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Key Points:

- Independent confirmation of long-term transient slip event preceding the M_w 9 Tohoku-oki earthquake
- Repeating earthquakes during 1996–2011 occurred at an accelerated rate near the M_w 9 source area
- Consistent estimates of slip acceleration are inferred from independent geodetic and seismicity data

Supporting Information:

- Texts S1 to S4, Table S1, Figures S1 to S12

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Long-term acceleration of aseismic slip preceding the M_w 9 Tohoku-oki earthquake: Constraints from repeating earthquakes

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Abstract A decadal-scale deformation transient preceding the 2011 M_w 9 Tohoku-oki, Japan, earthquake was reported from continuous GPS data and interpreted as accelerating aseismic slip on the Japan Trench megathrust. Given the unprecedented nature of this transient, independent confirmation of accelerating slip is required. Here we show that changes in the recurrence intervals of repeating earthquakes on the Japan Trench megathrust in the period 1996 to 2011 are consistent with accelerating slip preceding the Tohoku-oki earthquake. All sequences of repeating earthquakes with statistically significant trends in recurrence interval (at 95% confidence) offshore south central Tohoku occurred at an accelerating rate. Furthermore, estimates of the magnitude of slip acceleration from repeating earthquakes are consistent with the completely independent geodetic estimates. From a joint inversion of the GPS and seismicity data, we infer that a substantial portion of the megathrust experienced accelerating slip, partly surrounding the eventual rupture zone of the M_w 9 earthquake.

1. Introduction

Estimating spatiotemporal variations of aseismic slip on major plate boundaries is a fundamental step toward understanding the underlying mechanical processes that may influence the magnitude and timing of damaging earthquakes. Short-term foreshock activity, possibly associated with propagation of aseismic slip, has been found to precede recent large megathrust earthquakes, namely, the 2011 M_w 9.0 Tohoku-oki, Japan, [*Ando and Imanishi*, 2011; *Kato et al.*, 2012] and the 2014 M_w 8.1 Iquique, Chile, [*Hayes et al.*, 2014; *Ruiz et al.*, 2014; *Schurr et al.*, 2014] events. Furthermore, a very long duration deformation transient that spanned the period 1996–2011, prior to the 11 March 2011 M_w 9 Tohoku-oki event, was reported from continuous Global Positioning System (GPS) observations in northern Honshu, Japan [*Mavrommatis et al.*, 2014; *Yokota and Koketsu*, 2015] (Figure 1). The transient was not related to postseismic transients from several M_w ~6–7 earthquakes in the period 2003–2011 or larger historical earthquakes and was therefore interpreted as accelerating aseismic slip on the Japan Trench megathrust, i.e., a decadal-scale transient slip event [*Mavrommatis et al.*, 2014]. Given that such a long-duration transient slip event—preceding a M_w 9 earthquake—is unprecedented, providing independent confirmation of its occurrence is vital. Furthermore, land-based GPS data have poor spatial resolution of slip on the shallow, near-trench portion of the megathrust, where the M_w 9 rupture occurred [*Loveless and Meade*, 2011]; thus, the spatial relationship between the M_w 9 rupture area and the hypothesized accelerating creep is uncertain. Here we use independent observations of small repeating earthquakes that occurred on the Japan Trench megathrust to test for the GPS-inferred accelerating slip preceding the M_w 9 event and improve its spatial resolution.

Repeating earthquakes have nearly identical waveforms, magnitudes, and source locations and have been found in a number of tectonic settings including the San Andreas Fault, California, [*Bufe et al.*, 1977; *Vidale et al.*, 1994; *Nadeau and Johnson*, 1998; *Schaff et al.*, 1998; *Bürgmann et al.*, 2000] and the Japan Trench [*Igarashi et al.*, 2003; *Uchida et al.*, 2003; *Uchida and Matsuzawa*, 2011]. Sequences of repeating earthquakes respond to large nearby earthquakes with decreasing recurrence intervals that gradually recover to premainshock rates, consistent with their being driven by frictional afterslip [*Schaff et al.*, 1998; *Nadeau and McEvilly*, 2004; *Uchida et al.*, 2003; *Chen et al.*, 2010; *Taira et al.*, 2014; *Uchida et al.*, 2015]. Additionally, variations in recurrence intervals were correlated with independent geodetic measurements of fault creep [*Nadeau and McEvilly*, 1999]. These observations have led to the conceptual model that these earthquakes represent repeated failure of a single

