Are the frictional properties of creeping faults persistent?
Evidence from rapid afterslip following the 2011
Tohoku-oki earthquake

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11 March 2011 Mw 9.0 Tohoku-oki megathrust earthquake is the largest event worldwide whose early postseismic deformation was continuously recorded by a dense network of GPS receivers. Furthermore, this earthquake produced large stress changes in broad regions surrounding the coseismic rupture and thus provides an unprecedented opportunity to investigate the frictional behavior of RS regions on a real fault for a wide range of slip rates. In this study, we investigate the frictional behavior of afterslip areas using an inversion of postseismic GPS data after the Tohoku-oki earthquake.

1. Introduction

Geophysical observations and numerical studies have shown that creeping portions of faults have persistent rate-strengthening frictional properties and can act as barriers to earthquake rupture propagation. On the basis of GPS data following the 2011 Mw 9.0 Tohoku-oki earthquake in Japan, we find that the evolution of afterslip and postseismic shear stress on the plate interface is inconsistent with persistent rate-strengthening frictional properties but is consistent with slip-rate-dependent frictional properties that exhibit rate weakening (RW) at lower slip rates and rate strengthening (RS) at higher slip rates due to several mechanisms [Kaneko et al., 2010; Reifen et al., 2013 including thermal weakening [Kaneko et al., 2010], 2010]. An earthquake that initiates in a RW patch can propagate into surrounding RS regions where it is arrested if the RS property is sufficiently strong (i.e., large positive (a − b)σeff relative to the stress perturbations arising from the earthquake. Otherwise, the earthquake can propagate through the RS regions and trigger seismic slip on neighboring RW patches. This indicates that the degree of RS in stable regions is an important factor in determining the spatial extent of individual earthquakes [Kaneko et al., 2010].

In contrast, several experimental and numerical studies have shown that portions of a fault that exhibit RS behavior at low slip rates can become less RS with increasing slip rate and eventually become RW at higher slip rates due to several mechanisms [e.g., Reinen et al., 1991; Shibazaki et al., 2011; Noda and Lapusta, 2013] including thermal weakening [Noda and Lapusta, 2013]. This nonpersistent nature of frictional properties in RS regions has a significant influence on the spatial extent of individual earthquakes [Shibazaki et al., 2011; Noda and Lapusta, 2013]; however, the frictional behavior of RS regions upon real faults has not been quantified for a wide range of slip rates.

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that for afterslip following the 2003 main shock is an order of magnitude or more higher than (Figure 1b). The maximum slip rate immediately after the main shock was 3.5 m/yr, and that the locations of areas of large slip did not change significantly with time (Figure S5). Thus, the afterslip pattern following the Tohoku-oki earthquake enables us to study frictional behavior for higher slip rates than those considered previously [Perfettini and Avouac, 2004; Miyazaki et al., 2004; Hsu et al., 2006; Perfettini et al., 2010].

2. Inversion

To estimate the spatial and temporal evolution of afterslip, we use daily coordinate time series from 491 stations of a continuous GPS network in northeastern Japan from 11 March to 17 October 2011 (Text S1 in the supporting information). Coseismic displacements due to 5324 aftershocks with $M \geq 3.5$ are estimated and removed from the GPS time series (Text S1 and Figures S1 and S2).

We assume that the corrected postseismic deformation during the first 7 months following the main shock was due to afterslip on the subducting plate interface, following Ozawa et al. [2012]. The curved plate interface is modeled as a collection of triangular dislocation elements in a homogeneous elastic half-space [Thomas, 1993] which tessellate a model of the plate interface geometry [Nakajima and Hasegawa, 2006] (Figure S3). We apply a time-dependent inversion method [Fukuda et al., 2008] to the corrected GPS time series to estimate the spatial and temporal evolution of daily cumulative afterslip and afterslip rate on the model plate interface (Text S1).

The estimated cumulative afterslip during the first 7 months following the main shock is concentrated downdip of the area of large coseismic slip (Figure 1a). The estimated evolution of afterslip shows that slip decelerates with time and that the locations of areas of large slip do not change significantly with time (Figure S5). This spatial and temporal evolution is similar to that described previously [Ozawa et al., 2012]. The maximum slip rate exceeds 100 m/yr immediately after the main shock and is greater than 10 m/yr during the first ~15 days following the main shock (Figure 1b). The maximum slip rate immediately after the main shock is an order of magnitude or more higher than that for afterslip following the 2003 $M_W$ 8.3 Tokachi-oki earthquake (~7 m/yr) [Miyazaki et al., 2004] and the 2005 $M_W$ 8.7 Nias earthquake (~6 m/yr) [Hsu et al., 2006]. Thus, the afterslip pattern following the Tohoku-oki earthquake enables us to study frictional behavior for higher slip rates than those considered previously [Perfettini and Avouac, 2004; Miyazaki et al., 2004; Hsu et al., 2006; Perfettini et al., 2010].

