and 27.5-km locking depth) that provides the best fit to the horizontal and vertical GNSS velocity fields. The importance of locking time on horizontal surface velocity increases with increasing distance from the trench, such that the impact is weakest in the forearc region (100–200 km from the trench) and strongest in the backarc region (300–400 km from the trench) (solid curves in Figure 3b). Conversely, the locking depth has a broad influence on the inland velocities and a weak influence in the backarc region (red curves in Figure 3b). The locking depth controls the trench distance of the peak uplift signal (red curves in Figure 3c), and the locking time primarily influences the magnitude of the vertical velocities (solid curves in Figure 3c).

5. Discussion and Conclusions

In this study, we first explore the impacts of continental mantle viscosity (10^{18} , 10^{19} , and 10^{20} Pa·s) on the time dependency of surface deformation over the earthquake cycle (Figure 2). The modeled system with a viscosity of 10^{20} Pa·s behaves most elastically and results in insignificant temporal variation in surface deformation similar to the time-independent elastic solutions (e.g., Okada, 1985) (Figure 2c), while the system with a viscosity of 10^{18} Pa·s results in fast temporal variation in surface deformation and the interseismic deformation rates are predicted to be stabilized in ~50 years following the last great earthquake into a long-wavelength pattern in the horizontal direction (red curves in Figure 2a), in agreement with previous earthquake-cycle models employing the same order of viscosity values for the interseismic period (e.g., Govers et al., 2018; Sobolev & Muldashev, 2017). Time-variable features of interseismic surface deformation predicted by such high or low continental mantle viscosities seem contradictory to the leveling and GNSS observations (Figure 2). Only the system with the preferred viscosity of 10^{19} Pa·s predicts well the first-order temporal variation of leveling data and quantitatively explains the GNSS velocities and the elapsed time between the last great earthquake and GNSS measurements (Figure 2b). However, models with a viscosity of 10^{18} or 10^{19} Pa·s both predict a long-wavelength horizontal deformation pattern in the late-interseismic period; it may be therefore ambiguous to constrain the lower bound of mantle viscosity with only the late-interseismic horizontal observations (Li et al., 2015, 2018).

Our preferred viscosity is lower than the global average value of 10^{20} – 10^{21} Pa·s (e.g., Moucha et al., 2007) but supported by the presence of aqueous fluids released from the dehydrating slab in the mantle wedge (e.g., Billen & Gurnis, 2001; Bürgmann & Dresen, 2008; Hirth & Kohlstedt, 2004; Thatcher & Pollitz, 2008; Wang et al., 2012 and references therein). With this viscosity, our model predicts that persistent megathrust locking will continuously drive interseismic viscous flow in the mantle until the next megathrust earthquake occurs. Such flow amplifies the far-field deformation rate, which leads to a marked increase in the wavelength of the horizontal velocity field during the entire interseismic period (top panel of Figure 2b), such that the surface velocities in the backarc region are sensitive to the duration of megathrust locking (Figure 3b). Furthermore, these velocities are insensitive to megathrust locking depth due to their distance to the plate interface (Figure 3b). For a viscoelastic Earth model, the horizontal deformation during the late-stage interseismic period has a much longer wavelength than that predicted by purely elastic Earth models with physically reasonable locking depths (Figure S6). Elastic models would therefore tend to overestimate the locking depth in the late-stage interseismic period, as demonstrated in previous case studies in North Chile and Cascadia (Li et al., 2015, 2018).

While the vertical motions during the postseismic and interseismic periods are more difficult to interpret, they potentially provide diagnostic information for elucidating the underlying deformation mechanisms. Our model predicts rapid uplift across Shikoku Island immediately after the earthquake, which is consistent with the historical leveling observations (blue curves in the bottom panel of Figures 2b and 2d). The vertical deformation field gradually evolves into a rather flat pattern during the interseismic period, which is also

consistent with the leveling observations (green and red curves in the bottom panel of Figures 2b and 2c) and first-order predictions of previous viscoelastic models (e.g., Matsu'ura & Sato, 1989; Savage & Thatcher, 1992; Thatcher & Rundle, 1984). However, these previous models, as well as our models in this study (despite model misfits within the observational errors), do not appear to fit the vertical motion in great detail (Figure 3c) possibly because of the large uncertainty in the vertical observations, the heterogeneous viscosity structure (e.g., Li et al., 2017; Muto et al., 2016), unclear geological and geodynamic processes, which may cause unrecoverable permanent deformation at the earthquake-cycle time scale (e.g., Wang & Tréhu, 2016), and even some unknown physical processes across multiple space and time scales. These complexities indicate the need for further studies and a reconsideration of the simplifications employed in current models. To do this, inversion techniques and better-quality data might be also necessary. Nevertheless, the trench distance of the peak uplift signal is sensitive to the locking depth (Figure 3c) (e.g., Savage, 1983) and may provide a direct constraint on this parameter.

