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Offshore Landward Motion Shortly After a Subduction Earthquake Implies Rapid Relocking of the Shallow Megathrust

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Key Points:

- Landward motion of the overriding plate, attributed to postseismic relaxation, was observed offshore 2 months after the Tohoku earthquake
- Models show that landward motion only transmits from the slab to the overriding plate, reaching the surface, if the megathrust is locked
- Observations imply shallow megathrust relocking within 2 months of the Tohoku earthquake, consistent with unstably sliding behavior

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Geodetic observations after large subduction earthquakes reflect multiple postseismic processes, including megathrust relocking. The timing of relocking and the observational constraints on it are unclear. Relocking was inferred to explain some observed landward motion that occurs within months. It was also considered unable to explain other, greater landward motion, including that off the coast of Japan beginning weeks after the 2011 Tohoku earthquake, 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. We conclude that the Tohoku megathrust relocked within less than 2 months of the earthquake. This suggests 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. The deformation of the Earth's surface reflects multiple deep processes. One process is the restoration of interface locking. This means that elastic energy starts to accumulate again, building up toward 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 landward motion of the seafloor on the upper plate, observed beginning less than 2 months after the 2011 Japan earthquake. We use numerical simulations to show that locking the shallow portion of the plate interface is needed for landward motion to transmit from the lower plate to the upper plate, as happened in Japan. Landward motion is understood to occur below and in the lower plate because of mantle flow and deep sliding taking place after the earthquake and caused by it. 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., 2018, 2017; Peltzer et al., 1998; Remy et al., 2016; K. Wang et al., 2012). Figure 1 summarizes the main features of postseismic deformation at subduction zones. 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 (K. 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

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(Russia) megathrust rupture, followed 1 yr 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 1 yr 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 (Honsho et al., 2019; Sun et al., 2014; Tomita et al., 2017, 2014; Watanabe et al., 2014), beginning less than 2 months after the event (Japan Coast Guard, 2013). In contrast, the postseismic motion observed onshore was consistently oceanward over a period of at least 5 yr after the Tohoku earthquake (J. Wang et al., 2018). The offshore landward motion following the 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 (Agata et al., 2019; Dhar et al., 2022; Freed et al., 2017; Fukuda & Johnson, 2021; Muto et al., 2019; Noda et al., 2018; Suito, 2017; Sun & Wang, 2015; Sun et al., 2014; Yamagiwa et al., 2015). 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 K. 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 model with regularly repeating M_w 9.1 earthquakes to investigate this hypothesis (Figure 1 and Figure S1 in Supporting Information S1). We focus on large megathrust earthquakes that rupture the whole megathrust. 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 (Hardebeck, 2015; Ikari et al., 2011; Scholz, 1998) 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 133–3 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 (Hashimoto et al., 2009; Johnson et al., 2016; Yamanaka & Kikuchi, 2004). To complete the supercycle, the two intermediate and two external lateral asperities are unlocked 20 and 40 yr after the central asperity, respectively. Every asperity is unlocked every 300 yr. When an asperity is unlocked, coseismic slip releases all

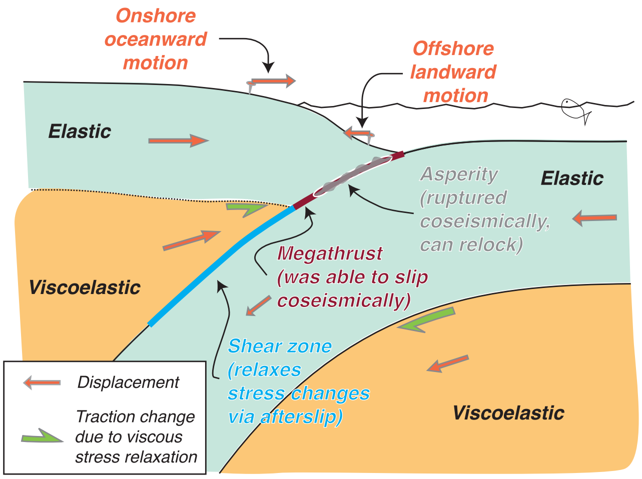

Figure 1. Schematic cross-section of deformation during the postseismic stage of the earthquake cycle. The subduction zone consists of two elastic lithospheric plates, separated by the megathrust interface and underlain by viscoelastic asthenospheric mantle. After the asperity ruptured during a megathrust earthquake, causing coseismically slip on the asperity and the rest of the megathrust, coseismic stress changes are relaxed. Postseismic relaxation includes bulk viscous flow in both asthenospheric domains, and rapid deep afterslip on the shear zone downdip of the megathrust. Postseismic relaxation produces additional convergent horizontal motion, with the oceanic domain moving landward and the continental/island arc domain moving landward. Landward surface motion is observed on land on the continental domain. After the 2011 Tohoku earthquake, opposing (landward) motion was observed on the seafloor at the tip of the overriding plate.