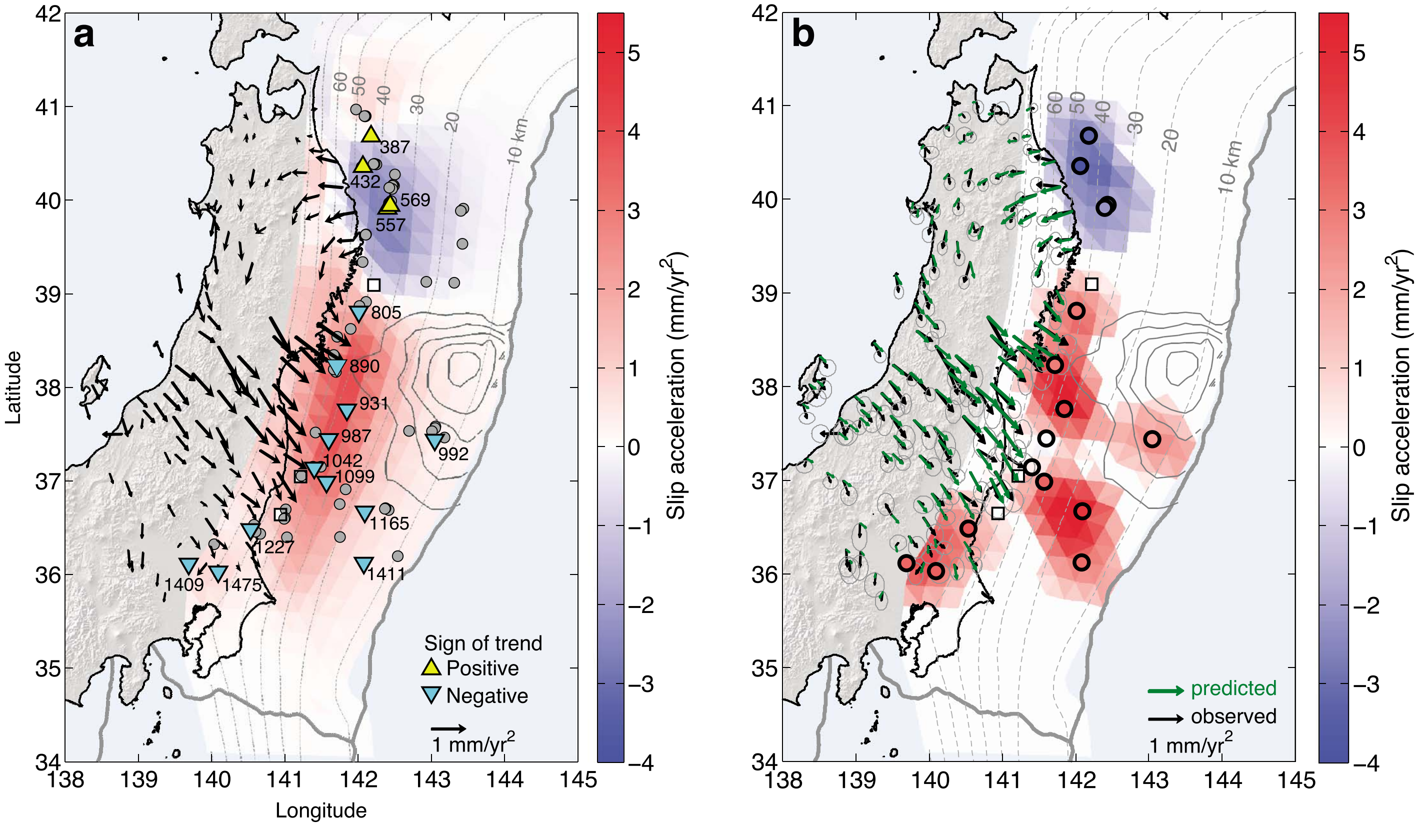

Figure 1. (a) Map of GPS station accelerations estimated by *Mavrommatis et al.* [2014] (black arrows). Colors (blue to red) represent dip-slip component of estimated slip acceleration on the plate interface based on the GPS data. Sequences of repeating earthquakes that pass the Mann-Kendall (MK) test for significant trends in their recurrence intervals (95% confidence) are shown as triangles, with yellow upward triangles indicating positive trends (decelerating recurrence) and cyan downward triangles indicating negative trends (accelerating recurrence). Gray circles are sequences that do not pass the MK test; white squares are sequences that do not pass the MK test and have a coefficient of variation in their recurrence interval less than 0.1 (near-regular recurrence). Contours of coseismic slip distribution of the 2011 M_w 9 Tohoku-oki earthquake in 10 m intervals from *Hooper et al.* [2013] are also shown. (b) Preferred model of slip acceleration on the plate interface resulting from the joint inversion of GPS and repeating earthquakes (colors as in Figure 1a). Circles show the estimated slip accelerations at the locations of the repeating earthquake sequences that passed the MK test. Observed GPS accelerations (same as in Figure 1a) shown as black arrows with 2σ error ellipses, predicted in green.

fault patch (asperity), driven by creep on the surrounding fault. The fault patch slips repeatedly in order to keep up with accumulated slip on the surrounding fault. As a consequence, variability in the recurrence interval can be interpreted as variability in the surrounding creep rate.

2. Trends in Recurrence Intervals of Repeating Earthquakes

We use a catalog of repeating earthquakes in which events offshore Northeastern Japan were grouped into sequences (families) based on the similarity of their waveforms [*Uchida and Matsuzawa*, 2013] (Figure S1 in the supporting information). The catalog includes only events that occurred on the upper surface of the Pacific Plate and whose focal mechanisms were similar to that of the Tohoku-oki earthquake (low-angle thrust) [*Uchida and Matsuzawa*, 2013]. The catalog is complete to M 2.5 for the period 1993 to 2011, prior to the Tohoku-oki earthquake (magnitudes determined by the Japan Meteorological Agency). Here we consider the time period 21 March 1996 to 6 February 2011, i.e., the same period as the GPS data analyzed by *Mavrommatis et al.* [2014].

Our approach is to test whether repeating earthquake sequences exhibit significant monotonic trends in recurrence interval. To observe a monotonic trend in recurrence interval, only sequences with at least three intervals (i.e., four events) can be used. We therefore limit the data to sequences with at least four events in the time period of interest. In addition, we retain only sequences in which events have an average magnitude of at least M 3 and a small variation in magnitude ($\sigma < 0.3$ units), and we exclude short-lived sequences

