



Did Short-Term Preseismic Crustal Deformation Precede the 2011 Great Tohoku-Oki Earthquake? An Examination of Stacked Tilt Records

Hirose, Hitoshi

Kato, Aitaro

Kimura, Takeshi

(Citation)

Geophysical Research Letters, 51(12):e2024GL109384

(Issue Date)

2024-06-28

(Resource Type)

journal article

(Version)

Version of Record

(Rights)

© 2024. The Author(s).

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

(URL)

<https://hdl.handle.net/20.500.14094/0100490250>



Geophysical Research Letters®



RESEARCH LETTER

10.1029/2024GL109384

Key Points:

- Tiltmeter records are used to determine whether a preseismic signal of the 2011 great Tohoku-oki earthquake is detected
- No acceleration-like tilt deformation from about 2 hr before the mainshock is recorded
- An upper bound on the size of the preslip immediately before the mainshock can be estimated from the noise level of the observation data

Supporting Information:

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

Correspondence to:

H. Hirose,
hitoshi.hirose@ruby.kobe-u.ac.jp

Citation:

Hirose, H., Kato, A., & Kimura, T. (2024). Did short-term preseismic crustal deformation precede the 2011 great Tohoku-oki earthquake? An examination of stacked tilt records. *Geophysical Research Letters*, 51, e2024GL109384. <https://doi.org/10.1029/2024GL109384>

Received 20 MAR 2024

Accepted 31 MAY 2024

Author Contributions:

Conceptualization: Hitoshi Hirose, Aitaro Kato

Data curation: Takeshi Kimura

Formal analysis: Hitoshi Hirose

Funding acquisition: Hitoshi Hirose, Aitaro Kato

Investigation: Hitoshi Hirose

Methodology: Hitoshi Hirose

Project administration: Hitoshi Hirose

Resources: Hitoshi Hirose, Takeshi Kimura

Software: Hitoshi Hirose

Supervision: Aitaro Kato

Validation: Hitoshi Hirose

Visualization: Hitoshi Hirose

Writing – original draft: Hitoshi Hirose

Did Short-Term Preseismic Crustal Deformation Precede the 2011 Great Tohoku-Oki Earthquake? An Examination of Stacked Tilt Records

Hitoshi Hirose^{1,2,3} , Aitaro Kato⁴ , and Takeshi Kimura³ 

¹Research Center for Urban Safety and Security, Kobe University, Kobe, Japan, ²Department of Planetology, Kobe University, Kobe, Japan, ³National Research Institute for Earth Science and Disaster Resilience, Ibaraki, Japan,

⁴Earthquake Research Institute, The University of Tokyo, Tokyo, Japan

Abstract The detection of preslip, occurring hours to days before a large earthquake, using geodetic measurements has been a major focus in earthquake prediction research. A recent study claims to have detected a preseismic signal interpreted as accelerating slip near the hypocenter of the 2011 great Tohoku-oki earthquake, starting approximately 2 hr before the mainshock. This claim is based on a stacking procedure using GNSS (Global Navigation Satellite System) data. However, a follow-up study demonstrated that the signal disappeared when specific GNSS noise was corrected. Here we utilize tiltmeter records, independent on GNSS, to check whether the claimed preseismic signal is detected using a similar stacking procedure. Our results show no acceleration-like deformation from 2 hr before the mainshock. This indicates that no precursory slip exceeded the noise level of the tilt data, and if any preslip occurred, it was less than 5.0×10^{18} Nm in seismic moment.

Plain Language Summary The ability to detect large earthquakes before they occur would be invaluable for mitigating damage. Researchers have been searching for precursory signals in crustal deformation data, believing that if precursory slip (fault movement before a major earthquake) is large enough, it could be detected by GNSS or tiltmeters, enabling earthquake prediction. The 2011 Tohoku-oki earthquake provided a valuable opportunity to study this phenomenon. Extensive data was collected, but previous studies found no significant pre-earthquake signals on timescales of hours to days. A recent GNSS study claimed an acceleration-like change 2 hr before the main shock, but another study using the same data disputed this. While reanalysis using the same GNSS data is important, it is also susceptible to the influence of the same noise sources. To avoid this, this study analyzed tiltmeter data, finding no evidence for the precursory deformation suggested earlier. This result indicates no significant precursory slip before the Tohoku-oki earthquake that causes deformation larger than a noise level of the tiltmeter data. This result can provide constraints on the magnitude of the precursory slip immediately before the mainshock.

1. Introduction

The detection of short-term preseismic slip (preslip) hours to days preceding a large earthquake has been one of the major targets of research aiming to predict earthquakes. The reason for aiming to detect preslip before a major earthquake is that it may enable issuing warnings before the earthquake occurs, allowing for disaster prevention measures such as evacuation to be implemented. Despite the retrospective investigations of preslip for various large earthquakes with geodetic data, reliable and widely accepted observations of short-term preslip are rare (e.g., Roeloffs, 2006).

