Offshore landward motion shortly after a subduction earthquake implies rapid relocking of the shallow megathrust

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Abstract

Geodetic observations after large subduction earthquakes reflect multiple postseismic processes, including megathrust relocking. What the timing of relocking is, and how well observations constrain it, is unclear. It has been inferred to explain some observed landward motion that occurs within months. It has also been considered unable to explain other, greater landward motion, including off the coast of Japan beginning weeks after the 2011 Tohoku earthquake, which is attributed to postseismic relaxation. We use generic, 3D numerical models to show that relocking, particularly of the shallow interface, is needed for postseismic relaxation to produce landward motion on the tip of the overriding plate. We argue that this finding is consistent with previous simulations that implicitly relock the megathrust where afterslip is not included, that the Tohoku megathrust thus relocked within less than two months of the earthquake, and that the shallow megathrust probably behaves as a true, unstably sliding asperity.

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Key Points:

- Landward velocities were observed as soon as two months after the 2011 Tohoku earthquake, offshore, on the overriding plate.
- These landward velocities are produced by postseismic relaxation (viscous and afterslip), but only if the megathrust is locked.
- Observations imply shallow megathrust relocking within two months of the Tohoku earthquake, consistent with unstably sliding behavior.

Abstract

Geodetic observations after large subduction earthquakes reflect multiple postseismic processes, including megathrust relocking. What the timing of relocking is, and how well observations constrain it, is unclear. It has been inferred to explain some observed landward motion that occurs within months. It has also been considered unable to explain other, greater landward motion, including off the coast of Japan beginning weeks after the 2011 Tohoku earthquake, which is attributed to postseismic relaxation. We use generic, 3D numerical models to show that relocking, particularly of the shallow interface, is needed for postseismic relaxation to produce landward motion on the tip of the overriding plate. We argue that this finding is consistent with previous simulations that implicitly relock the megathrust where afterslip is not included, that the Tohoku megathrust thus relocked within less than two months of the earthquake, and that the shallow megathrust probably behaves as a true, unstably sliding asperity.

Plain Language Summary

In the largest earthquakes, a tectonic plate suddenly slides under another, where previously the interface between them was largely locked and unable to slide. After these earthquakes, the deformation of the Earth's surface reflects multiple deep processes. One process is the restoration of locking of the boundary. This means that energy starts to accumulate again, building up towards the next earthquake. How long after an earthquake does the interface relock? Relocking is suggested to have caused some deformation observed months after some earthquakes, and so to have occurred by then. It is also thought to not explain the rapid westward motion of the seafloor close to the plate boundary, observed on the upper plate beginning less than two months after the 2011 Japan earthquake. We use numerical simulations to show that locking of the shallow portion of the plate interface is needed for westward motion to be transmitted from the lower plate, where it occurs because of mantle flow caused by the earthquake, to the tip of the upper plate, as happened in Japan. We conclude that this result agrees with simulations in previous studies, even though they were not interpreted in terms of locking by their authors.

1 Context, Aims and Approach

The postseismic geodetic signal after a megathrust earthquake consists of several contributions: viscoelastic relaxation in the asthenospheric mantle, postseismic slip (afterslip) on the megathrust and its downdip continuation, poroelastic relaxation, and relocking of the megathrust interface (e.g., Bedford et al., 2016; Fialko, 2004; Hoffmann et al., 2018; Hu et al., 2014; Jónsson et al., 2003; Li et al., 2017, 2018; Peltzer et al., 1998; Remy et al., 2016; Wang et al., 2012). Relocking marks the beginning of the accumulation of slip deficit in the new earthquake cycle. It results in shortening of the overriding plate and near-trench landward velocities comparable to, but lower than, the plate convergence rate. As oceanward motion due to viscous relaxation and afterslip wane, the effect of the newly locked megathrust becomes apparent in geodetic displacement time series as landward motion of the surface of the overriding plate. Landward motion progressively reaches farther from the trench with time (Wang et al., 2012). Detecting the timing of relocking is critical for understanding the mechanical state of the megathrust system and properly assessing the associated seismic hazard.

Evidence suggests that relocking occurs rapidly (within weeks to months) after large megathrust earthquakes (Govers et al., 2018). In particular, rapid relocking has been inferred from the decomposition and inversion of Global Navigation and Satellite Systems (GNSS) displacement time series following the 2010 M_W 8.8 Maule (Chile) and 2007 M_W 8.0 Pisco (Peru) earthquakes (Bedford et al., 2016; Remy et al., 2016). Relocking was also inferred from the occurrence of a normal faulting intraplate earthquake 2 months after the 2006 Kuril Islands (Russia) megathrust rupture, followed 1 year later by a thrust-fault intraplate earthquake (Lay et al., 2009), implying a rapid transition from extension to compression (Govers et al., 2018). Other evidence of the mechanical state of the megathrust may come from offshore observations, via Global Positioning System and acoustic (GPS-A) ranging, of landward horizontal postseismic motion close to the trench. However, these results have been inconclusive.