Our optimal model has a locking time of 65 years (Figure 3a), which is in good agreement with the elapsed time between the 1946 Nankai Earthquake and the GNSS measurements (i.e., 2005–2009), indicating rapid relocking after the megathrust earthquake (e.g., Bedford et al., 2016). Furthermore, the optimal locking depth (i.e., 25–30 km, Figure 3a) is relatively shallow, similar to that along the Cascadia subduction zone (e.g., Li et al., 2018; Wang et al., 2003) and consistent with the warm thermal state of this young subduction zone (Hyndman et al., 1995). However, a tradeoff between the continental mantle viscosity and locking depth exists when fitting the GNSS data. A higher value of continental mantle viscosity leads to a slower variation in the interseismic deformation rate for a constant locking depth (Figure 2) and subsequent broader range of optimal locking times (Figure S7). Therefore, more accurate constraints on the continental mantle viscosity are important for quantifying the megathrust locking state in future study.

Our study suggests that it is potentially misleading to assume a completely relaxed viscoelastic mantle when studying contemporary interseismic deformation in southwest Japan. Interpretations of the contemporary pattern of horizontal deformation in southwest Japan using a fully relaxed viscoelastic model may lead to underestimations of the locking depth and/or slip-deficit rate because the horizontal deformation rates are predicted to continuously increase when the mantle is undergoing interseismic relaxation (top panel of Figure 2b). Our results therefore suggest that it is necessary to re-evaluate the assumption of a fully relaxed mantle in southwest Japan in previous studies (e.g., Noda et al., 2018). Furthermore, the effects of the interseismically relaxing mantle driven by megathrust locking on surface deformation should be considered in locking determinations of some other subduction zones where great megathrust events have occurred a few decades ago, such as the subduction zones that caused the 1964 Alaska Earthquake (e.g., Li et al., 2016) and 1960 Valdivia Earthquake in South Chile (e.g., Moreno et al., 2011).

Future studies should seek to identify the surface velocity variation due to interseismic viscoelastic relaxation from over 2 decades (from the mid-1990s to the present day) of continuous GNSS records in southwest Japan (e.g., Sagiya & Kawashima, 2017). A key challenge to do this is the robust retrieval of the interseismic deformation field from the GNSS time series since it was strongly disturbed by the 2011 Tohoku-oki earthquake (e.g., Ozawa et al., 2011) and multiple slow slip events (e.g., Nishimura et al., 2013). Another challenge is separating the signal due to temporal variations in the kinematics along the plate interface, such as spatial variations in the locking distribution (e.g., Liu, 2013; Loveless & Meade, 2016; Nishimura et al., 2004) and aseismic slip along the plate interface (e.g., Mavrommatis et al., 2014; Meltzner et al., 2015). Despite these challenges, we believe that a longer time span of continuous GNSS monitoring in future will assist in detecting temporal variations in surface velocity, especially in the far field, which will be particularly useful in constraining the continental mantle viscosity and therefore the state of megathrust locking.

References

- Aagaard, B. T., Knepley, M. G., & Williams, C. A. (2013). A domain decomposition approach to implementing fault slip in finite-element models of quasi-static and dynamic crustal deformation. *Journal of Geophysical Research - Solid Earth*, 118(6), 3059–3079. <https://doi.org/10.1002/jgrb.50217>
- Ando, M. (1975). Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan. *Tectonophysics*, 27(2), 119–140. [https://doi.org/10.1016/0040-1951\(75\)90102-X](https://doi.org/10.1016/0040-1951(75)90102-X)
- Bedford, J., Moreno, M., Li, S., Oncken, O., Baez, J. C., Bevis, M., et al. (2016). Separating rapid relocking, afterslip, and viscoelastic relaxation: An application of the postseismic straightening method to the Maule 2010 cGPS. *Journal of Geophysical Research - Solid Earth*, 121(10), 7618–7638. <https://doi.org/10.1002/2016JB013093>