The 2011 great Tohoku-oki earthquake (M 9.0), which occurred close to well-developed geodetic observation networks, provided an opportunity to examine precursory crustal deformation and the presence or absence of preslip for a great earthquake. Various types of long-term (decadal) pre-earthquake crustal deformation have been reported, including a decrease in interplate coupling several years before the earthquake (Nishimura, 2012), acceleration of aseismic interplate slip on a decadal timescale (Marill et al., 2021; Mavrommatis et al., 2014), and a long-term slow slip event (SSE) (Yokota & Koketsu, 2015). For shorter timescales of less than a month, some observations of crustal deformation before the earthquake have been reported, such as an SSE detected by ocean bottom pressure (OBP) gauges about 1 month before the mainshock (Ito et al., 2013) and afterslip of the largest foreshock that occurred 2 days before the mainshock (Miyazaki et al., 2011; Ohta et al., 2012). However, no accelerating crustal deformation as expected for preslip was detected. This has been investigated using various

© 2024. The Author(s).

This is an open access article under the terms of the [Creative Commons Attribution License](https://creativecommons.org/licenses/by/4.0/), which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

Writing – review & editing:
Hitoshi Hirose, Aitaro Kato,
Takeshi Kimura

types of observation data, including GNSS (Global Navigation Satellite System) (e.g., Miyazaki et al., 2011), tiltmeter records (Hirose, 2011), and OBP gauges just above the mainshock hypocenter (Hino et al., 2013).

Recently, Bletery and Nocquet (2023, hereafter referred to as BN23) claimed to have observed a deformation that could be interpreted as accelerating slip near the hypocenters of 90 large earthquakes starting approximately 2 hr before the mainshocks by stacking high-rate GNSS time series around the world. They also claimed that the stacking analysis of GNSS data observed in Japan before the 2011 Tohoku-oki earthquake alone showed a similar accelerating phase about 2 hr before the Tohoku-oki mainshock. This indicates that the pre-Tohoku-oki data made one of the largest contributions to the global stack, likely due to the dense and large number of Japanese GEONET GNSS stations (e.g., Takamatsu et al., 2023). In response to BN23's claims, Bradley and Hubbard (2023) reanalyzed using the same data set. They applied a common mode noise correction, which was not considered in BN23's main results, and then performed the same stacking process as BN23. As a result, they did not observe the accelerating deformation claimed by BN23 starting about 2 hr before the mainshock.

Investigating the presence and magnitude of aseismic slip processes preceding earthquakes using crustal deformation data, which can directly observe aseismic slip, is crucial for understanding the physical processes leading to an earthquake rupture. While BN23 and Bradley and Hubbard (2023) presented the discussion based on GNSS data, they are not immune to the influence of GNSS-specific data processing and noise sources. An examination using crustal deformation data independent of GNSS allows for an argument that circumvents GNSS-specific issues. In this study, we utilize observation records from high-sensitivity accelerometers (tiltmeters) installed with the National Research Institute for Earth Science and Disaster Resilience (NIED) Hi-net (High-Sensitivity Seismograph Network Japan) (Obara et al., 2005; Okada et al., 2004). We perform similar data processing to BN23 using the tilt records to examine whether the crustal deformation they claim to have observed immediately before the mainshock can be detected or not.

2. Data

We used continuous observation records of NIED Hi-net high-sensitivity accelerometers (tiltmeters) (Obara et al., 2005; Okada et al., 2004). Characteristics of the tilt records are described in Text S1 in Supporting Information S1 and an example of the preprocessing is shown in Figure S1 in Supporting Information S1. We selected Hi-net stations located within 500 km from the epicenter of the 2011 Tohoku-oki earthquake (Figure 1). Note that the source parameters (hypocenter locations and focal mechanisms) listed in the SCARDEC database (Vallée & Douet, 2016) were used, following the approach of BN23. We analyzed tilt time-series data recorded at the selected stations from 1 December 2010 to 11 March 2011 (times in this paper are in Japan Standard Time (JST)). The original 20 Hz sampling rate records of the tiltmeters were downsampled to a 1-min sampling rate by averaging. Next, tidal components were subtracted from the records using the BAYTAP-G program (Tamura et al., 1991). Examples of the tidal correction process are illustrated in Figures S1 and S2 in Supporting Information S1. Specifically, we first downsampled the 1-min sampling data to 1-hr sampling data. Subsequently, we estimated the tidal components during the time period from 1 December 2010 to 1 March 2011. Using the results, we next predicted the 1-min sampling tilt time-series of the tidal components from 1 December 2010 to 11 March 2011. Finally, the predicted tidal tilt time-series was subtracted from the initial 1 min sampling tilt records. This correction accounts for the influence of large seismic waves from a number of foreshocks of the Tohoku-oki earthquakes, which persisted for about a month before the mainshock (e.g., Kato et al., 2012). These seismic waves, particularly after 9 March 2011, sometimes caused significant jumps (due to the high sensitivity of this sensor, it is thought that the jumps are likely caused by shifts in the sensor's neutral point before and after the arrival of strong seismic waves) that could bias the estimation of the tidal components in the tilt records. After the tidal correction, we further subtracted the coseismic offset caused by the largest foreshock on 9 March 2011. This was achieved by calculating the difference between the two averages for 6-hr-long tilt records just before and after the origin time of the foreshock (11:45 on 9 March 2011). Additionally, a linear trend estimated from the tilt records between 1 March 2011 and 9 March 2011 was subtracted from the entire time-series data. Throughout these procedures, we excluded tilt traces that appeared abnormal upon visual inspection and had missing observations. In total, observation data at 238 stations were used in the analysis (Figure 1).