3. Fault Frictional Properties

Previous studies have shown that the evolution of afterslip is consistent with steady state RS friction (equation (1)) with a positive and constant $(a - b)\sigma_{eff}$. Following the 2003 Tokachi-oki and 2005 Nias earthquakes, afterslip-related shear stress changes in afterslip areas evolved approximately linearly with the logarithm of slip rate, suggesting that afterslip is governed by steady state RS friction with constant $(a - b)\sigma_{eff}$ [Miyazaki et al., 2004; Hsu et al., 2006]. The use of a spring-slider model that employs steady state RS friction with constant $(a - b)\sigma_{eff}$ gives the following slip evolution with time $t$ in response to a shear stress step at $t = 0$ [Perfettini and Avouac, 2004]:

$$s(t) = \frac{(a - b)\sigma_{eff}}{k} \ln \left[ 1 + \frac{V_0}{V_{pl}} (e^{tc} - 1) \right]$$

where $k$ is the spring stiffness, $V_0$ is the initial slip rate immediately after the stress step, $V_{pl}$ is the load point velocity, which is taken as the plate velocity [Hsu et al., 2006; Perfettini et al., 2010], and $t_c$ is the characteristic decay time given by $t_c = \frac{(a - b)\sigma_{eff}}{kV_{pl}}$. Equation (2) successfully reproduces the temporal evolution of afterslip and postseismic deformation following many large earthquakes [Perfettini and Avouac, 2004; Hsu et al., 2006; Perfettini et al., 2010].
again suggesting that afterslip is governed by steady state RS friction with constant \((a-b)\sigma_{\text{eff}}\).

[10] We fit equation (2) to the time series of cumulative afterslip obtained from the inversion by estimating \((a-b)\sigma_{\text{eff}}k\) and \(V_0^b\) (Text S1), revealing that equation (2) does not reproduce the time series of afterslip (Figures 2a–2c). A set of parameters that provides the best fit to afterslip during the first 15 days following the main shock significantly underpredicts the subsequent slip, whereas another set of parameters that best fits the slip time series after the 51st day following the main shock does not reproduce the rapid early afterslip in the first month (Figures 2a–2c). Similarly, equation (2) does not reproduce the time series of the afterslip moment (Figure 2d and Text S1), indicating that the misfit between the inverted slip history and equation (2) is a robust feature. This result suggests that the temporal evolution of afterslip is inconsistent with steady state RS friction with constant \((a-b)\sigma_{\text{eff}}\).

[11] We next compute the spatial and temporal evolution of shear stress changes on the plate interface due to afterslip, using the inverted slip history [Thomas, 1993]. The steady state RS friction (equation (1)) with constant \((a-b)\sigma_{\text{eff}}\) predicts a positive linear relation between shear stress and the logarithm of slip rate. However, in contrast to this prediction, shear stress changes plotted as a function of the logarithm of slip rate exhibit convex upward curves (Figure 3a), which is again inconsistent with steady state RS friction with constant \((a-b)\sigma_{\text{eff}}\).

[12] If afterslip is governed by steady state RS friction (equation (1)), \((a-b)\sigma_{\text{eff}}\) is given by \(d\tau_{\text{eff}}/d\ln V\), i.e., the slope of the stress-log(slip rate) curve. Thus, the stress-log(slip rate) curves (Figure 3a) suggest that \((a-b)\sigma_{\text{eff}}\) is not a constant but is dependent on slip rate. We therefore determine \((a-b)\sigma_{\text{eff}}\) as a function of slip rate by fitting a quadratic function to each stress-log(slip rate) curve and calculating the slope of the function (Figures S6 and 3b). We then calculate the afterslip as a function of time assuming a spring-slider model by solving equation (1) together with a quasi-static force balance equation given by \(d\tau_{\text{eff}}/dt = k(V_{\text{pl}} - V)\) with the initial condition \(V(t = 0) = V_0^b\), where we use the rate-dependent \((a-b)\sigma_{\text{eff}}\) determined from the stress-log(slip rate) curves (Figure 3b). We fit this model to the time series of cumulative afterslip by adjusting \(V_0^b\) and \(k\). The predicted afterslip histories perform well in reproducing the inverted slip histories (Figures 3d–3f). In addition, the stress-log(slip rate) relations from the afterslip model exhibit convex upward patterns similar to those from the inversion (Figure 3c). Thus, the model of afterslip with the rate-dependent \((a-b)\sigma_{\text{eff}}\) successfully reproduces both the temporal evolution of afterslip and the convex upward stress-log(slip rate) relations that cannot be reconciled with the model with constant \((a-b)\sigma_{\text{eff}}\).

