www.sciencemag.org/cgi/content/full/science.1215141/DC1

Supporting Online Material for

Propagation of Slow Slip Leading Up to the 2011 M_w 9.0 Tohoku-Oki Earthquake

Aitaro Kato,* Kazushige Obara, Toshihiro Igarashi, Hiroshi Tsuruoka, Shigeki Nakagawa, Naoshi Hirata

*To whom correspondence should be addressed. E-mail: akato@eri.u-tokyo.ac.jp

Published 19 January 2012 on *Science* Express
DOI: 10.1126/science.1215141

This PDF file includes:

Materials and Methods
Fig. S1
Table S1
Full Reference List

Materials and Methods

Methods of a matched filter technique

The analysis procedure of a matched filter technique follows that of *Shelly et al*. (*15*) and *Peng and Zhao* (*16*). We here describe the procedure briefly. To detect missing foreshock events between 13 February and 11 March in 2011, we analyzed the continuous three-component velocity seismograms recorded at 14 stations along the Pacific coast for the same period (Fig. 1), operated by the National Research Institute for Earth Science and Disaster Prevention (NIED) and Tohoku University. As template events, we selected all 333 earthquakes listed in the JMA catalog between 13 February and 11 March (the M_w 9.0 mainshock origin).

For each template event at each station, we used 6 seconds of the waveform, starting 3 second before the S-wave arrival time computed using a one-dimensional velocity model proposed by the JMA. After down-sampling of the data from 100 Hz sampling frequency to 20 Hz, we applied a two-way 1–6 Hz Butterworth filter to the data. We calculated the correlation coefficient as a function of time, shifting the window in increments of 0.05 seconds through the continuous waveforms (see Fig. S1). At each point, the correlation coefficient between a template event waveform and a target waveform was calculated on every component at every station, and was averaged throughout. The same procedure was repeated for each template event.

We used the mean correlation coefficient as our detection statistic. To define a detection threshold we used the standard deviation (sigma) of the mean correlation coefficients for each event. We set a conservative threshold for a positive detection at 8 times sigma. This level was chosen to suppress spurious detections while retaining as much legitimate detection as possible. When the mean correlation peak exceeded this threshold level, it was labeled as a positive detection in a statistically significant way. As the detected events have similar waveforms at multiple stations as compared to the template event, their hypocenter locations must be close or identical (*15*, *16*).

We assigned the location of the detected event to that of the template event. For multiple detections in each 3 s window, we used the location of the template event with the highest mean correlation coefficient value. We assigned the time associated with the highest mean correlation coefficient value to its origin time of the detected event by subtracting the computed S-wave arrival time. Using relative distances between the multiple detected events, we estimated the average relative uncertainty in the detected event locations to be approximately 4 km. Finally, we computed the magnitude of the detected event based on the median value of the maximum amplitude ratios for all channels between the template and detected events, assuming that a tenfold increase in amplitude corresponds to one unit increase in magnitude (*16*).

Detection of repeating earthquakes

To identify repeating earthquakes in the JMA catalog, we used waveform data of earthquakes of M2.0 or larger listed in the catalog for the period from January 2002 to 11 March in 2011, in the studied area. We picked up earthquake pairs whose epicenter separations are up to 20 km, and calculated cross-correlation coefficients using 1–4, 2–8, and 4–16 Hz passband filtered waveforms. The time window was from P-wave onset to three seconds after direct S-wave arrival. We selected as a repeating earthquake pair, those whose cross-correlation coefficients, for the frequency range roughly corresponding to the corner-frequency of each event, were greater than 0.95 at two or more stations (*23*).

The detection criteria for the newly detected events (green stars in Figs. 2 and 3), which were found to resemble the repeating earthquakes in the JMA catalog, are the same as for the other events.