GPS-A observations at one offshore location above the 2005 M_W 7.2 Miyagi (Japan) megathrust earthquake indicate landward postseismic motion consistent with the signature of locking and interplate convergence starting one year after the event (Sato et al., 2011). Landward motion was also detected at some offshore GPS-A sites on the overriding plate following the 2011 M_W 9.1 Tohoku (Japan) earthquake, beginning less than two months after the event (Japan Coast Guard, 2013; Sun et al., 2014; Watanabe et al., 2014). However, the offshore landward motion following the 2011 Tohoku earthquake amounted to as much as 50 cm in the first year after the event (Sun et al., 2014). This amplitude is significantly more than can be explained merely by relocking and the far-field, steady-state convergence rate (8.3 cm/yr locally and as high as 9.1 cm/yr elsewhere on the Japan Trench) (Watanabe et al., 2014). Watanabe et al. (2014) therefore explicitly concluded that relocking is irrelevant for explaining the observed motion after the Tohoku earthquake. Peña et al. (2019) reached the same conclusion for the onshore postseismic displacement field due to the Maule earthquake, whose observed trench-perpendicular components were entirely landward. Explanations have instead focused on postseismic relaxation, particularly viscoelastic relaxation and afterslip, since poroelastic relaxation can only account for relatively small signals (Hu et al., 2014; Peña et al., 2019)

Various studies interpreting the postseismic observations following the Tohoku earthquake agree that the offshore landward motion is primarily caused by viscous relaxation (Sun et al., 2014; Sun & Wang, 2015; Yamagiwa et al., 2015; Freed et al., 2017; Suito, 2017; Noda et al., 2018; Agata et al., 2019; Muto et al., 2019; Fukuda & Johnson, 2021; Dhar et al., 2022). Specifically, viscous flow in the sub-slab asthenosphere produces landward surface motion, while flow in the asthenospheric wedge produces oceanward motion (Suito, 2017). Muto et al. (2019) and Noda et al. (2018) also conclude that afterslip contributes to the offshore landward motion on the overriding plate. A consensus is thus forming that the typical evolution of the megathrust system outlined by Wang et al. (2012), in which landward motion appears progressively as the effect of locking prevails over diminishing postseismic relaxation, is somewhat complicated by sub-slab postseismic relaxation producing early and strong landward motion of the offshore forearc, regardless of locking. However, there has been no convincing mechanical explanation for why, and under what conditions, the landward motion resulting from viscous relaxation in the sub-slab mantle has a surface expression on the overriding plate.

We suspect that the postseismic observations of rapid landward motion, offshore on the overriding plate, require rapid relocking of the megathrust, as the latter determines the mechanical coupling between the two plates. We use a quasi-dynamic three-dimensional (3D) finite element method (FEM) model with regularly repeating M_W 9.1 earthquakes to investigate this hypothesis (Fig. S1 of the Supporting Information). We use a uniform slab profile cut perpendicularly across the Japan Trench from the Slab2 model (Hayes et al., 2018), but do not otherwise incorporate the structure nor aim to reproduce the specific observed deformation of the Japan subduction zone. We use uniform elastic plates and linear viscoelastic asthenospheric mantle with a viscosity of 10^{18} Pa s in the postseismic period we study. We impose a constant motion at a rate of 90 mm/yr at either end of the downgoing plate. Slip deficit accumulates and is released according to megathrust locking and unlocking, similarly to Govers et al. (2018). We impose complete locking of portions of the megathrust (asperities) and allow frictionless creep on the rest of the megathrust and on its downdip continuation, consistent with observations (Scholz, 1998; Ikari et al., 2011; Hardebeck, 2015) and inverse model results (Herman & Govers, 2020). We use five asperities, rectangular in plan view, 50 km wide, centered 200 km along-trench from each other. We focus on the earthquake and postseismic deformation following the unlocking of the central asperity. This asperity extends horizontally from a distance of 133 km to 3 km from the trench, reaching very close to it in agreement with the shallow coseismic slip observed during the Tohoku earthquake (e.g., Meng et al., 2011). The lateral asperities extend horizontally from 83 to 133 km from the trench and serve to provide megathrust coupling elsewhere along the plate margin, as observed along the Japan trench (Yamanaka & Kikuchi, 2004; Hashimoto et al., 2009; Johnson et al., 2016). To complete the supercycle, the two intermediate and two external lateral asperities are unlocked 20 and 40 years after the central asperity, respectively. Every asperity is unlocked every 300 years. When an asperity is unlocked, coseismic slip releases all slip deficit, except for that due to locking of the other asperities. We treat the interface between slab and asthenospheric wedge, downdip of the megathrust, to be a viscoelastic shear zone (Tichelaar & Ruff, 1993; van Keken et al., 2002) with very low viscosity and the same elastic properties as the surrounding material (Govers et al., 2018; Muto et al., 2019). We let the shear zone accommodate relative motion at depths shallower than 80 km, where afterslip is commonly thought to occur (Diao et al., 2014; Sun et al., 2014; Yamagiwa et al., 2015; Hu et al., 2016; Freed et al., 2017). Afterslip occurs on the shear zone, immediately after the earthquake, relaxing as much as possible the elastic traction changes caused by coseismic deformation. We look at the cumulative horizontal surface motion during the first year after the earthquake, produced by the two major postseismic relaxation processes, afterslip and viscous relaxation, as well as continued plate convergence. The modeling method is described more thoroughly in Text S1 of the Supporting Information.

