The Delayed Decrease of Seismicity In The Eastern Margin of The Japan Sea Due To The Megathrust Event In 2011 Along The Japan Trench

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Title page:

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20 0064, Japan.
21 (go to new page)
22

23 **Abstract**

24 In the eastern margin of the Japan Sea, off the west coast of Tohoku district, the
25 seismicity increased right after the M9 megathrust event off the east coast of the Tohoku
26 district on March 11, 2011. Four months later, the seismicity decreased to the half level
27 of that before the M9 event. Such quantitative study was done by the point-process
28 model selection with AIC. The decrease lasted for eight years until an M6.7 event
29 occurred within the area in 2019. When we compare the seismicity change
30 between before and after the M9 event, with the post seismic change of the maximum
31 shear stress obtained by the viscoelastic simulation for a thousand years after the M9
32 event, we can estimate a loading rate of the shear stress in the area before the M9 as 24
33 kPa/y. For the term after the M9 event, the rate is a half of it; 12 kPa/y. When we
34 assume the whole dilatation change due to the M9 event had been canceled by the time
35 of the M6.7, the increasing rate of the mean stress after the M9 event is 21 kPa/y at
36 most. When we will be able to use JMA catalog for 2020 or later years, we can obtain
37 the seismicity level after the M6.7 quantitatively, and we will be able to narrow down
38 this estimation.

39

40 **Keywords**

41 The eastern margin of the Japan Sea, Seismicity decrease, Viscoelastic aftereffect,

42 Megathrust event, Point-process model selection, Strain rates before and after M9

43

44 **Main Text**

45 **Introduction**

46 The M9 mega-thrust inter-plate earthquake, which occurred off the Pacific coast of

47 the Tohoku district on Mar. 11, 2011 (here after “the M9 event”), drastically changed

48 the stress status of the northeastern Japan. The change was reflected as the dramatic

49 activation of seismicity in many areas which had been aseismic before (e.g. Ogata,

50 2012). Many papers were published (e.g. Toda et al., 2011; Ishibe et al., 2015)

51 explaining the change of seismicity in many regions for various receiver fault planes by

52 Coulomb Failure Stress change (ΔCFS).

53 In the eastern margin of the Japan Sea, which is 300 to 400-km away from the

54 center of the source area of the M9 event (Fig. 1) along the direction of the Pacific Plate

(PAC) motion towards the northeastern Japan, the immediate increase of seismicity was also observed like many other regions in Japan. That increase was mainly due to the occurrence of the M6.4 a half day after the M9 event (Table 1). It is a strike-slip type earthquake in the aftershock area of the destructive thrust earthquake of M7.7 in 1983. It was the largest event around the area at that time, since Japan Meteorological Agency (JMA) started to use unified seismic data of Japan for their catalog on Oct. 1, 1997.

In that region, we noticed that the significant decrease followed later (Tsumura, personal communication). The decrease sustained for more than a few years. We reported it promptly (Matsu'ura et al., 2017), and waited for the tentative hypocenter catalog of JMA would be revised for the inhomogeneous term after the M9 event. However, the M6.7 thrust event renewed the maximum M of the area on June 18, 2019. Following this event, the seismicity seems to revert to the level before the M9 event. The occurrence of the M6.7 event made us possible not only to describe the decrease of the seismicity, but also to estimate the stress status in the area for eight years after the M9 event.

Since the M9 event is gigantic, in addition to the coseismic effect, which is usually

used to explain the seismicity change by Δ CFS analysis, the viscoelastic post seismic effect for eight years must be another vital factor to affect the seismicity transition. When we quantitatively compare the post M9-changes of seismicity with the post seismic changes in stress field of the area, it will give us an estimation on the background stress status of the area. Here we examined the seismicity with the latest catalogue of JMA to be compared with the three dimensional simulation on the viscoelastic effect of the M9 event to the area.

Data and Method for the Seismicity Analysis

In Fig.1, the location of the studied area is shown. The A-A' line is parallel to the convergent direction of the Pacific Plate (PAC) toward the northeastern Japan. This line passes through the peak of the co-seismic slip in the focal region of the M9 event obtained by Hashimoto et al. (2012). The area around this line must be the most affected part in the eastern margin of the Japan Sea by the M9 event. In order to prevent intentional selection of earthquakes, events within the 150km×300km rectangle, whose shorter side is parallel to the line A-A', and whose center is on the line A-A', were

87 selected.