Acknowledgments

The GNSS data used in this study are from the online Supplemental File of Nishimura et al. (2018) (<http://doi.org/10.1130/GES01529.S1>), and the leveling data are from Wang and Tréhu (2016). Shaoyang Li is a JSPS International Research Fellow and was supported by the visiting program of the Earthquake Research Institute, the University of Tokyo. This work was supported by JSPS KAKENHI Grant Numbers JP18K03776 and JP17H01703 and by the Ministry of Education, Culture, Sports, Science, and Technology of Japan, under its Earthquake and Volcano Hazards Observation and Research Program. We would like to thank Gavin Hayes and two anonymous reviewers for inspiring and constructive comments. The figures were made using GMT software (Wessel & Smith, 1998).

- Billen, M. I., & Gurnis, M. (2001). A low viscosity wedge in subduction zones. *Earth and Planetary Science Letters*, 193(1-2), 227–236. [https://doi.org/10.1016/S0012-821X\(01\)00482-4](https://doi.org/10.1016/S0012-821X(01)00482-4)
- Bürgmann, R., & Dresen, G. (2008). Rheology of the lower crust and upper mantle: Evidence from rock mechanics, geodesy, and field observations. *Annual Review of Earth and Planetary Sciences*, 36, 531–567. <https://doi.org/10.1146/annurev.earth.36.031207.124326>
- Bürgmann, R., Kogan, M. G., Steblov, G. M., Hilley, G., Levin, V. E., & Apel, E. (2005). Interseismic coupling and asperity distribution along the Kamchatka subduction zone. *Journal of Geophysical Research*, 110(B7), B07405. <https://doi.org/10.1029/2005JB003648>
- Chlieh, M., Avouac, J. P., Sieh, K., Natawidjaja, D. H., & Galetzka, J. (2008). Heterogeneous coupling of the Sumatran megathrust constrained by geodetic and paleogeodetic measurements. *Journal of Geophysical Research*, 113(B5), B05305. <https://doi.org/10.1029/2007JB004981>
- Christensen, R. (1982). *Theory of viscoelasticity: An introduction*. New York and London: Academic Press.
- Govers, R., Furlong, K. P., Van de Wiel, L., Herman, M. W., & Broerse, T. (2018). The geodetic signature of the earthquake cycle at subduction zones: Model constraints on the deep processes. *Reviews of Geophysics*, 56(1), 6–49. <https://doi.org/10.1002/2017RG000586>
- Hayes, G. P., Moore, G. L., Portner, D. E., Hearne, M., Flamme, H., Furtney, M., & Smoczyk, G. M. (2018). Slab2, a comprehensive subduction zone geometry model. *Science*, 362(6410), 58–61. <https://doi.org/10.1126/science.aat4723>
- Hetland, E. A., & Hager, B. H. (2006). Interseismic strain accumulation: Spin-up, cycle invariance, and irregular rupture sequences. *Geochemistry, Geophysics, Geosystems*, 7, Q05004. <https://doi.org/10.1029/2005GC001087>
- Hirth, G., & Kohlstedt, D. (2004). Rheology of the upper mantle and the mantle wedge: A view from the experimentalists. *Inside the subduction Factory*, 138, 83–105. <https://doi.org/10.1029/138GM06>
- Hyndman, R. D., Wang, K., & Yamano, M. (1995). Thermal constraints on the seismogenic portion of the southwestern Japan subduction thrust. *Journal of Geophysical Research*, 100(B8), 15373–15392. <https://doi.org/10.1029/95JB00153>
- Ishibashi, K. (2004). Status of historical seismology in Japan. *Annals of Geophysics*, 47(2-3). <https://doi.org/10.4401/ag-3305>
- Ito, T., & Hashimoto, M. (2004). Spatiotemporal distribution of interplate coupling in southwest Japan from inversion of geodetic data. *Journal of Geophysical Research*, 109, B02315. <https://doi.org/10.1029/2002JB002358>
- Johnson, K. M., & Tebo, D. (2018). Capturing 50 years of postseismic mantle flow at Nankai subduction zone. *Journal of Geophysical Research - Solid Earth*, 123(11), 10,091–10,106. <https://doi.org/10.1029/2018JB016345>
- Kudo, T., Yamaji, A., Furumoto, M., & Nagao, T. (2001). Effective elastic thickness of island arc lithosphere under Japan. *Island Arc*, 10(2), 135–144. <https://doi.org/10.1111/j.1440-1738.2001.00314.x>
- Li, S., Freymueller, J., & McCaffrey, R. (2016). Slow slip events and time-dependent variations in locking beneath Lower Cook Inlet of the Alaska-Aleutian subduction zone. *Journal of Geophysical Research - Solid Earth*, 121(2), 1060–1079. <https://doi.org/10.1002/2015JB012491>