Figure 2 shows preprocessed tilt records at several stations closest to the epicenter of the mainshock (the locations of the selected stations are denoted in Figure 1). Large oscillations caused by active foreshocks and postseismic

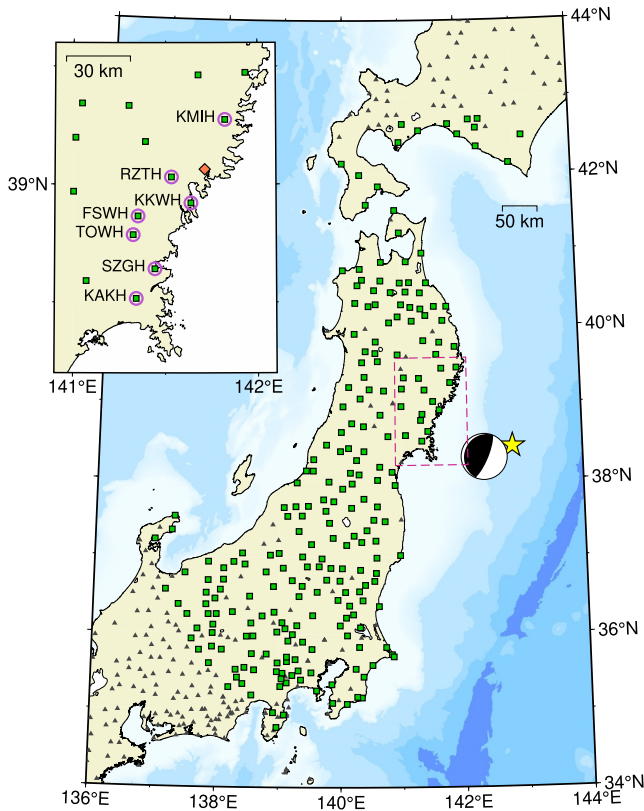


Figure 1. Map showing the NIED Hi-net station locations used in the analysis. Green rectangles show the locations of the stations used in the stacking analysis. Gray triangles denote the locations of Hi-net stations at the time of the 2011 great Tohoku-oki earthquake (not used in this study). The beach ball shows the focal mechanism of the mainshock on 11 March 2011 from the SCARDEC database. The star shows the epicenter of the largest foreshock on 9 March 2011. (inset) Enlarged view of the area shown in rectangle in the main map. Open circles with a station code represent the stations whose records are shown in Figure 2. Orange diamond shows the location of the Japan Meteorological Agency (JMA) Oofunato meteorological observatory.

processed tilt records (before applying the lowpass filter) from 1 March 2011 to 9 March 2011 (see Text S2 in Supporting Information S1 for discussion on the noise level of the tilt records).

$S(t)$ in Equation 1 can be converted to a time series representing the cumulative seismic moment of the slip:

$$M_0(t) = \frac{\mu A}{\sigma_g} S(t), \quad (2)$$

where μ is the rigidity, A is the area of the fault, and σ_g is defined as follows:

$$\sigma_g = \sum_i \frac{\vec{g}_i \cdot \vec{g}_i}{\sigma_i^2}. \quad (3)$$

$\vec{g}_i$ is calculated using Okada (1992)'s formulation assuming slip on a rectangular fault in a homogeneous elastic half-space (with μ assumed to be 40 GPa). We set A to be $1 \times 1 \text{ km}^2$, the same value as in BN23, effectively equivalent to a point source (the spatial distribution of the calculated $\vec{g}_i$ is shown in Figure S3 in Supporting Information S1).

movements after the largest foreshock on 9 March 2011 are evident. However, a preseismic slow accelerating phase is not clearly seen in the traces, as pointed out by Hirose (2011).