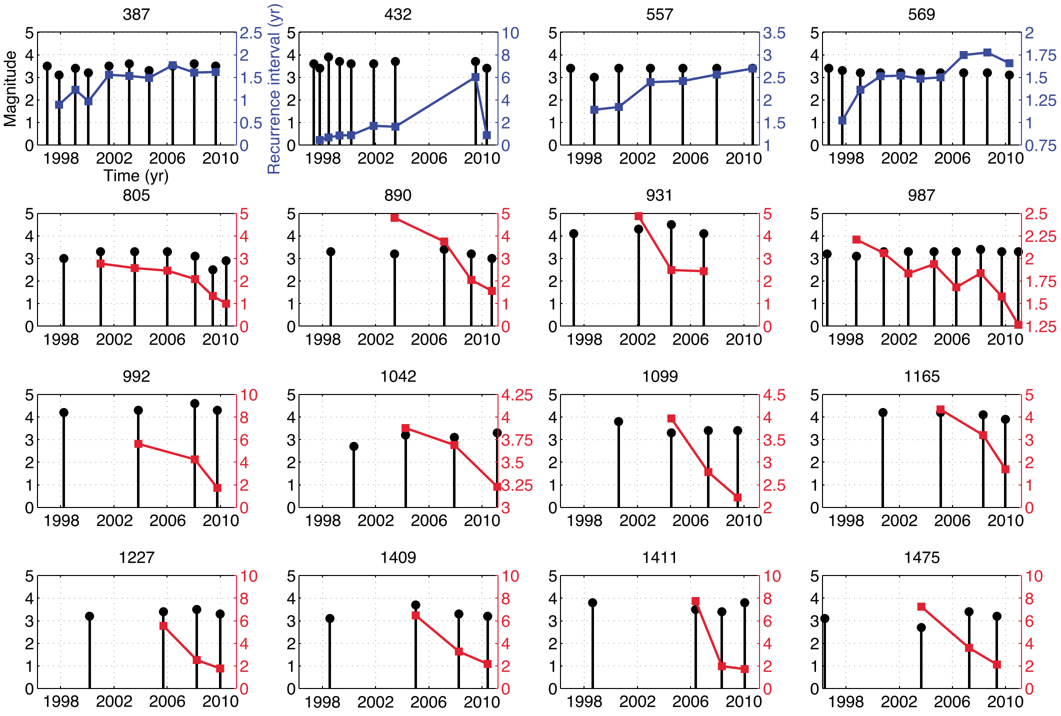

Figure 2. Chronology of repeating earthquakes with statistically significant monotonic trends in recurrence interval according to the Mann-Kendall test (95% confidence). Each panel corresponds to a sequence showing magnitudes (black stems) and recurrence interval as a function of time (blue curves if trend is positive, red if trend is negative). The locations of the sequences are shown in Figure 1a.

(details in Text S1). Seventy-six sequences satisfy all of the above criteria (Figures 1 and S1)—we use only these sequences for the rest of the analysis.

We first test whether any of these sequences exhibit a statistically significant monotonic trend in recurrence interval by applying the Mann-Kendall (MK) test for nonparametric trend detection [*Mann*, 1945; *Kendall*, 1948] (Text S2). Sixteen sequences pass the test at the 95% confidence level, i.e., exhibit monotonic trends in their recurrence intervals (Figures 1a and 2 and Table S1). Using the binomial distribution, we assess the collective significance of the individual tests as a whole [*Livezey and Chen*, 1983]: at the 95% confidence level, the probability that the observed percentage of sequences (16/76) passed the test by chance is negligible ($\sim 10^{-7}$) (Figure S3). Out of the 60 sequences that do not pass the MK test (at 95% confidence), three have a coefficient of variation in their recurrence interval less than 0.1 (Figures 1 and S4), meaning that these sequences exhibit near-regular recurrence (no trend).

The sign of the trend in the recurrence intervals of individual sequences has a highly systematic spatial pattern (Figure 1a). Offshore south central Tohoku (latitude range 36°–39°) 12 sequences that passed the MK test at 95% confidence display negative trends in recurrence interval, i.e., decreasing interval with time (accelerating recurrence). On the other hand, offshore northern Tohoku (latitude range 39°–41°), the remaining four sequences that passed the test show positive trends in recurrence interval, i.e., decelerating recurrence. Application of the collective significance test separately for sequences in the north and south yields a probability that the sequences passed the test by chance of 1.8% for the north (4/31 sequences passed) and $\sim 10^{-7}$ for the south (12/45 sequences passed). This implies that each of the two subsets of sequences is collectively significant at the 95% level, indicating that the observed along-strike dichotomy in the sign of the trend is significant. Relaxing the confidence level of the MK test to 90%, 17 sequences offshore south central Tohoku have decreasing recurrence interval, and one sequence exhibits increasing interval (Figure S5a). A similar pattern is observed after computing the Spearman's rank correlation coefficient, ρ, between recurrence interval and time in each of the 76 sequences: recurrence interval tends to monotonically decrease ($\rho < 0$) for most sequences in the south and monotonically increase ($\rho > 0$) for most sequences in the north (Figure S5b).

The spatial pattern of the trends of recurrence intervals of repeating earthquakes is entirely consistent with the distribution of slip acceleration inferred from the completely independent GPS data by *Mavrommatis et al.* [2014] (Figure 1a). Offshore northern Tohoku (Sanriku area), increasing recurrence intervals imply decelerating creep, which we interpret as afterslip from the 1994 M_w 7.7 Sanriku earthquake, in agreement with previous studies [*Igarashi et al.*, 2003; *Uchida et al.*, 2003; *Uchida and Matsuzawa*, 2013]. Offshore south central Tohoku, decreasing recurrence intervals imply long-term accelerating creep prior to the M_w 9 Tohoku-oki earthquake, confirming the inference from independent GPS observations [*Mavrommatis et al.*, 2014; *Yokota and Koketsu*, 2015].