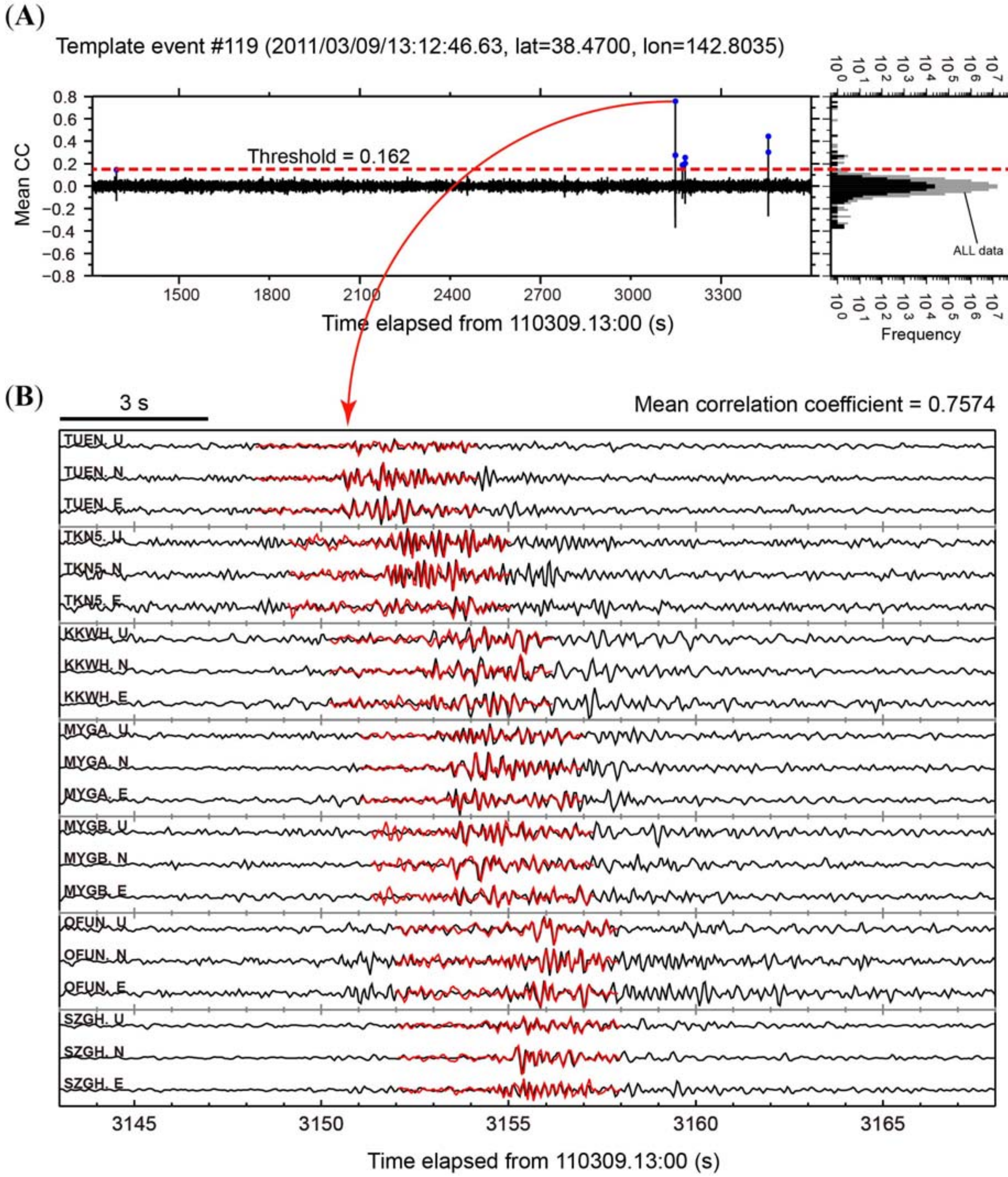

Figure S1 Mean correlation function and detection example. (**A**) Mean correlation function for one template event #119 against elapsed time from March 09, 2011, 13:00. Histogram of mean correlation values within this time window and entire period are shown to the right as black and gray bars. (**B**) Waveforms at the time detection for template event #119. Continuous earthquake waveforms are shown in black and template event waveforms in red for each component of 6 seismic stations arranged according to the epicentral distance. The station names and components are given to the left of each trace. Waveforms are bandpass filtered between 1 and 6 Hz, and template event amplitudes are scaled to match the continuous data.

Table S1. List of the time (T_h) required for afterslip to release half of the mainshock moment following major M7–8 plate-interface earthquakes that took place along the Japan and Kuril trenches. We used analysis results based on GEONET, a dense GPS geodetic network.

Event date	Longitude	Latitude	Depth(km)	M_w	T_h (months)	References
1994/12/28	143.7450	40.4300	0.00	7.6	2.23	(*26*)
2003/09/26	144.0785	41.7785	45.07	8.0	10.24	(*35*)
2004/11/29	145.2755	42.9460	48.17	7.0	0.80	(36)
2005/08/16	142.2778	38.1495	42.04	7.1	2.04–3.53	(*32*)*, (*37*)
2008/07/19	142.2645	37.5208	31.55	7.0	1.64	(*32*)*
2010/03/14	141.8180	37.7242	39.75	6.7	1.27	(*32*)*
2011/03/09	143.2798	38.3285	8.28	7.3	0.07	(*29*) This study

*We estimated the T_h values using average decay time determined for each station by *Suito et al.* (2011) (*32*), assuming an exponential decay of the afterslip moment.