Strong motions from the foreshocks cause spike-like signals in the tilt traces (Figure 2). To mitigate the effects of these spikes, we applied a low-pass filter with a cutoff frequency of $3.33 \times 10^{-3} \text{ Hz}$ (equivalent to 5 min) before applying the stacking method described in the next section.

3. Method

We follow the stacking method adopted in BN23. The key point of their method lies in computing the dot product between the observed vector time series (which includes two components: GNSS horizontal displacement in BN23 or tilt change in our study) at the i -th station, denoted as $\vec{u}_i(t)$, and the corresponding vector Green's function (a horizontal displacement vector in BN23 or a tilt change vector in our study) at the same station, represented as $\vec{g}_i$. This Green's function is expected from a unit (precursory) slip occurring in the same direction as the slip during the main shock on a fault plane at the hypocenter with the same orientation as the main shock fault plane. In our specific case, $\vec{u}_i(t)$ represents the tilt time series, while $\vec{g}_i$ corresponds to the tilt change vector predicted from unit slip along the plate interface (west-northwestward dipping fault plane in Figure 1). The dot product reaches its maximum value when the observed record exhibits movement in the same direction as $\vec{g}_i$.

The dot product time series calculated for each station is then summed across all selected stations and normalized by the noise level for each station, σ_i

$$S(t) = \sum_i \frac{\vec{u}_i(t) \cdot \vec{g}_i}{\sigma_i^2} \quad (1)$$

for the time period from 1 March 2011 to 14:46 on 11 March 2011 (the origin time of the Tohoku-oki mainshock). Here, N_{st} represents the number of selected stations. We evaluate σ_i as a standard deviation of the magnitude of the vector $\vec{u}_i(t)$ at each time epoch t (in our case, every 1 min) of the pre-