3. Estimating Slip From Recurrence Intervals

While the sign of the slip acceleration inferred from repeating earthquakes is consistent with the inference from independent GPS data, in order to quantitatively compare the magnitude of the acceleration, we need to estimate the amount of slip in each repeating event of a given seismic moment. We calculate the moments of the events in the catalog using their magnitudes and the standard relationship of *Hanks and Kanamori* [1979]. Following previous studies [*Scholz*, 1990; *Schaff et al.*, 1998; *Nadeau and Johnson*, 1998; *Beeler et al.*, 2001; *Nadeau and McEvilly*, 1999, 2004; *Chen et al.*, 2007; *Chen and Lapusta*, 2009], we assume that slip in a repeating earthquake of a given moment M_0 that occurs at time t has a constant, characteristic magnitude of $\bar{s} = V_L(t)T(t)$, where $V_L(t)$ is the average slip rate on the surrounding fault during the recurrence interval $T(t)$ between the last earthquake and time t. Slip within an asperity can be both seismic and aseismic. If slip is characteristic, $\bar{s}$ is independent of $V_L(t)$; hence, $V_L(t)$ and $T(t)$ are inversely proportional for the same M_0. For a sequence of events with characteristic moment $\overline{M_0}$ in which the hypothesis of steady V_L cannot be rejected (i.e., there is no significant trend in $T(t)$), the characteristic slip is thus equal to $\bar{s}(\overline{M_0}) = V_L\overline{T}(\overline{M_0})$, where $\overline{T}$ is the average recurrence interval in the sequence. Since the observables from a catalog of repeating earthquakes are only $\overline{T}$ and $\overline{M_0}$, additional information about V_L is required to compute $\bar{s}(\overline{M_0})$. *Nadeau and Johnson* [1998] used geodetic estimates of V_L and observations of $\overline{T}(\overline{M_0})$ to empirically compute $\bar{s}(\overline{M_0})$, neglecting aseismic slip. However, this model leads to extreme stress drops for the smallest events. Alternatively, one can use a physical model of repeating earthquake recurrence and compute $\bar{s}(\overline{M_0})$ using the value of V_L that best fits the observations of $\overline{T}(\overline{M_0})$ [*Beeler et al.*, 2001; *Chen and Lapusta*, 2009].

Only a small subset of the repeating sequences has significant trends in recurrence interval. For most of the sequences we cannot reject the hypothesis of steady V_L, and hence, we can use these sequences to fit models of $\overline{T}(\overline{M_0})$. Here we consider three different such models, which we refer to as (1) standard model, (2) Nadeau-Johnson model, and (3) Beeler model. The standard model represents each repeating earthquake as rupture on a circular crack that undergoes uniform stress drop; in addition, slip that is accommodated at the location of the repeating earthquake is assumed to be entirely seismic. The Nadeau-Johnson model [*Nadeau and Johnson*, 1998] is an empirical relationship between recurrence interval and moment based on observations from the San Andreas Fault, California. The Beeler model [*Beeler et al.*, 2001] allows for aseismic slip as part of the cumulative slip that is accommodated at the location of the repeating earthquake via a strain-hardening constitutive law. Further description of these models and their differences is provided in Text S3.

We fit each model to the observations of $\overline{T}(\overline{M_0})$ using a Markov chain Monte Carlo (MCMC) method (Text S3 and Figure S6). According to the Akaike information criterion (AIC) [*Akaike*, 1974] and Bayesian information criterion (BIC) [*Schwarz*, 1978], the Nadeau-Johnson and Beeler models give significantly better fits to the data than the standard model, with the Beeler model having slightly lower values of both BIC and AIC (Text S3). We adopt the Beeler model, which depends on three parameters: loading velocity, V_L, stress drop, $\Delta\tau$, and strain-hardening coefficient, C, which controls the ratio of aseismic to total slip. The fit to the data is shown in Figure 3a; while there is significant scatter in the data (presumably due to factors including spatial variability in creep rate and stress drop), the model captures the observed weak variation of recurrence interval with moment. The MCMC estimation results in probability distributions of the model parameters, with the maximum-likelihood estimates being $V_L = 5.0[4.1, 8.2]$ cm/yr, $\Delta\tau = 7.9[2.2, 9.8]$ MPa, and $C = 0.6[0.2, 1.4]$ MPa/cm, where the numbers in brackets are the 95% confidence limits. Our estimate of C is consistent with previous estimates for northern Japan of $C = 0.5-1$ MPa/cm [*Igarashi et al.*, 2003]. For each realization of V_L, $\Delta\tau$, and C, we have one realization of predicted relationship between recurrence