2 Model Results

In our first model, we immediately relock the entire ruptured asperity, from 3 km of horizontal distance from the trench down to a depth of 30 km and 133 km horizontally from the trench. Fig. 1 shows that the trench-perpendicular surface displacement in the first year after the earthquake is directed landward next to the trench on the overriding plate, as well as on the oceanic plate. Displacement is trenchward elsewhere on the overriding plate. The amplitude of landward displacement is largest (~30 cm) at the trench and decreases with distance from the trench and, to a lesser extent, with along-trench distance from the central asperity. Landward displacement reaches as far as ~45 km horizontally from the trench.

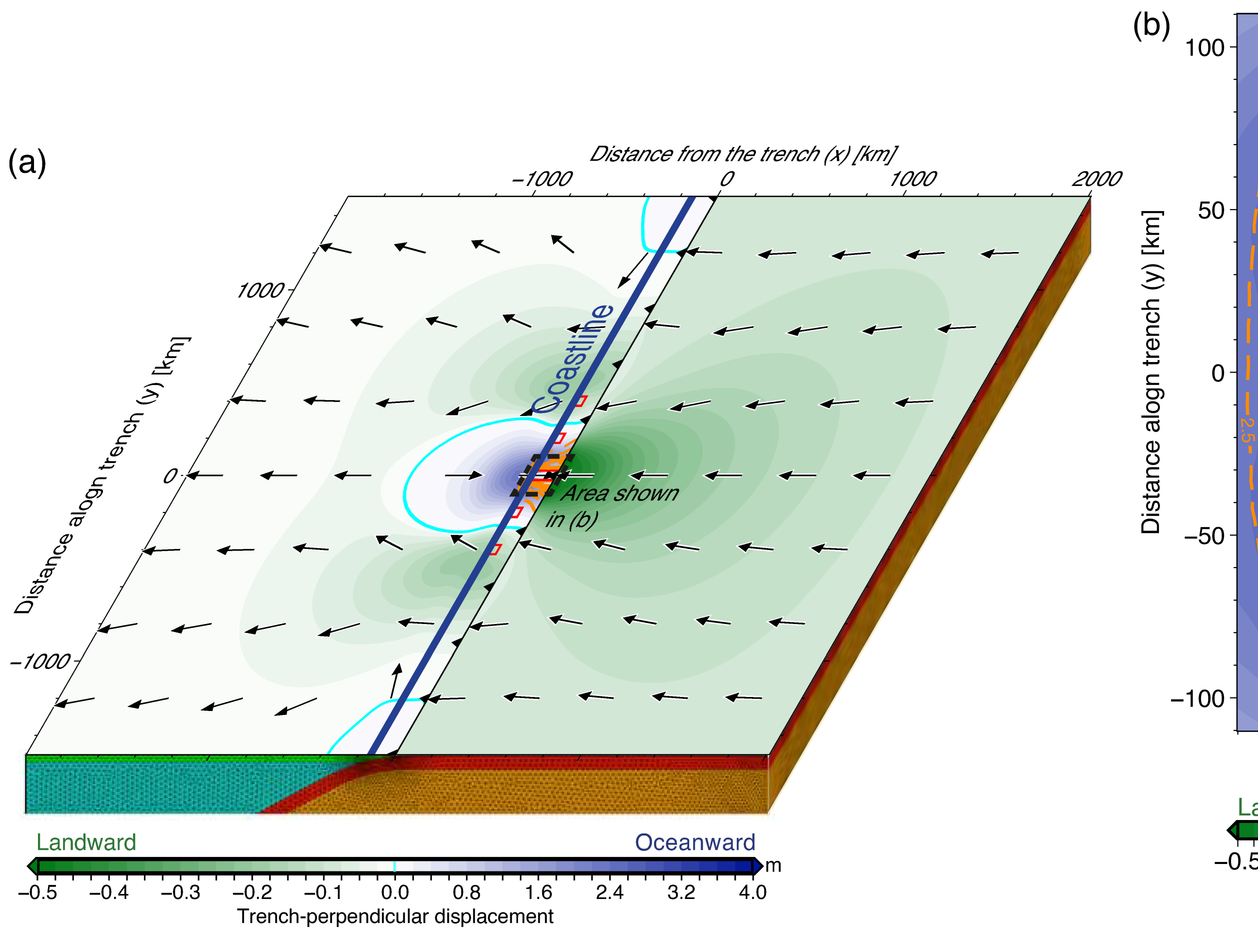

Figure 1. The whole asperity relocks instantly after the earthquake. Cumulative horizontal postseismic surface displacement after 1 year, assuming afterslip has ceased by then and including steady-state plate convergence. Colors show the trench-perpendicular displacement. Note that the color scale is asymmetrical, emphasizing the smaller (on the overriding plate) landward motion and de-emphasizing oceanward motion. Arrows show the displacement direction. The red rectangles show the surface projection of the outline of the asperities. The approximate location of the coastline, assumed to be directly above the downdip limit of the asperities is shown by the labeled line. The trench is shown as a barbed line. Dashed orange contours show coseismic displacement on the megathrust in 2.5 m increments. (**a**) Entire model, showing