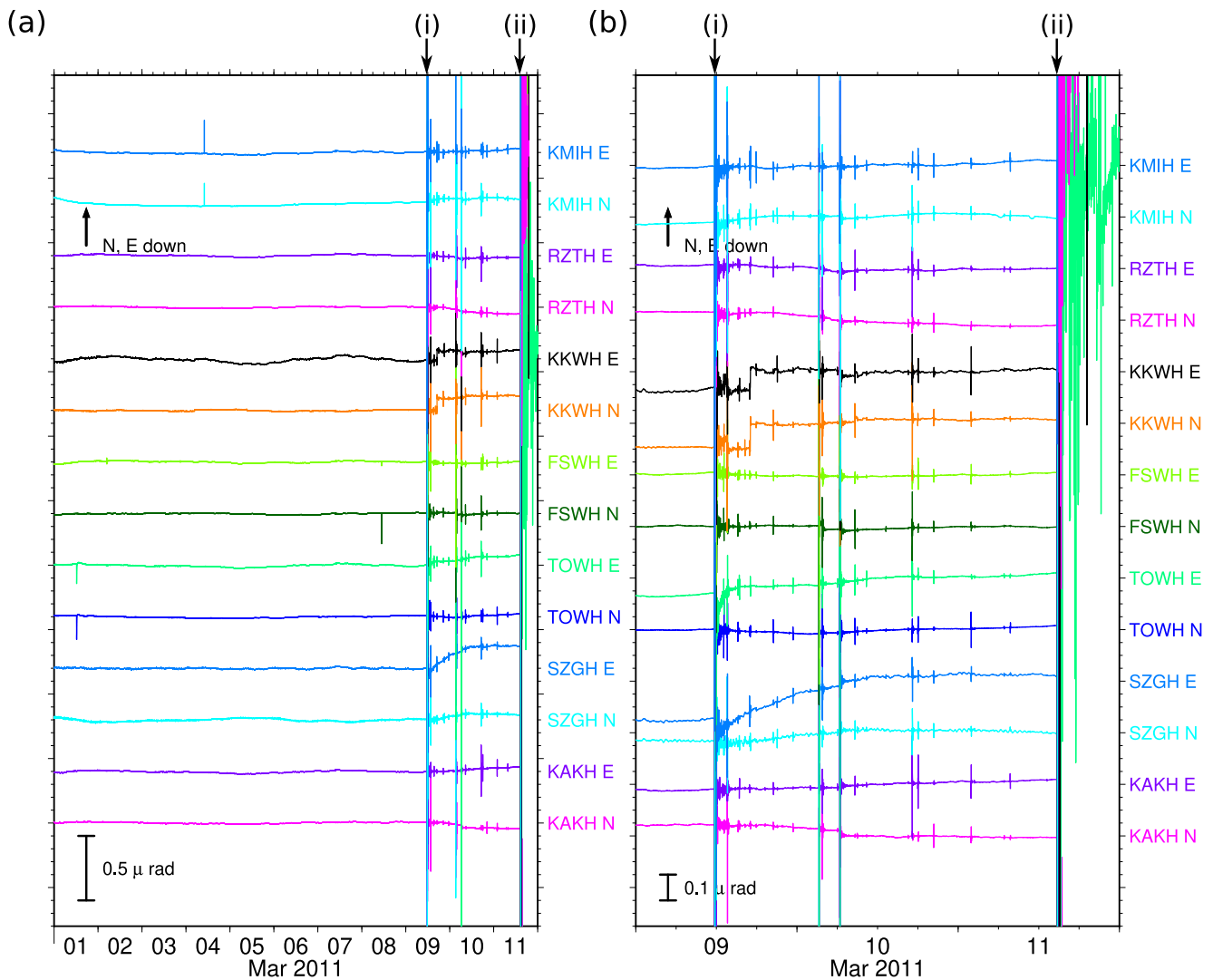


Figure 2. Observed tilt records at selected stations (the station locations are indicated in the inset in Figure 1). Traces after removal of tidal components, a coseismic jump at the largest foreshock on 9 March 2011, and a linear trend are shown. (a) Time series from 1 to 11 March 2011. (b) From 9 to 11 March 2011. Arrows on the top show the origin times of (i) the largest foreshock on 9 March and (ii) the Tohoku-oki mainshock on 11 March. Note that the vertical scales are different in (a) and (b).

4. Results and Discussion

Figure 3 shows the results of the stacking procedure. From 1 March to just before the largest foreshock on 9 March, there appears to be no significant change in $S(t)$ (Figure 3a) and $M_0(t)$ (Figure 3b), except for small fluctuations with nearly two cycles per day, probably residuals of tidal components that are not sufficiently corrected, as well as longer-term variations with time period of over 2 days, possibly caused by atmospheric pressure changes. Similar characteristics are also observed during another period (Figure S4 in Supporting Information S1 shows $S(t)$ and $M_0(t)$ during February 2011). After the largest foreshock, spike-like signals associated with subsequent intensive seismicity and slow relaxation-like changes following the largest foreshock are evident. Although BN23 claims that a preseismic accelerating phase started approximately 2 hr before the mainshock of the Tohoku-oki earthquake, such an abnormal signal can not be identified in our results (Figures 3c and 3d).

Now we can conclude that there was no preseismic tilt change larger than the noise level. In this sense, the noise level can be considered as the detection threshold for slip along the plate interface at the hypocenter. To characterize the noise level of the stacked trace $M_0(t)$, we compared the standard deviation to the expected wander for the 2-hr time interval assuming a power-law noise model (Agnew, 1992). Details of this comparison is described in Text S2 in Supporting Information S1. As a result, we defined the noise level of $M_0(t)$ (σ_{M_0}) as the standard