References and Notes

1. J. H. Dieterich, Modeling of rock friction 1. Experimental results and constitutive equations. *J. Geophys. Res.* **84**, 2161 (1979). doi:10.1029/JB084iB05p02161

2. M. Ohnaka, Earthquake source nucleation: A physical model for short-term precursors. *Tectonophysics* **211**, 149 (1992). doi:10.1016/0040-1951(92)90057-D

3. B. Shibazaki, M. Matsu'ura, Spontaneous processes for nucleation, dynamic propagation, and stop of earthquake rupture. *Geophys. Res. Lett.* **19**, 1189 (1992). doi:10.1029/92GL01072

4. M. Ohnaka, L. Shen, Scaling of the shear rupture process from nucleation to dynamic propagation: Implications of geometric irregularity of the rupturing surfaces. *J. Geophys. Res.* **104**, 817 (1999). doi:10.1029/1998JB900007

5. N. Lapusta, J. R. Rice, Y. Ben-Zion, G. Zheng, Elastodynamic analysis for slow tectonic loading with spontaneous rupture episodes on faults with rate- and state-dependent friction. *J. Geophys. Res.* **105**, 23765 (2000). doi:10.1029/2000JB900250

6. D. A. Dodge, G. C. Beroza, W. L. Ellsworth, Detailed observations of California foreshock sequences: Implications for the earthquake initiation process. *J. Geophys. Res.* **101**, 22371 (1996). doi:10.1029/96JB02269

7. W. L. Ellsworth, G. C. Beroza, Seismic evidence for an earthquake nucleation phase. *Science* **268**, 851 (1995). doi:10.1126/science.268.5212.851 Medline

8. J. Mori, H. Kanamori, Initial rupture of earthquakes in the 1995 Ridgecrest, California sequence. *Geophys. Res. Lett.* **23**, 2437 (1996). doi:10.1029/96GL02491

9. R. E. Abercrombie, J. Mori, Occurrence patterns of foreshocks to large earthquakes in the western United States. *Nature* **381**, 303 (1996). doi:10.1038/381303a0

10. J. J. McGuire, M. S. Boettcher, T. H. Jordan, Foreshock sequences and short-term earthquake predictability on East Pacific Rise transform faults. *Nature* **434**, 457 (2005). doi:10.1038/nature03377 Medline

11. M. Bouchon *et al.*, Extended nucleation of the 1999 M_w 7.6 Izmit earthquake. *Science* **331**, 877 (2011). doi:10.1126/science.1197341 Medline

12. F. Hirose, K. Miyaoka, N. Hayashimoto, T. Yamazaki, M. Nakamura, Outline of the 2011 off the Pacific coast of Tohoku earthquake (Mw 9.0)—Seismicity: Foreshocks, mainshock, aftershocks, and induced activity. *Earth Planets Space* **63**, 513 (2011). doi:10.5047/eps.2011.05.019

13. S. Ide, A. Baltay, G. C. Beroza, Shallow dynamic overshoot and energetic deep rupture in the 2011 M_w 9.0 Tohoku-Oki earthquake. *Science* **332**, 1426 (2011). doi:10.1126/science.1207020 Medline

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

15. D. R. Shelly, G. C. Beroza, S. Ide, Non-volcanic tremor and low-frequency earthquake swarms. *Nature* **446**, 305 (2007). doi:10.1038/nature05666 Medline

16. Z. Peng, P. Zhao, Migration of early aftershocks following the 2004 Parkfield earthquake. *Nat. Geosci.* **2**, 877 (2009). doi:10.1038/ngeo697

17. N. Aso, K. Ohta, S. Ide, Volcanic-like low-frequency earthquakes beneath Osaka Bay in the absence of a volcano. *Geophys. Res. Lett.* **38**, L08303 (2011). doi:10.1029/2011GL046935

18. Materials and methods are available as supporting material on *Science* Online.

19. T. Matsuzawa, N. Uchida, T. Igarashi, T. Okada, A. Hasegawa, Repeating earthquakes and quasi-static slip on the plate boundary east off northern Honshu, Japan. *Earth Planets Space* **56**, 803 (2004).