88 We used JMA hypocentral catalog obtained from its website on July 8th, 2021. For
89 the period from Oct. 1st, 1997 to the end of 2019, hypocenters of the depth of 60km or
90 shallower, JMA M2.0 or larger were selected. The total number of earthquakes for 8127
91 days are only 4224. Hereafter, those events plotted as red crosses in Fig. 1 are
92 examined. Among them, the three largest events are listed in Table 1. Although we
93 chose 60km as the depth limit, our target seismicity is only that in the shallow crust. We
94 chose 60km only to avoid losing some very shallow earthquakes in the early part of the
95 JMA catalog due to the poor depth accuracy for offshore events.

96 In Fig. 2, cumulative number of the whole data of 22.25 years are shown for the
97 whole term. Even from the simple cumulative numbers, it is apparent that the seismicity
98 increased right after the M9 event (Fig. 2(b), (c), and (d)). A half day after the M9
99 event, the second largest event of the area (M6.4) was induced within the aftershock
100 area of the 1983 event, and many earthquakes followed it. However, the seismicity
101 averaged over a long term after the M9 event is lower than that of before (Fig. 2(a)).

102 Since the seismicity of this area is not very active, we did not use ETAS model

103 (Ogata, 1988) for the point process analysis in the present study. We excluded the 9%
 104 data in the tail part, which is the half-year period after the largest event of M6.7 on June
 105 18, 2019, from the analysis to eliminate aftershocks of this largest event. A half year is
 106 too short to analyze the seismicity level after the M6.7 confidently. We examined 3844
 107 events, which occurred in the 7930 days since Oct. 1st, 1997, and focused on the base
 108 rate comparison before and after the M9 event.

109 When $N(M_{th}, S, E)$ is number of earthquakes of $M \geq M_{th}$ during the period from S
 110 to E, the averaged occurrence rate of $M \geq M_{th}$ for that term; $\lambda(M_{th}, S, E)$ is

$$111 \quad \lambda_{ave.} = \lambda(M_{th}, S, E) = \frac{N(M_{th}, S, E)}{(E-S)}. \quad (1)$$

112 The Poisson model with the rate $\lambda(M_{th}, 0, T_{all})$ is the simplest point process model
 113 that there was no significant change of λ temporarily, during the period of $\{0, T_{all}\}$.

114 Since the number of parameters (n_p) for this model is one, AIC of this model is

$$115 \quad AIC_{all} = AIC(M_{th}, 0, T_{all}, n_p) = 2(n_p - \ln Likelihood)$$

$$116 \quad = 2 - 2 \times N(M_{th}, 0, T_{all})(\ln \lambda_{ave.} - 1). \quad (2)$$

117 When λ changed at $t=T_c$, λ for the term before T_c , and λ for the term after T_c are,

$$118 \quad \lambda_{left} = \lambda(M_{th}, 0, T_c) = \frac{N(M_{th}, 0, T_c)}{T_c}, \quad (3)$$

$$\lambda_{right} = \lambda(M_{th}, T_c, T_{all}) = \frac{N(M_{th}, T_c, T_{all})}{(T_{all} - T_c)}, \quad (4)$$

and AIC of this model is

$$AIC_{T_c} = AIC(M_{th}, 0, T_c, 1) + AIC(M_{th}, T_c, T_{all}, 1) + 2 + Penalty, \quad (5)$$

$$AIC_{T_c} \leq \max. AIC_{T_c} = 18 - 2 \times N(M_{th}, 0, T_c) \times \{\ln \lambda_{left} - 1\} \\ - 2 \times N(M_{th}, T_c, T_{all}) \times \{\ln \lambda_{right} - 1\}. \quad (6)$$

The penalty of introducing T_c in a model is not larger than 12 (Kumazawa et al., 2010).

When $AIC_{T_c} < AIC_{all}$, the model with the rate change is selected, and the T_c of the best model minimizes AIC_{T_c} . In order to avoid the effect of inhomogeneity in the long term catalog, M_{th} of 2.5 and 3.0 are examined for model selections.