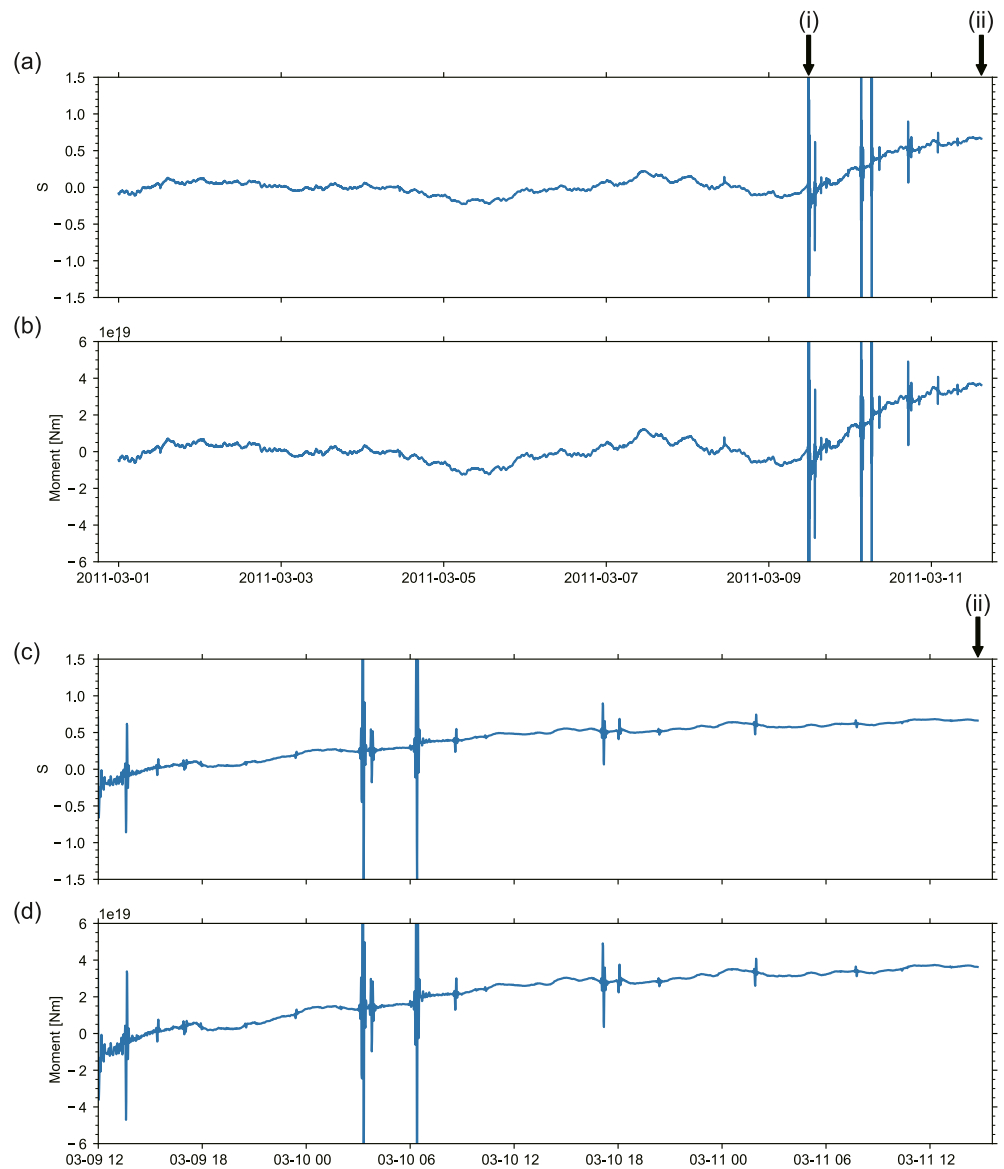


Figure 3. Stacking results of tilt records. (a) $S(t)$; and (b) $M_0(t)$; from 1 March 2011 to 11 March 2011 14:45. (c, d) Same as (a) and (b), respectively, but the results from 9 March 2011 12:00. Arrows at the top are the same as those in Figure 2. Note that the ranges of the vertical axes are clipped.

deviation for the 8 days after 1 March 2011. We obtain $\sigma_{M_0} = 5.0 \times 10^{18}$ Nm. The detection threshold in terms of moment can then be σ_{M_0} , and we can conclude that no preseismic slip larger than 5.0×10^{18} Nm (equivalent to moment magnitude 6.4) occurred. The magnitude of preseismic slip claimed by BN23 is 2.9×10^{19} Nm. This implies that if the claimed preseismic slip had actually occurred, we could have detected it with the tilt observation network. This observation supports the claim by Bradley and Hubbard (2023) that the reported 2-hr-long pre-seismic signal in the stacked GNSS record by BN23 can be an artifact caused by errors in the GNSS observations.

As we pointed out, a slow relaxation-like signal is observed after the largest foreshock on 9 March in the stacked records (Figure 3). The GNSS analysis by Bradley and Hubbard (2023) shows a similar transient signal in the stacked trace probably caused by the afterslip of the foreshock. Ohta et al. (2012) estimated a source model of the afterslip following the largest foreshock based on postseismic crustal deformation observed using GNSS and OBP gauges. We now examine whether the transient postseismic change after 9 March, as shown in Figure 3, is caused by the afterslip following the largest foreshock. To investigate this, we modeled a simplified source fault based on the slip distribution estimated by Ohta et al. (2012). We

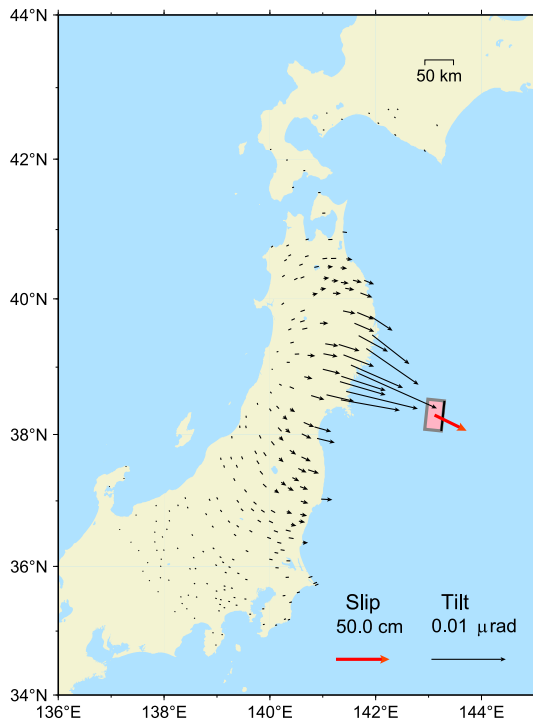


Figure 4. Synthetic tilt changes caused by a simplified model of the afterslip of the largest foreshock on 9 March 2011 (Ohta et al., 2012). A pink rectangle with a red arrow denote the fault geometry and slip vector of the assumed fault slip model. Solid arrows show the calculated tilt change vectors (an orientation of a vector indicates the tilting down direction).