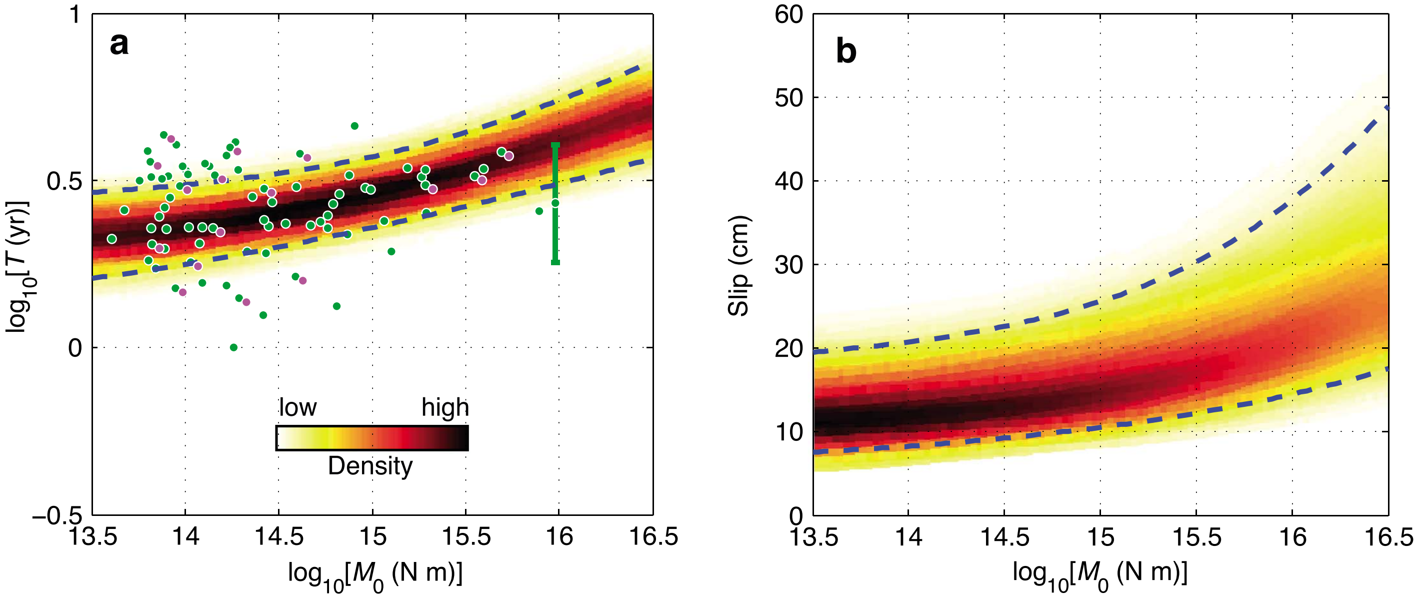

Figure 3. (a) Fit of the *Beeler et al.* [2001] model to the observed variation between recurrence interval and seismic moment of repeating earthquake sequences. Dots plot average recurrence intervals, $\overline{T}$, and moments, $\overline{M_0}$, of the 76 sequences used in the analysis (sequences that failed the Mann-Kendall test in green, those that passed in magenta). Background color shows the density of fitted models of $\overline{T}(\overline{M_0})$ estimated using MCMC sampling. Blue dashed curves are 95% confidence limits. Error bar indicates average standard deviation of the recurrence intervals. (b) Slip as a function of moment predicted from the distribution of $\overline{T}(\overline{M_0})$ in Figure 3a. Colors as in Figure 3a.

interval and moment, $\overline{T}(\overline{M_0})$ (equation (S10)), and slip and moment, $\overline{s}(\overline{M_0})$; the latter is independent of V_L and is given by

$$\overline{s}(\overline{M_0}) = \Delta\tau \left[\frac{1}{1.81\mu} \left(\frac{\overline{M_0}}{\Delta\tau} \right)^{1/3} + \frac{1}{C} \right], \tag{1}$$

where $\mu = 30$ GPa is the assumed shear modulus. The uncertainty from the scatter in the data is therefore propagated into the prediction of slip (Figure 3b).

Each realization of the model parameters derived from the MCMC estimation yields one realization of slip as a function of moment, $\overline{s}(\overline{M_0})$. Using these realizations and the dates and moments of the events in each sequence of repeating earthquakes, we compute many realizations of cumulative slip history, $s(t)$, for each sequence (Figure S7). The calculation of cumulative slip takes into account the variation of both recurrence interval and moment within each sequence.

4. Slip Acceleration Inferred From Repeating Earthquakes

We model cumulative slip history at the location of a given repeating sequence, $s(t)$, as a superposition of steady creep, constant acceleration, and rapid afterslip following moderate to large earthquakes

$$s(t) = s_0 + \dot{s}_0 \cdot (t - t_0) + \frac{1}{2}\ddot{s} \cdot (t - t_0)^2 + s_{\text{aft}}(t), \tag{2}$$

where s_0 is the slip at the time t_0 of the first event in the sequence, $\dot{s}_0$ is the initial slip rate, $\ddot{s}$ is the slip acceleration, and $s_{\text{aft}}(t)$ is the cumulative afterslip. Equation (2) is based on the constant acceleration model of *Mavrommatis et al.* [2014] that was used to fit GPS time series from the same time period. The constant acceleration is a first-order approximation to the actual long-term slip transient and is only applicable to the period under consideration.

Some of the cumulative slip at the locations of the repeating earthquakes results from rapid afterslip following several moderate to large earthquakes that occurred in the period 2003–2011. We correct for afterslip from $M_w > 6.3$ earthquakes before interpreting any residual, long-term slip transient as follows. We use the afterslip prediction of *Johnson et al.* [2013], who modeled transient postseismic deformation from 2003 to

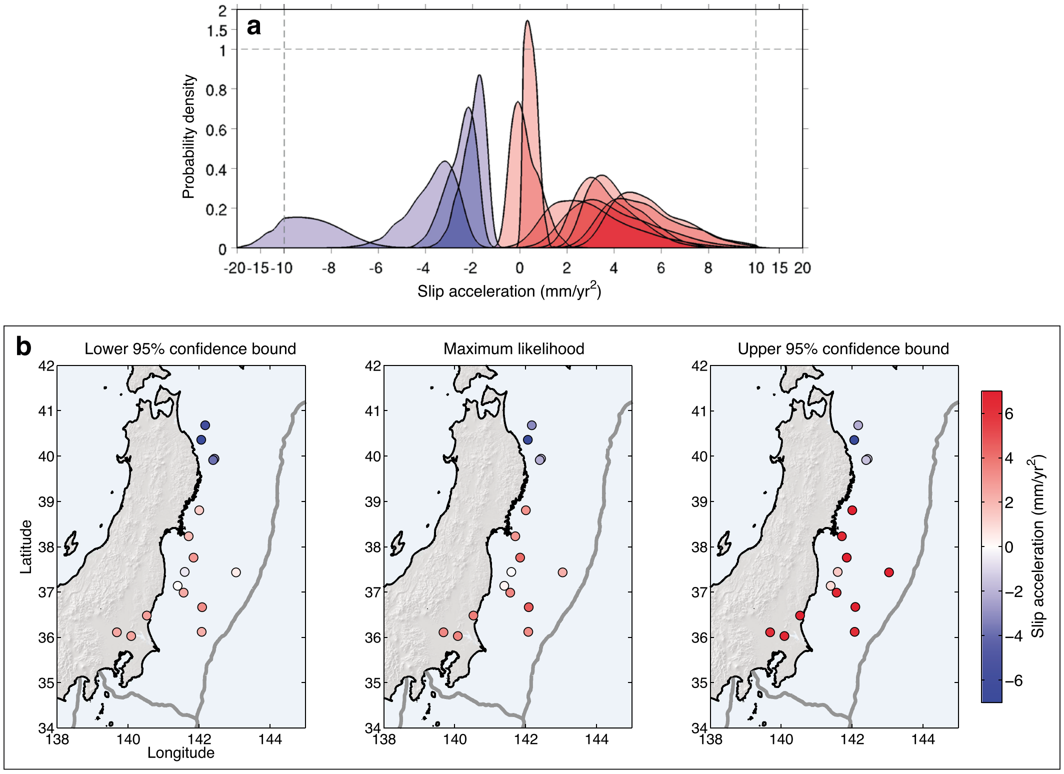

Figure 4. (a) Probability density functions (PDFs) of slip acceleration corrected for afterslip from each sequence of repeating earthquakes that passed the Mann-Kendall (MK) test. Distributions for sequences offshore northern Tohoku (39° – 41° latitude) are shown in blue, south central Tohoku (36° – 39° latitude) in red. Dashed gray lines mark changes in scale increments (for clarity). (b) Spatial distribution of estimated slip acceleration at the locations of the repeating sequences that passed the MK test. Panels correspond to lower 95% confidence bounds (left), maximum-likelihood values (middle), and upper 95% confidence bounds (right), derived from the PDFs in Figure 4a.