128

129 **Result on the seismicity transition**

130 In Fig. 3(a), λ_{left} and λ_{right} of $M_{th}=2.5$ are shown at T_c of each day. When the
131 M6.4 event and its aftershocks became inconspicuous, λ_{right} became rather stable.
132 Models with T_c within a few-year term after the M9 event give far smaller AIC (Fig.
133 3(c)) than that of Eq. (2). It is confirmed that the occurrence-rate decrease delayed for a
134 few months from the occurrence time of the M9 event (Fig. 3(d)). In order to detect the

start of that delayed decrease correctly, data within the one month after the M9 event is excluded in the next analysis (Fig. 4). When $M_{th}=3.0$, the similar delayed decrease of AIC is also confirmed (Fig. 5). T_c s with smallest three AICs of each model are listed in Table 2 with each occurrence rate. From Figs. 3, 4, and 5, and Table2, it is apparent that the change point T_c is not very sharp. λ_{right} is a half of λ_{left} for each M_{th} . This delayed decrease started about four months from the M9 event. Even the immediately induced M6.4 event and its aftershocks are included, the delayed decrease is significant (Fig. 3). The decrease rate sustained for more than four years, which made us notice it even from the raw distribution maps of epicenters.

Due to the COVID-19, the JMA hypocenter catalog is not yet fixed for 2020 and 2021 at present. Since available catalog after the M6.7 covers only a half year, we cannot obtain λ for the period after M6.7 by eliminating its aftershocks in this study precisely. However, the most right part of Fig. 2 looks that λ after the M6.7 at the end of 2019 is larger than λ_{right} . This must be verified in the future study with a longer catalog. In this study, we report that the seismicity decrease to the half level prevailed for eight years after four-month immediate activation after the M9 event.

151

152 **Estimation of viscoelastic effect of the M9 event to the area**

153 In order to estimate the deviatoric stress field of the studied area for eight years
154 after the M9 event, not only the coseismic change, but also the post seismic viscoelastic
155 effect of the M9 event should be included consistently. Fortunately, Hashima et al.
156 (2014) already calculated coseismic and post seismic strain fields for a thousand years
157 after the M9 event in the three dimensional space. In Figs. 6 and 7, vertical sections
158 along A-A' line of Fig. 1, of changes in dilatation and the maximum shear strain after
159 the M9 event are shown according to their simulation. They used the coseismic slip
160 distribution of the M9 event obtained by Hashimoto et al. (2012), because the PAC
161 plate geometry (Hashimoto et al., 2004) of the simulation is in common with their
162 source inversion. They simulated the elastic coseismic change and the viscoelastic after
163 effect with the structure shown in Table 3. The area we examined the seismicity is the
164 shallow part of the left end of their simulated region (400~550 km horizontally remotod
165 to the WNW direction from the trench axis on the A-A' line).

166 In Fig. 8, temporal changes of the mean stress and the maximum shear stress at the

167 point shown in Fig. 6 (10km-depth and -422km from the trench axis on A-A') are
168 plotted. Since that point is in the elastic layer, the dilatation and the maximum shear
169 strain are proportional to the mean stress (the expanding direction is positive), and the
170 maximum shear stress, respectively.

171 The simple approximated expression of the isotropic stress $\sigma_{iso}(t)$ of the point (-
172 422, 10) at time t (solid line of Fig. 8) is

$$\sigma_{iso}(t) = 0.128 + 0.104 \times (1 - \exp^{-0.057t}) \quad \text{when } t \leq 40y \text{ in MPa.}$$

(7)

175 The increase rate decays with an exponential function with a half-life of 12 years. About
176 a quarter of the coseismic dilatation increased in 40 years after the M9 event due to the
177 viscoelastic post effect. After around fifty years, $\sigma_{iso}(t)$ starts decreasing, and only
178 35% of the coseismic dilatation is left at $t=1000y$ (see Fig. 10 of Hashima et al., 2014)
179 in this region.