- Li, S., Moreno, M., Bedford, J., Rosenau, M., Heidbach, O., Melnick, D., & Oncken, O. (2017). Postseismic uplift of the Andes following the 2010 Maule earthquake: Implications for mantle rheology. *Geophysical Research Letters*, 44(4), 1768–1776. <https://doi.org/10.1002/2016GL071995>
- Li, S., Moreno, M., Bedford, J., Rosenau, M., & Oncken, O. (2015). Revisiting viscoelastic effects on interseismic deformation and locking degree: A case study of the Peru-North Chile subduction zone. *Journal of Geophysical Research - Solid Earth*, 120(6), 4522–4538. <https://doi.org/10.1002/2015JB011903>
- Li, S., Wang, K., Wang, Y., Jiang, Y., & Dosso, S. E. (2018). Geodetically inferred locking state of the Cascadia megathrust based on a viscoelastic Earth model. *Journal of Geophysical Research - Solid Earth*, 123(9), 8056–8072. <https://doi.org/10.1029/2018JB015620>
- Liu, Y. (2013). Numerical simulations on megathrust rupture stabilized under strong dilatancy strengthening in slow slip region. *Geophysical Research Letters*, 40(7), 1311–1316. <https://doi.org/10.1002/grl.50298>
- Liu, Z., Owen, S., Dong, D., Lundgren, P., Webb, F., Hetland, E., & Simons, M. (2010). Estimation of interplate coupling in the Nankai trough, Japan using GPS data from 1996 to 2006. *Geophysical Journal International*, 181(3), 1313–1328. <https://doi.org/10.1111/j.1365-246X.2010.04600.x>
- Loveless, J. P., & Meade, B. J. (2016). Two decades of spatiotemporal variations in subduction zone coupling offshore Japan. *Earth and Planetary Science Letters*, 436, 19–30. <https://doi.org/10.1016/j.epsl.2015.12.033>
- Matsu'ura, M., & Sato, T. (1989). A dislocation model for the earthquake cycle at convergent plate boundaries. *Geophysical Journal International*, 96(1), 23–32. <https://doi.org/10.1111/j.1365-246X.1989.tb05247.x>
- Mavrommatis, A. P., Segall, P., & Johnson, K. M. (2014). A decadal-scale deformation transient prior to the 2011 Mw 9.0 Tohoku-oki earthquake. *Geophysical Research Letters*, 41(13), 4486–4494. <https://doi.org/10.1002/2014GL060139>
- Mazzotti, S., Le Pichon, X., Henry, P., & Miyazaki, S. I. (2000). Full interseismic locking of the Nankai and Japan-west Kurile subduction zones: An analysis of uniform elastic strain accumulation in Japan constrained by permanent GPS. *Journal of Geophysical Research*, 105(B6), 13159–13177. <https://doi.org/10.1029/2000JB900060>
- McCaffrey, R., Qamar, A. I., King, R. W., Wells, R., Khazaradze, G., Williams, C. A., et al. (2007). Fault locking, block rotation and crustal deformation in the Pacific Northwest. *Geophysical Journal International*, 169(3), 1315–1340. <https://doi.org/10.1111/j.1365-246X.2007.03371.x>
- Melosh, H. J., & Fleitout, L. (1982). The earthquake cycle in subduction zones. *Geophysical Research Letters*, 9(1), 21–24. <https://doi.org/10.1029/GL009i001p00021>
- Meltzner, A. J., Sieh, K., Chiang, H. W., Wu, C. C., Tsang, L. L., Shen, C. C., et al. (2015). Time-varying interseismic strain rates and similar seismic ruptures on the Nias-Simeulue patch of the Sunda megathrust. *Quaternary Science Reviews*, 122, 258–281. <https://doi.org/10.1016/j.quascirev.2015.06.003>
- Métois, M., Socquet, A., & Vigny, C. (2012). Interseismic coupling, segmentation and mechanical behavior of the central Chile subduction zone. *Journal of Geophysical Research*, 117, B03406. <https://doi.org/10.1029/2011JB008736>
- Miyashita, K. (1987). A model of plate convergence in southwest Japan, inferred from leveling data associated with the 1946 Nankaido earthquake. *Journal of Physics of the Earth*, 35(6), 449–467. <https://doi.org/10.4294/jpe.1952.35.449>
- Moreno, M., Melnick, D., Rosenau, M., Bolte, J., Klotz, J., Echter, H., et al. (2011). Heterogeneous plate locking in the South-Central Chile subduction zone: Building up the next great earthquake. *Earth and Planetary Science Letters*, 305(3-4), 413–424. <https://doi.org/10.1016/j.epsl.2011.03.025>
- Moucha, R., Forte, A. M., Mitrovica, J. X., & Daradich, A. (2007). Lateral variations in mantle rheology: Implications for convection related surface observables and inferred viscosity models. *Geophysical Journal International*, 169(1), 113–135. <https://doi.org/10.1111/j.1365-246X.2006.03225.x>