2011 using an asperity model in which patches on the Japan Trench that generated M_w 6.3 – 7.2 earthquakes undergo uniform stress drops at the times of the earthquakes, while surrounding regions creep according to a steady state velocity-strengthening friction law (Figure S8). While the afterslip prediction is somewhat sensitive to the location of the modeled asperities, in most cases the modeled afterslip is small compared to the total cumulative slip (Figure S7). Probability density functions of slip acceleration, $\ddot{s}$, in each repeating sequence are estimated by subtracting the local afterslip from each realization of cumulative slip in that sequence and fitting the residual time series $(s(t) - s_{\text{aft}}(t))$ with a quadratic polynomial, as in equation (2), imposing a nonnegativity constraint on the instantaneous slip rate (Figures 4a and S9).

In 15 out of the 16 sequences that passed the MK test, we can reject zero slip acceleration (corrected for afterslip) with very high confidence, and the signs of the accelerations are consistent with the trends in the recurrence intervals (Figure 4a): in all four sequences offshore northern Tohoku that exhibited decelerating recurrence, the probability of negative slip acceleration is >99%; and in 11 out of the 12 sequences offshore south central Tohoku that exhibited accelerating recurrence, the probability of positive slip acceleration is also >99%. Figure 4b shows the spatial pattern of the resulting acceleration at the locations of the 16 sequences that passed the MK test. If we include the other 60 sequences that did not pass the MK test, we still observe a pattern of mostly negative slip accelerations in the north and positive in the south, albeit with more variability (Figure S10). However, the accelerations in those sequences are less reliable as they do not exhibit a clear monotonic signal and hence are likely to be biased due to other unmodeled effects. Such effects may include interactions between nearby repeating asperities, local stress increases due to the occurrence of larger earthquakes, and afterslip following $M_w < 6.3$ events. Offshore south central Tohoku, the maximum-likelihood value of the slip acceleration in the sequences that passed the MK test is on average 2.9 mm/yr^2. The spatially averaged slip acceleration in the same region inferred by *Mavrommatis et al.* [2014] using GPS data ranged between 2.6 and 4.0 mm/yr^2. Even though the repeating earthquakes and the GPS time series are completely independent data sets, both the spatial pattern and the magnitude of slip accelerations are remarkably consistent between the two. This result adds further confidence to the interpretation of accelerating creep on the megathrust preceding the Tohoku-oki earthquake.

5. Joint GPS/Repeating Earthquake Estimation of Slip Acceleration

Repeating earthquakes can improve spatial resolution of slip acceleration on the megathrust relative to GPS-only inversions. Using accelerations in GPS time series, *Mavrommatis et al.* [2014] imaged slip acceleration to be concentrated in depths greater than ~20 km, downdip of the M_w 9 rupture area (Figure 1a). The inference of negligible shallow acceleration is a result of a minimum-norm regularization of the underdetermined inverse problem and the poor resolution of shallow slip from GPS [*Loveless and Meade*, 2011]. Here we perform a joint inversion (Text S4) in which we fit both the GPS station accelerations and the estimated slip acceleration at the locations of the repeating earthquake sequences that passed the MK test (Figure 1b). We impose second-order Tikhonov regularization (Laplacian smoothing) on patches that are located within some radius r from the location of each sequence and minimum-norm regularization everywhere else. The rationale here is that repeating earthquakes reflect slip locally on the fault, which should be spatially smooth, but we conservatively minimize slip acceleration outside these areas to the lowest amplitude required to fit the GPS. This results in a slip distribution that is locally smooth near the repeating earthquakes (Figure S11). A lower bound on r can be placed assuming that the local slip rate never exceeds the plate convergence rate in the 15 year observation period, and an upper bound on r can be placed based on the area of the fault that consists of locked asperities. Based on approximations of these bounds, we choose $r = 50$ km (Text S4 and Figure S12). Figure 1b shows the distribution of slip acceleration on the plate interface resulting from the joint inversion for $r = 50$ km.

The constraints from repeating earthquakes produce slip acceleration offshore south central Tohoku that is more heterogeneous than the GPS-only result (Figure 1). Even though the roughness of the slip acceleration depends on the choice of regularization (Figures S11 and S12), the estimated acceleration exhibits at least two robust features. First, two repeating sequences offshore Fukushima prefectures (latitude 37°–37.5°) demand locally negligible slip acceleration at a depth of ~40 km. Second, three repeating sequences at depths shallower than ~20 km require significant acceleration in parts of the shallow megathrust, mostly south of the rupture area of the M_w 9 Tohoku-oki earthquake, with one sequence requiring small acceleration inside the rupture area (Figures 1b and 4b).