[13] As opposed to our results, Ozawa et al. [2012] argued that the model with constant \((a-b)\sigma_{\text{eff}}\) (equation (2)) can perform well in fitting time series of afterslip moment if the loading velocity \(V_{\text{pl}}\) is adjusted as an unknown and
concluded that the evolution of afterslip is governed by the steady state RS friction (equation (1)) with constant \((a - b)\sigma_{\text{eff}}\). However, we find that \(V_{pl}\) must be significantly greater than the plate velocity (0.084 m/yr \cite{Sella et al., 2002}) to fit the afterslip and moment time series \((V_{pl} = 1.0 - 1.5\ m/yr\ for\ afterslip\ and\ V_{pl} \approx 0.4\ m/yr\ for\ moment)\). Furthermore, even if \(V_{pl}\) is large enough to fit the afterslip time series, the steady state RS friction with constant \((a - b)\sigma_{\text{eff}}\) does not predict the convex upward stress-log(slip rate) relations derived from the inversion (Figure 3a). We therefore conclude that the evolution of afterslip is inconsistent with a constant \((a - b)\sigma_{\text{eff}}\).

\cite{Perfettini et al., 2010} The estimated values of \((a - b)\sigma_{\text{eff}}\) for slip rates lower than 10 m/yr are on the order of 0.1 MPa (Figure 3b). These values are comparable with values of \((a - b)\sigma_{\text{eff}}\) estimated from afterslip following previous \(M_W \leq 8.7\) earthquakes with slip rates lower than 10 m/yr \cite{Perfettini and Avouac, 2004; Miyazaki et al., 2004; Hsu et al., 2006; Perfettini et al., 2010}. For slip rates between 10 and 100 m/yr, the estimated values of \((a - b)\sigma_{\text{eff}}\) are on the order of 0.01 MPa (Figure 3b), an order of magnitude smaller than previous estimates for lower slip rates. The rate dependence of \((a - b)\sigma_{\text{eff}}\) is qualitatively similar to the laboratory-measured rate dependence of \(a - b\) for antigorite serpentinite \cite{Reinen et al., 1991} in the sense that a higher slip rate leads to a reduced degree of RS. Alternatively, the rate dependence of \((a - b)\sigma_{\text{eff}}\) could result from time-dependent \(\sigma_{\text{eff}}\) due to temporal variations in pore fluid pressure. Elevated pore pressure in the afterslip area could induce postseismic fluid flow away from the area due to poroelastic effects \cite{Koerner et al., 2004}. Such fluid flow would gradually reduce the pore pressure in the afterslip area and could generate the rate dependence of \((a - b)\sigma_{\text{eff}}\).

\subsection{4. Discussion}

\cite{Shimamura et al., 2004} The reduced degree of RS at high slip rates promotes the propagation of seismic slip from a RW patch into surrounding RS regions \cite{Kaneko et al., 2010}. Therefore, early interplate aftershocks initiated on RW patches surrounded by rapid afterslip could be promoted to rupture broader RS regions than preseismic and late postseismic earthquakes initiated on the same patches. \textit{Shimamura et al.} \cite{2011} reported that an \(M 5.9\) interplate aftershock, which occurred 9 days after the Tohoku-oki earthquake in the afterslip area, ruptured the area of the \(M \sim 4.8\) repeating earthquake sequence offshore of Kamaiishi (\(\sim 39.3^\circ\ E, \sim 142.1^\circ\ N\)) \cite{Matsuzawa et al., 2002}, as well as an adjacent area where earthquakes had not been observed before the Tohoku-oki earthquake. Consequently, the radius of the \(M 5.9\) rupture was five times as large as that of the \(M \sim 4.8\) repeating earthquakes \cite{Shimamura et al., 2011}. This increase in rupture dimension could possibly be explained by enhanced rupture of the RS region adjacent to the \(M \sim 4.8\) repeating earthquake patch due to a reduced RS property associated with rapid afterslip.

\cite{Konca et al., 2008} There is growing evidence that great earthquakes \((M_{\text{W}} > 8)\) occur in regions that include the rupture areas of smaller earthquakes \((M_{\text{W}} \sim 7–8)\) \cite[e.g., Nanyama et al., 2003; Konca et al., 2008]{}. The rate dependence of
(a–b)σ_{\text{eff}} found for the Tohoku-oki afterslip may provide an explanation of this noncharacteristic behavior. If an earthquake that nucleated on a RW patch produces a sufficiently large stress increase in surrounding RS regions, slip on the RS regions would be substantially accelerated, and reduced (a–b)σ_{\text{eff}} at high slip rates would prevent the RS regions from acting as barriers to rupture propagation. Consequently, the earthquake would rupture multiple RW patches, potentially resulting in a great earthquake. Otherwise, slip in RS regions would not be accelerated sufficiently and the RS regions would act as barriers to rupture propagation due to the larger (a–b)σ_{\text{eff}} at lower slip rates, resulting in a smaller earthquake that ruptures only a single RW patch. If the transition from RS to RW behavior occurs at higher slip rates [Reinen et al., 1991; Shibasaki et al., 2011; Noda and Lapusta, 2013], it would further promote the rupture of multiple RW patches [Shibasaki et al., 2011]. Therefore, the rate-dependent behavior of (a–b)σ_{\text{eff}} in RS regions may provide a key to the occurrence of great earthquakes. To further understand the role of the rate dependence of (a–b)σ_{\text{eff}} in determining the spatial extent of earthquakes, it is important to quantify (a–b)σ_{\text{eff}} for real faults, considering slip rates higher than those employed here.

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