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; Freed et al., 2017; Hu et al., 2016; Sun et al., 2014; Yamagiwa et al., 2015). 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 by continued plate convergence. The modeling method is described more thoroughly in Text S1 in Supporting Information S1.

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 and 133 km horizontally from the trench. Figure 2 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. Landward motion occurs throughout the oceanic domain, in the slab and sub-slab asthenosphere, and also extends to the mechanically coupled forearc directly above the shallow megathrust, including the solid surface at the tip of the overriding plate (Figure S2 in Supporting Information S1).

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. Displacement of the overriding plate is trenchward in this case, with no zone of landward motion close to the trench (Figures S3 and S4 in Supporting Information S1).

Does landward motion of the overriding plate require relocking of the entire asperity? Twenty kilometers was sometimes considered the updip limit of the frictionally unstable, potentially seismogenic portion of the megathrust (Byrne et al., 1988; Scholz, 1998). Relocking the deep part of the asperity only, between 20 and 30 km depth, is insufficient to produce landward displacement on the overriding plate during the first year after the earthquake (Figures S5 and S6 in Supporting Information S1). 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).

Relocking of only the shallow portion of the central asperity, above 20 km depth, yields landward postseismic surface displacement at the near-trench tip of the overriding plate, at the surface (Figure S7 in Supporting Information S1) and in the subsurface (Figure S8 in Supporting Information S1). However, the maximum surface 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.