6. Discussion and Conclusions

Our estimates of slip from repeating earthquakes are conditional on the common assumption of a repeating earthquake representing failure of a small seismogenic asperity that is isolated within an area of the fault that creeps stably [*Nadeau and Johnson*, 1998; *Nadeau and McEvilly*, 1999; *Beeler et al.*, 2001; *Chen and Lapusta*, 2009]. *Sammis and Rice* [2001] proposed an alternative mechanism for repeating earthquakes, in which these are modeled as ruptures of small weak asperities at the borders between much larger locked asperities and creeping patches. The Sammis-Rice model reproduces the observed scaling $\overline{T} \propto \overline{M_0}^{1/6}$ of *Nadeau and Johnson* [1998]. However, the slip per event in the Sammis-Rice model is not simply related to the local creep rate by $\overline{s} = V_L(t)T(t)$, as it is in the isolated asperity model. Nevertheless, according to the Sammis-Rice model, increasing stressing rate due to increasing creep rate would still result in decreasing recurrence interval, i.e., the effect would be the same as with the isolated asperity model. The result of the nonparametric Mann-Kendall test is independent of any particular model of repeating earthquakes beyond the interpretation that decreasing recurrence interval reflects increasing creep rate. This increases our confidence in the inference of accelerating creep offshore south central Tohoku.

We find that GPS and repeating earthquake data from Northeastern Japan are best explained by decadal-scale accelerating creep, some of which occurred at shallow depths (~10 to 20 km). The rupture zone of the Tohoku-oki earthquake appears to be partly outlined by slip acceleration (Figure 1b), implying that a substantial portion of the megathrust experienced accelerating aseismic slip, while most of the rupture area of the Tohoku-oki earthquake was either locked or creeping at a constant rate during the 15 years before its occurrence. Accelerating creep would result in increasing stressing rate on the locked parts of the megathrust, thereby promoting nucleation of moderate to large earthquakes. This could explain the higher rate of $M_w \sim 7$ events in the decade leading up to the Tohoku-oki earthquake [*Sato et al.*, 2013].

This study provides completely independent confirmation of a geodetically inferred long-term aseismic slip transient [*Mavrommatis et al.*, 2014; *Yokota and Koketsu*, 2015] and adds to the growing body of work reporting evidence of short- and long-term increases in seismic activity and transient slip preceding the Tohoku-oki earthquake [*Hasegawa and Yoshida*, 2015]. Long-duration transients preceding massive megathrust earthquakes have not been observed before; however, few networks could have the resolving power for such a finding. Whether the Tohoku transient implies that the physical conditions are unique to the Japan Trench compared to other subduction zones is unknown. To address this question, improving geodetic and seismic instrumentation of subduction zones worldwide is vital.

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References

Akaike, H. (1974), A new look at the statistical model identification, *IEEE Trans. Autom. Control*, *19*(6), 716–723, doi:10.1109/TAC.1974.1100705.

Ando, R., and K. Imanishi (2011), Possibility of M_w 9.0 mainshock triggered by diffusional propagation of after-slip from M_w 7.3 foreshock, *Earth Planets Space*, *63*(7), 767–771, doi:10.5047/eps.2011.05.016.

Beeler, N., D. Lockner, and S. Hickman (2001), A simple stick-slip and creep-slip model for repeating earthquakes and its implication for microearthquakes at Parkfield, *Bull. Seismol. Soc. Am.*, *91*(6), 1797–1804, doi:10.1785/0120000096.

Bufe, C. G., P. W. Harsh, and R. O. Burford (1977), Steady-state seismic slip - A precise recurrence model, *Geophys. Res. Lett.*, *4*(2), 91–94, doi:10.1029/GL004i002p00091.

Bürgmann, R., D. Schmidt, R. Nadeau, M. d'Alessio, E. Fielding, D. Manaker, T. McEvilly, and M. Murray (2000), Earthquake potential along the northern Hayward fault, California, *Science*, *289*(5482), 1178–1182, doi:10.1126/science.289.5482.1178.

Chen, K. H., R. M. Nadeau, and R.-J. Rau (2007), Towards a universal rule on the recurrence interval scaling of repeating earthquakes?, *Geophys. Res. Lett.*, *34*, L16308, doi:10.1029/2007GL030554.

Chen, K. H., R. Bürgmann, R. M. Nadeau, T. Chen, and N. Lapusta (2010), Postseismic variations in seismic moment and recurrence interval of repeating earthquakes, *Earth Planet. Sci. Lett.*, *299*(1), 118–125, doi:10.1016/j.epsl.2010.08.027.

Chen, T., and N. Lapusta (2009), Scaling of small repeating earthquakes explained by interaction of seismic and aseismic slip in a rate and state fault model, *J. Geophys. Res.*, *114*, B01311, doi:10.1029/2008JB005749.

Hanks, T. C., and H. Kanamori (1979), A moment magnitude scale, *J. Geophys. Res.*, *84*(B5), 2348–2350, doi:10.1029/JB084iB05p02348.

Hasegawa, A., and K. Yoshida (2015), Preceding seismic activity and slow slip events in the source area of the 2011 M_w 9.0 Tohoku-Oki earthquake: A review, *Geosci. Lett.*, *2*(1), 1–13, doi:10.1186/s40562-015-0025-0.

Hayes, G. P., M. W. Herman, W. D. Barnhart, K. P. Furlong, S. Riquelme, H. M. Benz, E. Bergman, S. Barrientos, P. S. Earle, and S. Samsonov (2014), Continuing megathrust earthquake potential in Chile after the 2014 Iquique earthquake, *Nature*, *512*(7514), 295–298, doi:10.1038/nature13677.

Hooper, A., J. Pietrzak, W. Simons, H. Cui, R. Riva, M. Naeije, A. Terwisscha van Scheltinga, E. Schrama, G. Stelling, and A. Socquet (2013), Importance of horizontal seafloor motion on tsunami height for the 2011 $M_w = 9.0$ Tohoku-Oki earthquake, *Earth Planet. Sci. Lett.*, *361*, 469–479, doi:10.1016/j.epsl.2012.11.013.

Igarashi, T., T. Matsuzawa, and A. Hasegawa (2003), Repeating earthquakes and interplate aseismic slip in the northeastern Japan subduction zone, *J. Geophys. Res.*, *108*(B5), 2249, doi:10.1029/2002JB001920.