- 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>
- Nishimura, T., Hirasawa, T., Miyazaki, S. I., Sagiya, T., Tada, T., Miura, S., & Tanaka, K. (2004). Temporal change of interplate coupling in northeastern Japan during 1995–2002 estimated from continuous GPS observations. *Geophysical Journal International*, 157(2), 901–916. <https://doi.org/10.1111/j.1365-246X.2004.02159.x>
- Nishimura, T., Matsuzawa, T., & Obara, K. (2013). Detection of short-term slow slip events along the Nankai Trough, southwest Japan, using GNSS data. *Journal of Geophysical Research - Solid Earth*, 118(6), 3112–3125. <https://doi.org/10.1002/jgrb.50222>
- Nishimura, T., Yokota, Y., Tadokoro, K., & Ochi, T. (2018). Strain partitioning and interplate coupling along the northern margin of the Philippine Sea plate, estimated from Global Navigation Satellite System and Global Positioning System-Acoustic data. *Geosphere*, 14(2), 535–551. <https://doi.org/10.1130/GES01529.1>
- Noda, A., Saito, T., & Fukuyama, E. (2018). Slip-deficit rate distribution along the Nankai Trough, southwest Japan, with elastic lithosphere and viscoelastic asthenosphere. *Journal of Geophysical Research - Solid Earth*, 123(9), 8125–8142. <https://doi.org/10.1029/2018JB015515>
- Obara, K., Tanaka, S., Maeda, T., & Matsuzawa, T. (2010). Depth-dependent activity of non-volcanic tremor in southwest Japan. *Geophysical Research Letters*, 37, L13306. <https://doi.org/10.1029/2010GL043679>
- Okada, Y. (1985). Surface deformation due to shear and tensile faults in a half-space. *Bulletin of the Seismological Society of America*, 75(4), 1135–1154.
- Ozawa, S., Nishimura, T., Suito, H., Kobayashi, T., Tobita, M., & Imakiire, T. (2011). Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake. *Nature*, 475(7356), 373–376. <https://doi.org/10.1038/nature10227>
- Pollitz, F., Banerjee, P., Grijalva, K., Nagarajan, B., & Bürgmann, R. (2008). Effect of 3-D viscoelastic structure on post-seismic relaxation from the 2004 M = 9.2 Sumatra earthquake. *Geophysical Journal International*, 173(1), 189–204. <https://doi.org/10.1111/j.1365-246X.2007.03666.x>
- Pollitz, F. F., McCrory, P., Wilson, D., Svarc, J., Puskas, C., & Smith, R. B. (2010). Viscoelastic-cycle model of interseismic deformation in the northwestern United States. *Geophysical Journal International*, 181(2), 665–696. <https://doi.org/10.1111/j.1365-246X.2010.04546.x>
- Sagiya, T., & Kawashima, Y. (2017). Decadal variations in interseismic deformation rate associated with a subduction zone earthquake cycle. In *AGU Fall Meeting Abstracts*.
- Sagiya, T., Miyazaki, S. I., & Tada, T. (2000). Continuous GPS array and present-day crustal deformation of Japan. *Pure and Applied Geophysics*, 157(11–12), 2303–2322. <https://doi.org/10.1007/PL00022507>
- Sagiya, T., & Thatcher, W. (1999). Coseismic slip resolution along a plate boundary megathrust: The Nankai Trough, southwest Japan. *Journal of Geophysical Research*, 104(B1), 1111–1129. <https://doi.org/10.1029/98JB02644>
- Savage, J. C. (1983). A dislocation model of strain accumulation and release at a subduction zone. *Journal of Geophysical Research*, 88(B6), 4984–4996. <https://doi.org/10.1029/JB088iB06p04984>