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

21. Z. Peng, Y. Ben-Zion, Spatiotemporal variations of crustal anisotropy from similar events in aftershocks of the 1999 M7.4 İzmit and M7.1 Düzce, Turkey, earthquake sequences. *Geophys. J. Int.* **160**, 1027 (2005). doi:10.1111/j.1365-246X.2005.02569.x

22. T. Chen, N. Lapusta, 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 (2009). doi:10.1029/2008JB005749

23. T. Igarashi, Spatial changes of inter-plate coupling inferred from sequences of small repeating earthquakes in Japan. *Geophys. Res. Lett.* **37**, L20304 (2010). doi:10.1029/2010GL044609

24. H. Dragert, K. Wang, T. S. James, A silent slip event on the deeper Cascadia subduction interface. *Science* **292**, 1525 (2001). doi:10.1126/science.1060152 Medline

25. K. Obara, Phenomenology of deep slow earthquake family in southwest Japan: Spatiotemporal characteristics and segmentation. *J. Geophys. Res.* **115**, B00A25 (2010). doi:10.1029/2008JB006048

26. K. Heki, S. Miyazaki, H. Tsuji, Silent fault slip following an interplate thrust earthquake at the Japan Trench. *Nature* **386**, 595 (1997). doi:10.1038/386595a0

27. S. Miyazaki, P. Segall, J. Fukuda, T. Kato, Space time distribution of afterslip following the 2003 Tokachi-Oki earthquake: Implications for variations in fault zone frictional properties. *Geophys. Res. Lett.* **31**, L06623 (2004). doi:10.1029/2003GL019410

28. N. Uchida *et al.*, Quasi-static slip on the plate boundary associated with the 2003 M8.0 Tokachi-Oki and 2004 M7.1 off-Kushiro earthquakes, Japan. *Gondwana Res.* **16**, 527 (2009). doi:10.1016/j.gr.2009.04.002

29. S. Miyazaki, J. J. McGuire, P. Segall, Seismic and aseismic fault slip before and during the 2011 off the Pacific coast of Tohoku earthquake. *Earth Planets Space* **63**, 637 (2011). doi:10.5047/eps.2011.07.001

30. N. Kato, S. Yoshida, A shallow strong patch model for the 2011 great Tohoku-Oki earthquake: A numerical simulation. *Geophys. Res. Lett.* **38**, L00G04 (2011). doi:10.1029/2011GL048565

31. Y. Yagi, M. Kikuchi, T. Nishimura, Co-seismic slip, post-seismic slip, and largest aftershock associated with the 1994 Sanriku-Haruka-Oki, Japan, earthquake. *Geophys. Res. Lett.* **30**, 2177 (2003). doi:10.1029/2003GL018189

32. H. Suito, T. Nishimura, M. Tobita, T. Imakiire, S. Ozawa, Interplate fault slip along the Japan Trench before the occurrence of the 2011 off the Pacific coast of Tohoku earthquake as inferred from GPS data. *Earth Planets Space* **63**, 615 (2011). doi:10.5047/eps.2011.06.053

33. H. Houston, B. G. Delbridge, A. G. Wech, K. C. Creager, Rapid tremor reversals in Cascadia generated by a weakened plate interface. *Nat. Geosci.* **4**, 404 (2011). doi:10.1038/ngeo1157

34. J. Nakajima, A. Hasegawa, Anomalous low-velocity zone and linear alignment of seismicity along it in the subducted Pacific slab beneath Kanto, Japan: Reactivation of subducted fracture zone? *Geophys. Res. Lett.* **33**, L16309 (2006). doi:10.1029/2006GL026773

35. The Geospatial Information Authority of Japan (GSI), *Rep. Coord. Comm. Earthquake Predict. Jpn.* (**73**, pp. 40, 2005; http://cais.gsi.go.jp/YOCHIREN/report/kaihou73/02_02.pdf).

36. The Geospatial Information Authority of Japan (GSI), *Rep. Coord. Comm. Earthquake Predict. Jpn.* (**76**, pp. 72, 2006; http://cais.gsi.go.jp/YOCHIREN/report/kaihou76/2-3.pdf).

37. The Geospatial Information Authority of Japan (GSI), *Rep. Coord. Comm. Earthquake Predict. Jpn.* (**77**, pp. 91, 2007; http://cais.gsi.go.jp/YOCHIREN/report/kaihou77/3-2.pdf).