the surface motion and the overriding plate, asthenospheric wedge, subducting oceanic plate, and oceanic asthenosphere. (**b**) Surface motion in the central part of the model (marked and labeled in (a)). The extent of the relocked portion of the asperity, coinciding here with the whole asperity, is shown by the diagonal light green lines.

In the second experiment, we do not relock any part of the central asperity after the earthquake, letting it slip freely postseismically together with the surrounding subduction interface. Fig. 2 shows that surface displacement of the overriding plate is trenchward in this case, with no zone of landward motion close to the trench.

Does landward motion of the overriding plate require relocking of the entire asperity? In our third experiment, we relock only the deep portion of the central asperity, between 20 and 30 km depth. 20 km was sometimes considered the updip limit of the frictionally unstable, potentially seismogenic portion of the megathrust (Byrne et al., 1988; Scholz, 1998). Fig. 3 shows that relocking the deep part of the asperity is insufficient to produce landward displacement on the overriding plate during the first year after the earthquake. The amplitude of trenchward displacement above the asperity is nevertheless lower (i.e., less oceanward) than with no relocking whatsoever. We note that the shallow unlocked asperity and adjacent portions of the megathrust are not completely free to slip, because the mechanical continuity of both plates limits the slip that can occur in the vicinity of the relocked portion (Herman et al., 2018).