- Savage, J. C., & Thatcher, W. (1992). Interseismic deformation at the Nankai Trough, Japan, subduction zone. *Journal of Geophysical Research*, 97(B7), 11117–11135. <https://doi.org/10.1029/92JB00810>
- Sobolev, S. V., & Muldashev, I. A. (2017). Modeling seismic cycles of great megathrust earthquakes across the scales with focus at post-seismic phase. *Geochemistry, Geophysics, Geosystems*, 18(12), 4387–4408. <https://doi.org/10.1002/2017GC007230>
- Sun, T., & Wang, K. (2015). Viscoelastic relaxation following subduction earthquakes and its effects on afterslip determination. *Journal of Geophysical Research - Solid Earth*, 120(2), 1329–1344. <https://doi.org/10.1002/2014JB011707>
- Thatcher, W. (1984). The earthquake deformation cycle at the Nankai Trough, southwest Japan. *Journal of Geophysical Research*, 89(B5), 3087–3101. <https://doi.org/10.1029/JB089iB05p03087>
- Thatcher, W., & Pollitz, F. F. (2008). Temporal evolution of continental lithospheric strength in actively deforming regions. *GSA Today*, 18(4/5), 4. <https://doi.org/10.1130/GSAT01804-5A.1>
- Thatcher, W., & Rundle, J. B. (1984). A viscoelastic coupling model for the cyclic deformation due to periodically repeated earthquakes at subduction zones. *Journal of Geophysical Research*, 89(B9), 7631–7640. <https://doi.org/10.1029/JB089iB09p07631>
- Trubienko, O., Fleitout, L., Garau, J. D., & Vigny, C. (2013). Interpretation of interseismic deformations and the seismic cycle associated with large subduction earthquakes. *Tectonophysics*, 589, 126–141. <https://doi.org/10.1016/j.tecto.2012.12.027>
- Walcott, R. I. (1973). Structure of the earth from glacio-isostatic rebound. *Annual Review of Earth and Planetary Sciences*, 1(1), 15–37. <https://doi.org/10.1146/annurev.ea.01.050173.000311>
- Wallace, L. M., Beavan, J., McCaffrey, R., & Darby, D. (2004). Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. *Journal of Geophysical Research*, 109(B12), B12406. <https://doi.org/10.1029/2004JB003241>
- Wang, K., Hu, Y., & He, J. (2012). Deformation cycles of subduction earthquakes in a viscoelastic Earth. *Nature*, 484(7394), 327–332. <https://doi.org/10.1038/nature11032>
- Wang, K., & Tréhu, A. M. (2016). Invited review paper: Some outstanding issues in the study of great megathrust earthquakes – The Cascadia example. *Journal of Geodynamics*, 98, 1–18. <https://doi.org/10.1016/j.jog.2016.03.010>
- Wang, K., Wells, R., Mazzotti, S., Hyndman, R. D., & Sagiya, T. (2003). A revised dislocation model of interseismic deformation of the Cascadia subduction zone. *Journal of Geophysical Research*, 108(B1), 2026. <https://doi.org/10.1029/2001JB001227>
- Wessel, P., & Smith, W. H. F. (1998). New, improved version of the Generic Mapping Tools released. *Eos, Transactions American Geophysical Union*, 79, 579. <https://doi.org/10.1029/98EO00426>
- Yoshioka, S., & Ito, Y. (2001). Lateral variations of effective elastic thickness of the subducting Philippine Sea plate along the Nankai Trough. *Earth, Planets and Space*, 53(4), 261–273. <https://doi.org/10.1186/BF03352383>
- Yoshioka, S., & Matsuoka, Y. (2013). Interplate coupling along the Nankai Trough, southwest Japan, inferred from inversion analyses of GPS data: Effects of subducting plate geometry and spacing of hypothetical ocean-bottom GPS stations. *Tectonophysics*, 600, 165–174. <https://doi.org/10.1016/j.tecto.2013.01.023>