180 The maximum shear stress $S_{max}(t)$ (broken line in Fig. 8) can be expressed as

$$S_{max}(t) = (0.194 + 0.014t) \quad \text{when } t \leq 3y, \quad (8)$$

$$S_{max}(t) = S_{max}(3) + 0.26 \times (1 - \exp^{-0.047(t-3)}) \quad \text{when } 3y < t \leq 40y \text{ in MPa.} \quad (9)$$

For the first three years, s_{max} increases almost linearly. Then the increase rate decays with an exponential function with a half-life of 14.75 years. In the examined area, the post seismic maximum shear stress change for 40 years is a half of the coseismic change. As Fukahata and Matsu'ura(2018) pointed out, even the viscosity is set to be 10^{19} Pa s, the relaxation time at this point is larger than 10 years. The relaxation time of the isotropic stress is slightly shorter than that of maximum shear stress in the studied area. After around a hundred years, the maximum shear stress starts decreasing in this region. However, only 7% of its value at $t=100y$ decreases at $t=1000y$ (see Fig. 11 of Hashima et al., 2014).

The coseismic changes of the mean stress, and of the maximum shear stress at the point are 0.13 MPa, and 0.19 MPa, respectively. After eight years ($t=8$), these increased to 0.17 MPa, and 0.29 MPa, respectively. Until the thrust-type M6.7 occurred in 2019, the post seismic dilatation was 30% of the coseismic dilatation, while the post seismic maximum shear stress increase was the half of the coseismic change.

Discussion

Among seismicity changes after a large event, activations such as aftershocks are often easy to be detected regardless of the seismicity status before that large event. The ETAS effect boosts the detectability of seismicity increase. It is no wonder that DeVries et al. (2018) selected $\Delta\tau_{\max}$ that corresponds only to the activation (Matsu'ura and Terakawa, 2021) as the best indicator for predicting spatial patterns of aftershocks. However, what we found this time is the decrease to the half level that lasted for eight years after the main shock. In our case, $\Delta\tau_{\max}$ is not a good indicator at all. Since ΔCFS depends on the orientations of receiver faults, it can be used to explain the decrease of seismicity as well as the increase. However, it is impossible to determine fault orientations of all 3884 events we analyzed. ΔCFS is not very effective to what we found.

As Terakawa et al. (2013) pointed out, the occurrence of the M6.4 should be affected by the change of pore fluid pressure in the aftershock area of the 1983 event. Its fault orientation was not at all favorable to the background stress field, which is roughly compressional in the direction of the PAC subduction. Recently, Terakawa et al. (2020) expanded ΔCFS to the change of energetics-based Failure Stress (ΔEFS) as the index

215 for predicting induced seismicity after a large event. ΔEFS does not depend on the
216 orientations of receivers, and it does include the change of pore fluid pressure due to a
217 large earthquake. In the four month-period between the occurrence time of the M9 event
218 and the T_c determined in the third section, ΔEFS must be used for the analysis, since
219 the change of pore fluid pressure in the studied area should have affected the seismicity.
220 However, after T_c , the seismicity of the area is so stable for eight years. We can treat
221 the pore fluid pressure after T_c as a part of the background stress field, which should
222 have been changing very smoothly in the area, after the drastic change of pore fluid had
223 been settled before T_c .

224 Therefore, we assume that the gradually changing crustal stress after T_c was the
225 summation of the background tectonic stress and the coseismic and post seismic stress
226 changes due to the M9 event. The post-seismic increase of 96 kPa in the maximum
227 shear stress for eight years resulted in the post seismicity of the area. To sustain the
228 double level of seismicity for years before the M9 event, the double of the post
229 maximum shear stress change is necessary. It give us 24 kPa/y in the studied area as the
230 tectonic accumulation rate of shear stress before the M9 event. This rates give us a

231 recurrence time estimation of about two hundred years for a major event of this area
232 with 5 MPa stress drop. As the shear strain rate, it is equivalent to $4 \times 10^{-7}/y$.

233 When we assume that the dilatation due to the M9 event, including both coseismic
234 and post seismic changes, had been almost canceled by the time of the M6.7 in the
235 studied area, the tectonic rate of the compressional stress in this area after the M9 event
236 becomes 21 kPa/y. It is also equivalent to the strain rate of $4 \times 10^{-7}/y$. If we assume that
237 the recovery was half of the pre-M9 level at the time of M6.7, the rate is 10 kPa/y. In
238 order to determine the current mean stress status, we should examine the post M6.7
239 seismicity quantitatively in future study with a catalog with the extended period.