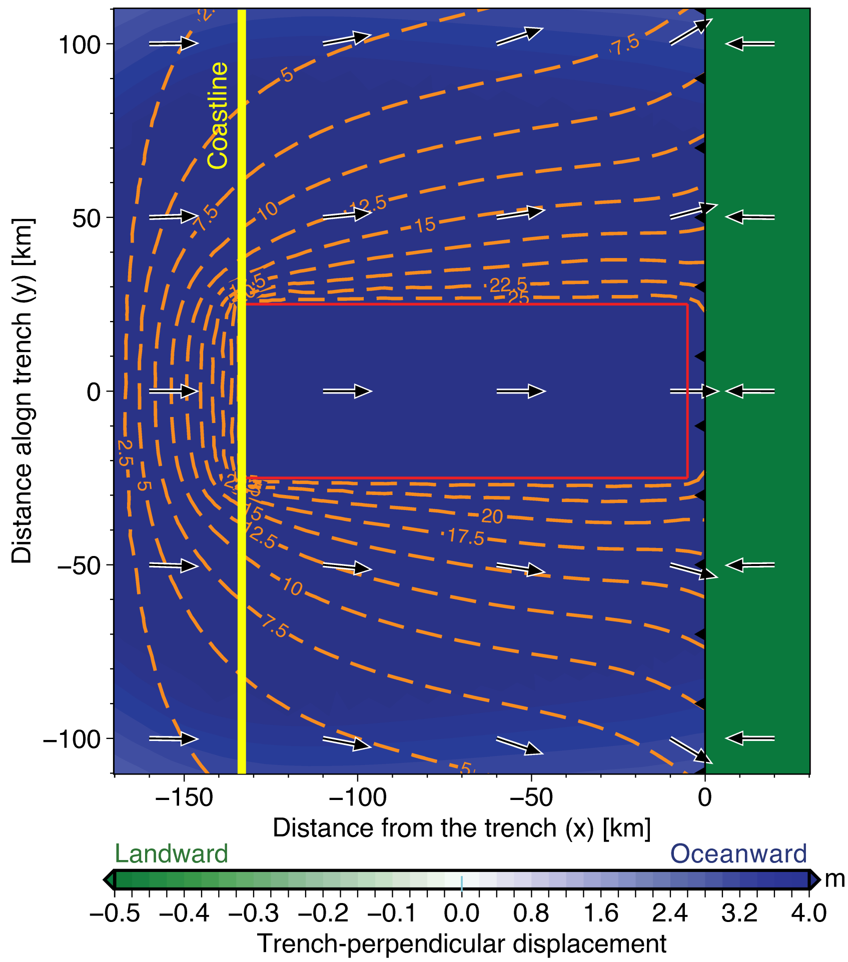

Figure 2. No part of the asperity relocks after the earthquake. Cumulative horizontal postseismic surface displacement during the 1 year after the earthquake, including afterslip and 1 year of viscous relaxation. Graphical choices are the same as in Fig. 1(b).

In our fourth and last model, we test the relocking of only the shallow portion of the central asperity, above 20 km depth. This does result in landward postseismic surface displacement at the near-trench tip of the overriding plate (Fig. 4). However, the maximum amplitude of landward displacement in the first year (~28 cm) and its trench-perpendicular spatial extent (~25 km) are both smaller (slightly and substantially, respectively) than with relocking of the whole asperity.

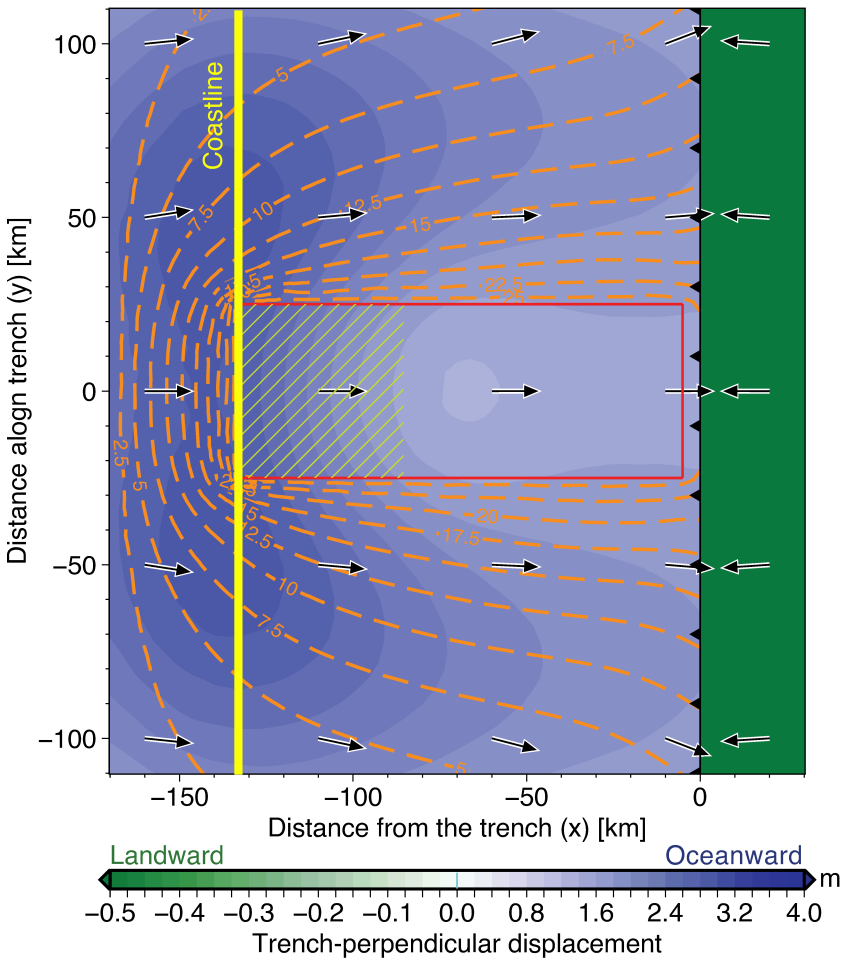

Figure 3. Only the deep positions of the asperity (beyond 20 km depth from the surface) relocks after the earthquake. Cumulative horizontal postseismic surface displacement during the 1 year after the earthquake, including afterslip and 1 year of viscous relaxation. Graphical choices are the same as in Fig. 1(b).