Johnson, K. M., A. P. Mavrommatis, and P. Segall (2013), Overlapping afterslip and coseismic slip on the Northern Japan subduction interface inferred from physical models of slip and GPS time series from 2003–2011, Abstract G31C-06 presented at 2013 Fall Meeting, AGU, San Francisco, Calif., 9–13 Dec.

Kato, A., K. Obara, T. Igarashi, H. Tsuruoka, S. Nakagawa, and N. Hirata (2012), Propagation of slow slip leading up to the 2011 M_w 9.0 Tohoku-Oki earthquake, *Science*, *335*(6069), 705–708, doi:10.1126/science.1215141.

Kendall, M. G. (1948), *Rank Correlation Methods*,Griffin, Oxford, U. K., doi:10.2307/2333282.

Livezey, R. E., and W. Chen (1983), Statistical field significance and its determination by Monte Carlo techniques, *Mon. Weather Rev.*, *111*(1), 46–59, doi:10.1175/1520-0493(1983)111<0046:SFSAID>2.0.CO;2.

Loveless, J. P., and B. J. Meade (2011), Spatial correlation of interseismic coupling and coseismic rupture extent of the 2011 $M_w = 9.0$ Tohoku-oki earthquake, *Geophys. Res. Lett.*, *38*, L17306, doi:10.1029/2011GL048561.

Mann, H. B. (1945), Nonparametric tests against trend, *Econometrica*, *13*, 245–259, doi:10.2307/1907187.

Mavrommatis, A. P., P. Segall, and K. M. Johnson (2014), A decadal-scale deformation transient prior to the 2011 $M_w 9.0$ Tohoku-oki earthquake, *Geophys. Res. Lett.*, *41*, 4486–4494, doi:10.1002/2014GL060139.

Nadeau, R. M., and L. R. Johnson (1998), Seismological studies at Parkfield VI: Moment release rates and estimates of source parameters for small repeating earthquakes, *Bull. Seismol. Soc. Am.*, *88*(3), 790–814.

Nadeau, R. M., and T. V. McEvilly (1999), Fault slip rates at depth from recurrence intervals of repeating microearthquakes, *Science*, *285*(5428), 718–721, doi:10.1126/science.285.5428.718.

Nadeau, R. M., and T. V. McEvilly (2004), Periodic pulsing of characteristic microearthquakes on the San Andreas Fault, *Science*, *303*(5655), 220–222, doi:10.1126/science.1090353.

Ruiz, S., M. Metois, A. Fuenzalida, J. Ruiz, F. Leyton, R. Grandin, C. Vigny, R. Madariaga, and J. Campos (2014), Intense foreshocks and a slow slip event preceded the 2014 Iquique M_w 8.1 earthquake, *Science*, *345*(6201), 1165–1169, doi:10.1126/science.1256074.

Sammis, C. G., and J. R. Rice (2001), Repeating earthquakes as low-stress-drop events at a border between locked and creeping fault patches, *Bull. Seismol. Soc. Am.*, *91*(3), 532–537, doi:10.1785/0120000075.

Sato, T., S. Hiratsuka, and J. Mori (2013), Precursory seismic activity surrounding the high-slip patches of the 2011 M_w 9.0 Tohoku-Oki earthquake, *Bull. Seismol. Soc. Am.*, *103*(6), 3104–3114, doi:10.1785/0120130042.

Schaff, D. P., G. C. Beroza, and B. E. Shaw (1998), Postseismic response of repeating aftershocks, *Geophys. Res. Lett.*, *25*(24), 4549–4552, doi:10.1029/1998Gl900192.

Scholz, C. H. (1990), *The Mechanics of Earthquakes and Faulting*, Cambridge Univ. Press, Cambridge, U. K., doi:10.1017/cbo9780511818516.

Schurr, B. et al. (2014), Gradual unlocking of plate boundary controlled initiation of the 2014 Iquique earthquake, *Nature*, *512*, 299–302, doi:10.1038/nature13681.

Schwarz, G. (1978), Estimating the dimension of a model, *Ann. Stat.*, *6*(2), 461–464, doi:10.1214/aos/1176344136.

Taira, T., R. Bürgmann, R. M. Nadeau, and D. S. Dreger (2014), Variability of fault slip behavior along the San Andreas Fault in the San Juan Bautista Region, *J. Geophys. Res. Solid Earth*, *119*, 8827–8844, doi:10.1002/2014JB011427.

Uchida, N., and T. Matsuzawa (2011), Coupling coefficient, hierarchical structure, and earthquake cycle for the source area of the 2011 off the Pacific coast of Tohoku earthquake inferred from small repeating earthquake data, *Earth Planets Space*, *63*(7), 675–679, doi:10.5047/eps.2011.07.006.

Uchida, N., and T. Matsuzawa (2013), Pre-and postseismic slow slip surrounding the 2011 Tohoku-oki earthquake rupture, *Earth Planet. Sci. Lett.*, *374*, 81–91, doi:10.1016/j.epsl.2013.05.021.

Uchida, N., T. Matsuzawa, A. Hasegawa, and T. Igarashi (2003), Interplate quasi-static slip off Sanriku, NE Japan, estimated from repeating earthquakes, *Geophys. Res. Lett.*, *30*(15), 1801, doi:10.1029/2003GL017452.

Uchida, N., K. Shimamura, T. Matsuzawa, and T. Okada (2015), Postseismic response of repeating earthquakes around the 2011 Tohoku-oki earthquake: Moment increases due to the fast loading rate, *J. Geophys. Res. Solid Earth*, *120*, 259–274, doi:10.1002/2013JB010933.

Vidale, J., W. Ellsworth, A. Cole, and C. Marone (1994), Variations in rupture process with recurrence interval in a repeated small earthquake, *Nature*, *368*, 624–626, doi:10.1038/368624a0.

Yokota, Y., and K. Koketsu (2015), A very long-term transient event preceding the 2011 Tohoku earthquake, *Nat. Commun.*, *6*, 5934, doi:10.1038/ncomms6934.