240 As the order estimation of the background loading rate in the eastern margin of the
241 Japan Sea, we get 24 kPa/y of shear rate for the term before the M9 event, and 12 kPa/y
242 of shear rate for the term after the M9 event. Since the seismicity decrease we found
243 was stable for eight years, ignoring the effect of changes in the pore fluid pressure of the
244 area does not affect our estimations seriously. We also ignore the effect of after slips
245 around the source area of the M9 event, because the studied area is more than 150 km
246 away from the regions slipping afterwards. As the background accumulation rate of

compressional mean stress after the M9 event, we get 21 kPa/y or lower. With the analysis of the seismicity after the M6.7 event, it will be better to use ΔEFS to examine post-M9 mean-stress status further.

The rate of horizontal strain obtained from GPS data for the eastern margin of the Japan Sea before the M9 event (Sagiya, 2004) is a quarter of what we obtained in this study. Fukahata et al. (2020) obtained EW-direction deformation rates from GPS data in the Niigata region as $6 \times 10^{-8}/y$ for pre-M9, and $3 \times 10^{-8}/y$ for post-M9 terms. Their strain rates are two dimensional. Plane strain is usually smaller than three-dimensional strain. It is considered that rates we obtained are within the permissible range of the GPS observation. The shear strain rate for the post-M9 term we obtained is a half of the pre-M9 term. It is coincide with what Fukahata et al (2020) obtained.

Conclusion

We examined the delayed decrease of seismicity of the area in the eastern margin of the Japan Sea with the point process model selection. The area remotes 300-400 km horizontally away along the plate motion direction from the center of the mega-thrust event in 2011. In this area, the seismicity increased right after the M9 event with the

263 induced M6.4 strike-slip event. After about four months, the seismicity became the half
264 level of that before the M9 event. The decreased rate lasted for eight years. After 8.25
265 years, an M6.7 thrust-type event occurred in the area. Due to the aftershocks of this
266 event, we cannot determine the base occurrence rate at present yet with the fixed JMA
267 catalogue. However, the raw cumulative number curve suggests that the seismicity is
268 recovering after the M6.7.

269 Referring the viscoelastic simulation, the coseismic and post seismic dilatation
270 change for eight years due to the M9 was examined. It gives the 21 kPa/y as the
271 maximum tectonic increase rate of mean compressional stress on this area after the M9
272 event, when we assume the occurrence of the M6.7 represents the full recovery of the
273 compressional stress field in the eastern margin of the Japan Sea. When the JMA
274 catalogue will allow us to analyze seismicity after the M6.7 fully, the mean stress level
275 at present will be clearer.

276 From the post seismic maximum shear strain change and the half level of the
277 seismicity after the M9 event, the pre-M9 seismicity in the area suggests 24 kPa/y as the
278 rate of tectonic shear stress increase before the M9 event. The estimated loading rates of

this region are a several times larger than those obtained from the GPS data in the plane strain framework. However, our finding that the pre-M9 term rate is the double of the post-M9 term well agrees with that obtained for EW-deformation rate in Niigata (Fukahata et al., 2020). For a long-term hazard estimation of the eastern margin of the Japan Sea area, the rates we obtained will be another proxy values.

Declarations

The authors *must* provide the following sections under the heading “Declarations”.

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

List of abbreviations

- ΔCFS: Coulomb Failure Stress change
- ΔEFS: the change of energetics-based failure stress
- F-net: F-net Broadband Seismograph Network

295 JMA: Japan Meteorological Agency

296 PAC: the Pacific Plate

297 **Availability of data and materials**

298 Mw, mechanism, and hypocentral depth of centroid moment tensor

299 solutions for most major events in and around Japan are available at the

300 F-net website: <https://www.fnet.bosai.go.jp/top.php?LANG=en> (obtained

301 on July 8, 2021).

302 JMA hypocenter catalogue is available at: <http://www.data.jma.go.jp/>

303 [svd/eqev/data/bulletin/hypo.html](http://www.data.jma.go.jp/svd/eqev/data/bulletin/hypo.html). (obtained on July 8, 2021) However,

304 JMA revises the past hypocenter catalogues irregularly. Most revisions

305 are usually trifling matters.

306 **Competing interests**

307 *Not applicable*

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312 **Authors' contributions**

313 Ritsuko S. Matsu'ura analysed the seismicity. Akinori Hashima prepared
314 the viscoelastic calculations. Takeo Ishibe examined the F-net data in the
315 area for the discussion.