calculated a tilt change vector for each station location using the same approach as in the evaluation of $\vec{g}_i$ in Equation 3. The result (Figure 4) shows that the expected tilting directions at most of the sites with larger tilt changes range from east to southeast and that the maximum magnitude of these tilt changes is approximately 1.2×10^{-8} radians. On the other hand, we measured the observed tilt change for each station for 24 hr from 12:20 on 9 March 2011 (well after the strong motion of the foreshock had sufficiently decreased). Figure S5 in Supporting Information S1 shows the distribution of the postseismic tilt changes. The directions of the observed tilt change vectors are not systematically distributed as can be seen from the synthetic tilt changes in Figure 4 but rather appears to be closer to random and the magnitude of the observed tilt changes is significantly larger than the calculated values at most sites. As an example, the synthetic tilt vector at station SZGH is 9.9×10^{-9} radians in the east-southeastward down direction, while the tilt time-series for this station shows a transient tilt change with a duration of approximately 24 hr in the east-northeastward down direction with a magnitude of 2.1×10^{-7} radians (Figure 2). Therefore, we conclude that a significant fraction of the observed postseismic transient was not caused by the afterslip, and any tilt deformation due to the afterslip was, at most, only a small fraction of the overall signal. Since SZGH is one of the closest stations to the epicenter of the mainshock, it has one of the largest weights in the stacking procedure in Equation 1 (see Figure S6 in Supporting Information S1). Consequently, we infer that the slow relaxation-like change after the largest foreshock in the stacked traces (Figure 3) was not the effect of postseismic deformation caused by the afterslip. Instead, it was likely due to other factors, such as instrument responses or mechanical coupling between the sensor and a borehole, in response to the strong ground shaking of the foreshock (e.g., Ueda et al., 2010).

5. Conclusions

We explored the possibility of precursory acceleration before the 2011 Tohoku-oki earthquake, which was reported by BN23 based on high-rate GNSS observation records. We used the tilt records from the NIED Hi-net, which are independent of the GNSS records, and performed similar data processing as BN23.

The data processing proceeded as follows: we calculated the dot product between the observed tilt vector time series and the corresponding tilt vector expected at each observation station if a fault slip in the same direction as the mainshock occurred at the hypocenter of the mainshock. We then stacked the time series normalized by the noise level at each station.

As a result, we did not observe the acceleration-like crustal movement reported by BN23 from approximately 2 hr before the mainshock. Therefore, we concluded that there was no precursory fault slip about 2 hr before the mainshock that exceeded the noise level of the tilt data we relied on. This indicates that any such slip, if it occurred, was less than 5.0×10^{18} Nm in seismic moment.

Data Availability Statement

The tilt records can be accessed at <https://doi.org/10.17598/NIED.0028>. The SCARDEC database (Vallée & Douet, 2016) is available at <http://scardec.projects.sismo.ipgp.fr/>. The computer code for calculating tilt deformation due to dislocation developed by Okada (1992) can be obtained from an NIED web page (https://www.bosai.go.jp/information/dc3d_e.html). The atmospheric pressure and precipitation data can be obtained from a Japan Meteorological Agency webpage <https://www.data.jma.go.jp/obd/stats/etrm/index.php>.

Acknowledgments

We would like to thank Associate Editor Victor Tsai and two anonymous reviewers for their constructive and helpful comments. We are grateful to the NIED members who work for maintaining the Hi-net facilities. This study was supported by JSPS KAKENHI Grants JP21H05205, JP21H05206 and JP21K03702, and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan, under its The Second Earthquake and Volcano Hazards Observation and Research Program.