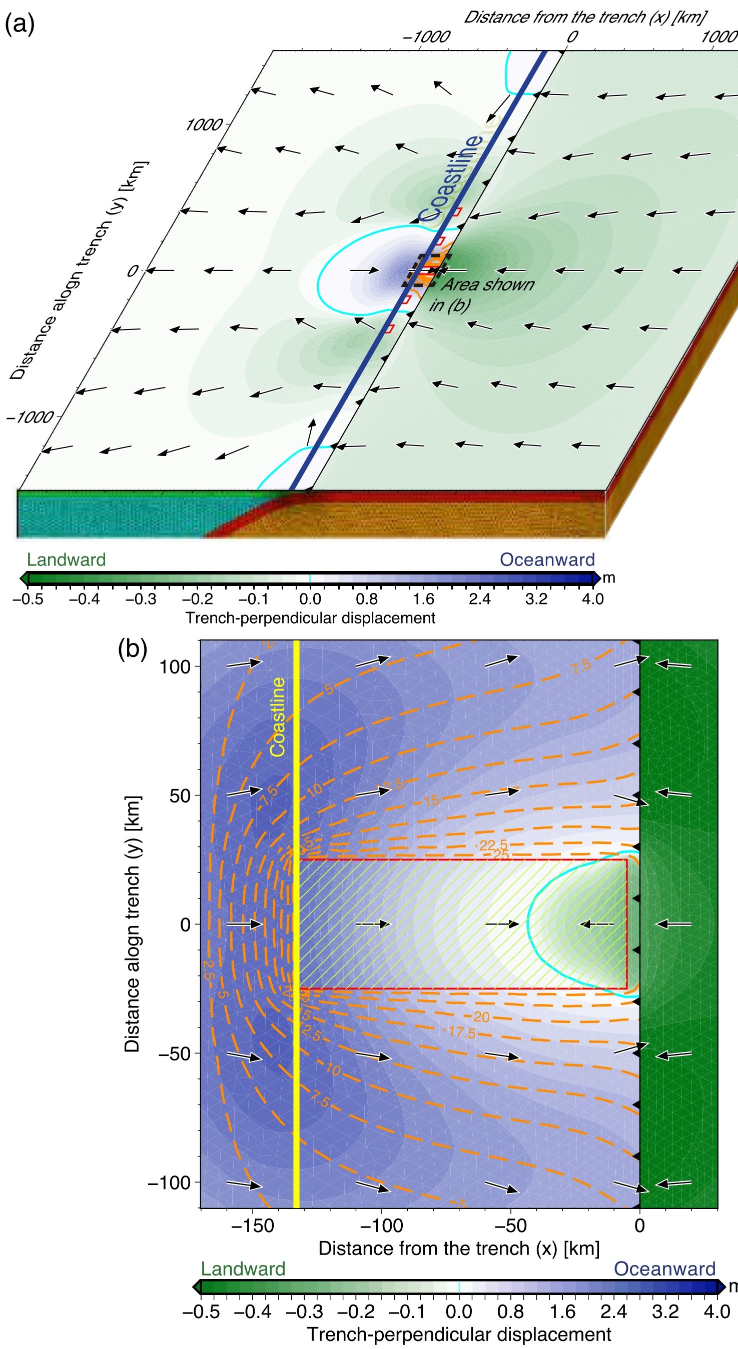

Figure 2. The whole asperity relocks instantly after the earthquake. Cumulative horizontal postseismic surface displacement after 1 yr, assuming afterslip has ceased by then and including steady-state plate convergence. Colors show the trench-perpendicular displacement. Note that the color scale is asymmetrical, 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.

3. Discussion and Conclusions

3.1. Interpretation, Consistency With Previous Research, and Limitations

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 K. Wang et al. (2012). Our results show that landward motion of the near-trench tip of the overriding plate requires mechanical coupling of the two plates on the megathrust. We interpret the cause of this for this dependency as follows: the near-trench portion of the slab, moving landward because 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 (Agata et al., 2019; Dhar et al., 2022; Freed et al., 2017; Fukuda & Johnson, 2021; Muto et al., 2019; Noda et al., 2018; Suito, 2017; Sun & Wang, 2015; Sun et al., 2014; Yamagiwa et al., 2015), 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). 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 back slip 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.

Previous studies generally consider afterslip to consist of all postseismic slip on the interface. This includes slip that releases slip deficit and associated elastic strains that were accumulated interseismically due to megathrust locking and not released coseismically. This afterslip is often assumed to decay in time while spatially stationary (e.g., Bedford et al., 2016). However, postseismic slip also occurs passively on unlocked portions of the megathrust as a result of interplate convergence and viscous relaxation. Since a lack of afterslip implies that the interface is locked, that is, does not slip, we can interpret the results of previous studies in terms of relocking by observing the afterslip distributions they use. 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. Diao et al. (2014) and Noda et al. (2018) invert exclusively onshore displacement time series into afterslip, with different slab geometries. They find no significant afterslip above a depth of 20 km below solid ground, corresponding to ∼150 and ∼90 km of horizontal distance from the trench, respectively, in each geometry. Freed et al. (2017) and Yamagiwa et al. (2015) invert onshore and offshore geodetic displacement time series into afterslip. 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. Dhar et al. (2022) and Muto et al. (2019) invert onshore and offshore geodetic observations with stress-driven afterslip. Muto et al. (2019) use 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. Dhar et al. (2022) use a 3D model and find a lack of afterslip as deep as 40 km below sea level in the central part of the rupture, and generally shallower than 30 km except for shallow afterslip to the south of the coseismic rupture zone and of the observed postseismic landward motion. 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 possibly due to the relatively limited peak amplitude of coseismic slip (27 m). Our choice of a single, uniform Maxwell viscosity also probably plays a role. In fact, previous studies find that explaining observations requires a spatially inhomogeneous, temporally variable effective viscosity, with lower short-term values particularly at the base of the slab (Agata et al., 2019, 2018;

Freed et al., 2017; Muto et al., 2019; Sun et al., 2014). However, there is no widespread agreement and best-fitting viscosities vary greatly with modeling methodology (Fukuda & Johnson, 2021). We do not aim to specifically reproduce observations and thus we do not explore different amplitudes and spatio-temporal distributions of viscosity that previous studies consider. Other models study megathrust behavior and include sophisticated methodologies that go beyond continuum mechanics and can provide insight into the specifics of the relocking mechanism. For instance, Caniven et al. (2021) use a discrete element method (Cundall & Strack, 1979; Morgan, 2015) that considers elastic particles interacting frictionally and indicates that megathrust relocking is controlled by fault dilatancy and contraction. Our models do not approach the full physical complexity of megathrust and bulk deformation at subduction zones. Rather, they merely establish that relocking, whatever its cause, is needed for the landward motion due to postseismic relaxation to extend from the slab to the top of the overriding plate, consistently with the results of previous modeling studies. Future work that considers additional complexity can investigate the role of specific relaxation and relocking mechanisms and patterns in explaining specific GNSS observations. Additionally, some interpretations of the likely behavior of the megathrust in vicinity of the Tohoku rupture can be made from the need of relocking to explain the observed presence of landward motion of the offshore portion of the overriding plate.