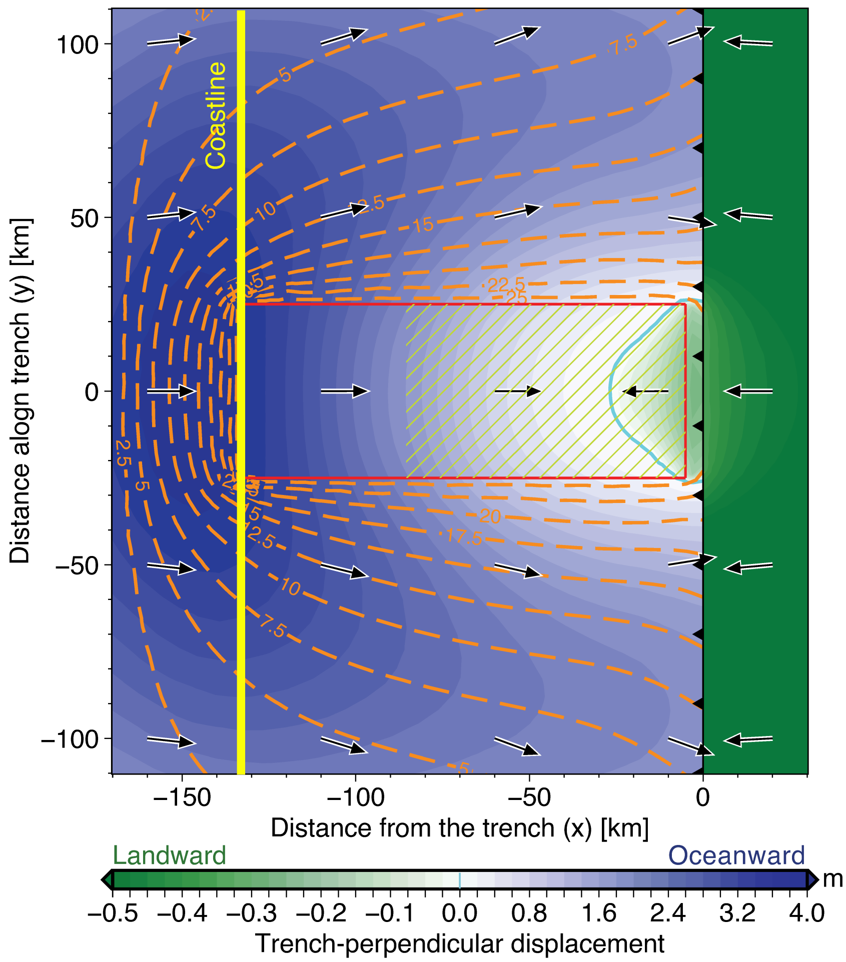

Figure 4. Only the shallow positions of the asperity (above 20 km depth from the surface) relocks after the earthquake. Cumulative horizontal postseismic surface displacement during the 1 year after the earthquake, including afterslip and 1 year of viscous relaxation. Graphical choices are the same as in Fig. 1(b).

3 Discussion and Conclusions

4.1 Physical Interpretation and Consistency with Previous Research

In our model results, the oceanic and continental domains generally have convergent, opposing motion, respectively landward and trenchward. Viscous flow and afterslip allow the shallow slab and the overriding plate in the vicinity of the rupture to further extend, continuing to release stresses accumulated during the interseismic period, as they accommodated convergence by shortening. This behavior is consistent with previously published results (e.g., Muto et al., 2019; Noda et al., 2018; Suito, 2017; Sun et al., 2014; Yamagiwa et al., 2015) and with the overview of deformation during megathrust earthquake cycles by Wang et al. (2012). Our results show that mechanical coupling of the two plates on the megathrust is needed for the near-trench tip of the overriding plate to move landward. We interpret the cause of this for this dependency as follows: the near-trench portion of the slab, moving landward as a result of postseismic viscous relaxation and afterslip, transmits its landward motion to the thin portion of overriding plate directly above it, if and only if the locked megathrust provides mechanical coupling between them. Without any coupling, the megathrust slips freely and accommodates the opposite bulk motion of the two domains.