References

- Agnew, D. C. (1992). The time-domain behavior of power-law noises. *Geophysical Research Letters*, 19(4), 333–336. <https://doi.org/10.1029/91GL02832>
- Bletery, Q., & Nocquet, J.-M. (2023). The precursory phase of large earthquakes. *Science*, 381(6655), 297–301. <https://doi.org/10.1126/science.adg2565>
- Bradley, K., & Hubbard, J. (2023). Earthquake precursors? Not so fast. *Earthquake Insights*. <https://doi.org/10.62481/310cc439>
- Hino, R., Inazu, D., Ohta, Y., Ito, Y., Suzuki, S., Inuma, T., et al. (2013). Was the 2011 Tohoku-Oki earthquake preceded by aseismic preslip? Examination of seafloor vertical deformation data near the epicenter. *Marine Geophysical Research*, 35(3), 181–190. <https://doi.org/10.1007/s11001-013-9208-2>
- Hirose, H. (2011). Tilt records prior to the 2011 off the Pacific coast of Tohoku earthquake. *Earth Planets and Space*, 63(7), 655–658. <https://doi.org/10.5047/eps.2011.05.009>
- Ito, Y., Hino, R., Kido, M., Fujimoto, H., Osada, Y., Inazu, D., et al. (2013). Episodic slow slip events in the Japan subduction zone before the 2011 Tohoku-Oki earthquake. *Tectonophysics*, 600, 14–26. <https://doi.org/10.1016/j.tecto.2012.08.022>
- Kato, A., Obara, K., Igarashi, T., Tsuruoka, H., Nakagawa, S., & Hirata, N. (2012). Propagation of slow slip leading up to the 2011 Mw 9.0 Tohoku-oki earthquake. *Science*, 335(6069), 705–708. <https://doi.org/10.1126/science.1215141>
- Marill, L., Marsan, D., Socquet, A., Radiguet, M., Cotte, N., & Rousset, B. (2021). Fourteen-year acceleration along the Japan Trench. *Journal of Geophysical Research: Solid Earth*, 126(11), e2020JB021226. <https://doi.org/10.1029/2020JB021226>
- Mavrommatis, A. P., Segall, P., & Johnson, K. M. (2014). A decadal-scale deformation transient prior to the 2011 Mw 9.0 Tohoku-oki earthquake. *Geophysical Research Letters*, 41(13), 4486–4494. <https://doi.org/10.1002/2014GL060139>
- Miyazaki, S., McGuire, J. J., & Segall, P. (2011). Seismic and aseismic fault slip before and during the 2011 off the Pacific coast of Tohoku Earthquake. *Earth Planets and Space*, 63(7), 637–642. <https://doi.org/10.5047/eps.2011.07.001>
- Nishimura, T. (2012). Crustal deformation of northeastern Japan based on geodetic data for recent 120 years. *Journal of the Geological Society of Japan*, 118(5), 278–293. <https://doi.org/10.5575/geosoc.2012.0027>
- Obara, K., Kasahara, K., Hori, S., & Okada, Y. (2005). A densely distributed high-sensitivity seismograph network in Japan: Hi-net by National Research Institute for Earth Science and Disaster Prevention. *Review of Scientific Instruments*, 76(2), 021301. <https://doi.org/10.1063/1.1854197>
- Ohta, Y., Hino, R., Inazu, D., Ohzono, M., Ito, Y., Mishina, M., et al. (2012). Geodetic constraints on afterslip characteristics following the March 9, 2011, Sanriku-oki earthquake, Japan. *Geophysical Research Letters*, 39(16). <https://doi.org/10.1029/2012GL052430>
- Okada, Y. (1992). Internal deformation due to shear and tensile faults in a half-space. *Bulletin of the Seismological Society of America*, 82(2), 1018–1040. <https://doi.org/10.1785/BSSA0820021018>
- Okada, Y., Kasahara, K., Hori, S., Obara, K., Sekiguchi, S., Fujiwara, H., & Yamamoto, A. (2004). Recent progress of seismic observation networks in Japan—Hi-net, F-net, K-NET and KiK-net. *Earth Planets and Space*, 56(8), xv–xxviii. <https://doi.org/10.1186/BF03353076>
- Roeloffs, E. A. (2006). Evidence for aseismic deformation rate changes prior to earthquakes. *Annual Review of Earth and Planetary Sciences*, 34(1), 591–627. <https://doi.org/10.1146/annurev.earth.34.031405.124947>
- Takamatsu, N., Muramatsu, H., Abe, S., Hatanaka, Y., Furuya, T., Kakiage, Y., et al. (2023). New GEONET analysis strategy at GSI: Daily coordinates of over 1300 GNSS CORS in Japan throughout the last quarter century. *Earth Planets and Space*, 75(1), 49. <https://doi.org/10.1186/s40623-023-01787-7>
- Tamura, Y., Sato, T., Ooe, M., & Ishiguro, M. (1991). A procedure for tidal analysis with a Bayesian information criterion. *Geophysical Journal International*, 104(3), 507–516. <https://doi.org/10.1111/j.1365-246X.1991.tb05697.x>
- Ueda, H., Fujita, E., Ukawa, M., & Yamamoto, E. (2010). Automated technique for anomalous volcanic crustal deformation detection and source estimation by using real time tiltmeter data. *Report of the National Research Institute for Earth Science and Disaster Prevention*, 76, 21–32. <https://doi.org/10.24732/nied.00001200>
- Vallée, M., & Douet, V. (2016). A new database of source time functions (STFs) extracted from the SCARDEC method. *Physics of the Earth and Planetary Interiors*, 257, 149–157. <https://doi.org/10.1016/j.pepi.2016.05.012>
- Yokota, Y., & Koketsu, K. (2015). A very long-term transient event preceding the 2011 Tohoku earthquake. *Nature Communications*, 6(1), 5934. <https://doi.org/10.1038/ncomms6934>