3.2. 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 2 months after the event (Japan Coast Guard, 2013). This implies that relocking occurred within a few weeks of the Tohoku earthquake. Rapid relocking was previously inferred from the decomposition of geodetic displacement time series after other large megathrust earthquakes, specifically 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). Dixon et al. (2014), Malservisi et al. (2015), and Voss et al. (2017) invert GNSS time series into afterslip and slow-slip events (SSEs) after the much smaller 2012 M_w 7.6 Nicoya earthquake. They find that afterslip decays with a dominant characteristic timescale of 70 days (Malservisi et al., 2015), after which SSEs only occur later and outside of the coseismic rupture area. Rapid relocking is thus not without support in previous research analyzing geodetic observations.

From the perspective of fault friction theories, rapid relocking of a ruptured fault asperity is compatible with the rate-and-state formulation (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. According to the common understanding of rate-and-state fault friction and its role in earthquake cycle behavior, afterslip and stable creep (i.e., a lack of interseismic coupling) 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; Freed et al., 2017; Japan Meteorological Agency, 2012). 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 (Freed et al., 2017; Muto et al., 2019; Noda et al., 2018; Sun & Wang, 2015; Sun et al., 2014; Yamagiwa et al., 2015), 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).

Our results show a need for rapid relocking of the shallow megathrust to produce landward postseismic motion offshore on the overriding plate. At the same time, the rapidly relocked area of a fault is generally understood to be a frictionally unstable interface. The most straightforward interpretation of these two factors together suggests that the shallow megathrust in the Tohoku region is a true asperity: unstably sliding, slipping coseismically and frictionally locked during the interseismic stage. This is in contrast with the conventional expectation that the shallow megathrust be stably sliding and unlocked interseismically (Loveless & Meade, 2010; Tsuru et al., 2000). This wisdom was partly challenged by observations of unusually large slip hosted by the shallow megathrust during the Tohoku earthquake (Meng et al., 2011). Herman et al. (2018) pointed out that slip deficit can accumulate on a low-friction portion of the megathrust passively locked by the mechanical continuity of the plates and the adjacent truly locked asperity, in a process they called pseudo-coupling. Noda and Lapusta (2013) instead proposed a shallow megathrust with frictional properties that allow it to be stably sliding interseismically and still slip substantially coseismically in a dynamic rupture simulation. These proposed mechanisms could reconcile stably sliding interseismic behavior with large coseismic slip. Furthermore, it is unclear whether the behavior of the Tohoku megathrust in the most recent earthquake reflects permanent frictional properties of the megathrust, or whether these properties changed during the last cycle.

In light of our model results, the rapid postseismic landward motion observed offshore the Tohoku earthquake suggests that the shallow megathrust there behaved as a true asperity, at least during the last cycle, without requiring the rupture to extend beyond the unstably sliding portion. This would imply that the nature of the shallow megathrust has been 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 could be stably sliding and have only hosted substantial coseismic slip because of dynamic rupture effects and/or pseudo-coupling. In this case, an explanation must be provided to explain sufficient coupling of the shallow megathrust shortly after the earthquake 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 in agreement with similar conclusions of rapid relocking drawn from onshore GNSS observations for other earthquakes, such as the 2010 Maule and 2007 Pisco earthquakes (Bedford et al., 2016; Remy et al., 2016). This suggests that rapid relocking is not restricted to a specific event or subduction zone. Near-trench, postseismic geodetic observations should detect evidence of shallow megathrust relocking, if any, following earthquakes producing substantial postseismic relaxation. However, a lack of postseismic landward motion, as for the first year following the 2005 Miyagi earthquake (Sato et al., 2011), does not necessarily imply a general lack of relocking. In particular, the lack of landward motion might be explained by locking being restricted to greater 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 2 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.

Data Availability Statement

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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