Our conclusion regarding the link between megathrust relocking and near-trench landward motion seemingly contradicts the studies that explain the postseismic displacement following the Tohoku earthquake with no need for locking (Sun et al., 2014; Sun & Wang, 2015; Yamagiwa et al., 2015; Freed et al., 2017; Suito, 2017; Noda et al., 2018; Agata et al., 2019; Muto et al., 2019; Fukuda & Johnson, 2021; Dhar et al., 2022), as well as the specific claim that relocking is largely irrelevant for explaining the observed offshore landward motion after the Tohoku earthquake (Watanabe et al., 2014). However, this apparent contradiction is due to those studies considering the effect of relocking to be only the signal due to continued far-field interplate convergence in addition to megathrust locking. This follows from the use of the backslip approach (Matsu'ura & Sato, 1989) in megathrust system models. However, when studying the early postseismic period, we must consider the effect of interplate coupling, if any, interacting with the motion due to postseismic relaxation, not merely with steady-state interplate convergence. Furthermore, previous studies implicitly assume that the interface does not slip, i.e., it is locked, where afterslip is not explicitly incorporated in the model. We can thus interpret their results in terms of relocking by observing the afterslip distribution they use, if any. Suito (2017) does not include afterslip in his model. Sun et al. (2014) impose an afterslip distribution that has near-zero values in the entirety of the rupture zone. Muto et al. (2019) invert onshore and offshore geodetic observations with stress-driven afterslip in a two-dimensional (2D) model and find no afterslip within 130 km of horizontal distance from the trench and only very minor afterslip between 130 and 150 km. Yamagiwa et al. (2015) and Freed et al. (2017) invert onshore and offshore geodetic displacement time series into afterslip, after modeling viscous relaxation, using 3D models. They find little afterslip above 25 km depth below sea level, or within ~150 km of horizontal distance from the trench, in the region where offshore landward displacements are observed, at any time after the earthquake, although there is some shallow afterslip immediately to the south and, in the results of Freed et al., farther north. Noda et al. (2018) invert onshore displacement time series only, with a different slab geometry, and find no significant afterslip above 20 km depth below solid ground, i.e. within ~150 km of the trench, with a map-view distribution in general agreement with Yamagiwa et al. (2015) and Freed et al. (2017), but without the shallow afterslip. In all these models, then, the shallow interface is implicitly locked postseismically at the location where landward postseismic displacement is observed geodetically and produced by the models themselves.

The peak amplitude of landward displacement in our fully relocked model results (30 cm) is smaller than that (50 cm) observed in the first year after the Tohoku earthquake and reproduced by previous modeling studies (e.g., Sun et al., 2014). The reason for the smaller amplitude in our results is likely due to the relatively limited peak amplitude of coseismic slip (27 m) and uniform Maxwell viscosity. Previous studies find the need for a spatially inhomogeneous, temporally variable effective viscosity, with lower short-term values particularly at the base of the slab (Sun et al., 2014; Freed et al., 2017; Agata et al., 2018, 2019; Muto et al., 2019), although there is no widespread agreement and best fitting viscosities vary greatly with modeling methodology (Fukuda & Johnson, 2021). Having established that previously published modeling studies are consistent with our findings and do show relocking, while closely reproducing observations, we see no need to develop a more detailed model specifically tailored to this subduction zone.

4.2 Spatio-temporal Features of Relocking and Fault Friction

The necessity of a locked megathrust implies that relocking has already occurred when landward motion is observed there. In the case of the Tohoku earthquake, the earliest, less reliable postseismic GPS-A observations indicate that landward motion was already occurring less than two months after the event (Japan Coast Guard, 2013). This implies that relocking occurred within a few weeks of the Tohoku earthquake. Near-instantaneous relocking of a ruptured fault asperity is compatible with the rate-and-state treatment of fault friction (Dieterich, 1979; Ruina, 1983). In fact, if the asperity is understood as an unstably sliding, rate-weakening portion of the fault, near-instantaneous relocking is expected, as it immediately follows the end of the unstable sliding episode that constitutes the earthquake. Afterslip and stable creep (i.e., a lack of interseismic coupling) only occur outside of the velocity-weakening, unstably sliding, seismogenic portion of the fault. This behavior can be seen, for instance, in the synoptic model of Marone (1998), the rupture simulation of Barbot et al. (2012) for part of the San Andreas fault, and the sophisticated numerical model of postseismic relaxation after the Tohoku earthquake of Muto et al. (2019).

Our model results indicate that near-trench landward postseismic motion of the overriding plate is not produced by relocking the asperity at intermediate depths (between 20 and 30 km below sea level), at which the Tohoku earthquake rupture is thought to have nucleated (Chu et al., 2011; Japan Meteorological Agency, 2012; Freed et al., 2017). Instead, relocking the uppermost portion (above 20 km depth) is necessary and sufficient for producing landward postseismic motion on the overriding plate, although with a smaller amplitude and spatial extent than when the deeper asperity is also relocked. This finding is based on our rather coarse examination, considering cumulatively all postseismic deformation during the first year after the earthquake and only one depth limit between the shallow and deeper megathrust. However, it is consistent with the results of more sophisticated simulations (Sun et al., 2014; Sun & Wang, 2015; Yamagiwa et al., 2015; Freed et al., 2017; Noda et al., 2018; Muto et al., 2019), when interpreting afterslip in terms of locking or lack thereof. Our conclusions indicate that offshore geodetic observations can detect the spatio-temporal evolution of megathrust relocking, which is relevant for seismic hazard assessment and provides insights into the nature of the shallow megathrust. Our work can thus be seen as a pilot study for the SZ4D MegaArray initiative (McGuire et al., 2017).

The need for rapid relocking of the shallow megathrust, together with the interpretation of the rapidly relocked area as a frictionally unstable interface, suggests that the shallow megathrust in the Tohoku region is not merely a low-friction interface passively locked by the mechanical continuity of the plates and the adjacent truly locked asperity (the pseudo-coupling discussed by Herman et al., 2018). Rather, the shallow interface, previously thought to be stably sliding (Tsuru et al., 2000; Loveless & Meade, 2010), is likely a true asperity, that is, unstably sliding and, interseismically, frictionally locked. This would explain the unusually large slip the shallow megathrust hosted during the Tohoku earthquake (Meng et al., 2011), without requiring the rupture to extend beyond the unstably sliding portion. However, it would also imply that the nature of the shallow megathrust has been profoundly misunderstood and in fact resembles that of the deeper megathrust, despite the less consolidated material and different ambient conditions at shallower depths. Alternatively, the shallow megathrust might have frictional properties that allow it to be stably sliding interseismically and still slip substantially coseismically, as proposed by Noda & Lapusta (2013). However, in that case care must be taken to ensure that the postseismic behavior of such a hybrid shallow megathrust is sufficiently locked as to produce postseismic landward motion. In general, future research should use tailored numerical models to test what degree of locking is compatible with the offshore postseismic observations, considering different spatial and temporal distributions of afterslip together with a realistic geometry and rheology.

The conclusion that rapid shallow megathrust relocking is needed to explain the offshore postseismic GPS-A observations following the Tohoku earthquake is compatible with similar conclusions drawn from onshore GNSS observations for other earthquakes, such as the Maule and 2007 and Pisco earthquakes (Bedford et al., 2016; Remy et al., 2016). Near-trench, postseismic geodetic observations should detect evidence of shallow megathrust relocking, following earthquakes producing substantial postseismic relaxation. However, a lack of postseismic landward motion does not necessarily imply a general lack of relocking. In particular, the lack of landward motion, as for the Miyagi earthquake, might be explained by locking being restricted to shallower depths (implying along-trench variations in the frictional character of the shallow megathrust). Alternatively, it might be due to the oceanward signal of deep afterslip overcoming the small landward signal due to interplate convergence in the absence of substantial viscous relaxation, as for the M_W 7.2 Miyagi event. Additionally, the interaction of afterslip distribution with the specific local geometry might determine whether the limit of the landward signature of deep afterslip occurs on the overriding plate, as proposed by Noda et al. (2018).

Megathrust relocking, including at shallow depths, is needed to allow postseismic relaxation, which produce landward motion in the slab and sub-slab mantle, to also affect the near-trench tip of the overriding plate. Offshore postseismic observations can differentiate between a locked and unlocked shallow megathrust and provide evidence of very rapid (within two months) shallow relocking after the Tohoku event. Observations suggest that the shallow megathrust above 20 km depth in the Tohoku region behaves as an unstably sliding asperity.

Acknowledgments

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The mesh generator program Gmsh (Geuzaine & Remacle, 2009) was used to make the finite element meshes for the numerical models. The Generic Mapping Tools (Wessel et al., 2019), and Adobe Illustrator were used for visualization.

Open Research

The model output files that we used for the figures of this paper are digitally stored in the Yoda repository of Utrecht University and are available under the CC-BY license at https://doi.org/10.24416/UU01-SS41UK.

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