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322 **Authors' information**

323

324 **References**

325 DeVries, P.M.R., Viégas, F., Wattenberg, M., Meade, B.J. (2018) Deep learning of
326 aftershock patterns following large earthquakes. Nature 560, 632–634. doi.org/10.1038/

327 s41586-018-0438-y

328 Fukahata, Y. & Matsu'ura, M. (2018) Characteristics of viscoelastic crustal deformation
329 following a megathrust earthquake: discrepancy between the apparent and intrinsic
330 relaxation time constants, *Pure Appl. Geophys.*, **175**, 549-558, doi: 10.1007/s00024-
331 017-1735-3.

332 Fukahata, Y., Meneses-Gutierrez, A., Sagiya, T. (2020) Detection of plastic strain using
333 GNSS data of pre- and post-seismic deformation of the 2011 Tohoku-oki earthquake,
334 *Earth Planets Space*, 72:18, doi.org/10.1186/s40623-020-1144-1.

335 Hashima, A., Fukahata, Y., Hashimoto, C., Matsu'ura, M. (2014) Quasi-static strain and
336 stress fields due to a moment tensor in elastic-viscoelastic layered half-space, *Pure*
337 *Appl. Geophys.*, 171: 1669-1693.

338 Hashimoto, C., Fukui, K., Matsu'ura, M. (2004) 3-D modelling of plate interfaces and
339 numerical simulation of long-term crustal deformation in and around Japan, *Pure Appl.*
340 *Geophys.*, 161: 2053-2068.

341 Hashimoto, C., Noda, A., Matsu'ura, M. (2012) The Mw 9.0 northeast Japan
342 earthquake: total rupture of a basement asperity, *Geophys. J. Inter.*, 189: 1-5.

doi:10.1111/j.1365-246X. 2011.05368.x.

Ishibe, T., Shimazaki, K., Satake, K. (2011) Change in seismicity beneath the Tokyo metropolitan area due to the 2011 off the Pacific coast of Tohoku Earthquake. *Earth Planet Sp* 63, 40. <https://doi.org/10.5047/eps.2011.06.001>

Kumazawa, T., Ogata, Y., Toda, S. (2010) Precursory seismic anomalies and transient crustal deformation prior to the 2008 Mw = 6.9 Iwate-Miyagi Nairiku, Japan, earthquake, *J. Geophys. Res.*, 115, B10312, doi:10.1029/2010JB007567.

Matsu'ura, M., Terakawa, T. (2021) Decomposition of elastic potential energy and a rational metric for aftershock generation, *Geophys. J. Int.* (2021) 227, 162–168. <https://doi.org/https://doi.org/10.1093/gji/ggab206>.

Matsu'ura, R. S., Ishibe, T., Tsumura, K. (2017) Significant Decrease of Seismicity in the Northeastern Margin of the Japan Sea after the Mega Thrust Event on Mar. 11, 2011, *Proceedings JpGU-AGU Joint Meeting 2017*, SSS05-10. (p.14-15 of the pdf available at: http://www2.jpгу.org/meeting/2017/PDF2017/S-SS05_O_e.pdf).

Ogata, Y. (1988) Statistical models for earthquake occurrences and residual analysis for point processes, *J. Am. Statist. Asso.*, 83(401), 9–27. <https://doi.org/10.2307/22889149>

359 27.

360 Ogata, Y. (2012) Long-term probability forecast of the regional seismicity that was
361 induced by the M9 Tohoku-Oki earthquake, Rep. Coordinating Committee for Earthq.
362 Prediction, 88, 92-99 (in Japanese).

363 Sagiya, T. (2004) A decade of GEONET: 1994–2003 —The continuous GPS
364 observation in Japan and its impact on earthquake studies—. *Earth Planet Sp.*, 56, xxix–
365 xli. <https://doi.org/10.1186/BF03353077>

366 Terakawa, T., Hashimoto, C., Matsu'ura, M. (2013) Changes in seismic activity
367 following the 2011 Tohoku-oki earthquake: Effects of pore fluid pressure. *Earth Planet.*
368 *Sci. Lett.*, 365, 17-24. doi:10.1016/j.epsl.2013.01.017

369 Terakawa, T., Matsu'ura, M. Noda, A. (2020) Elastic strain energy and pore fluid
370 pressure control of aftershocks, *Earth planet. Sci. Lett.*, 535, 16103.
371 <https://doi.org/10.1016/j.epsl.2020.116103>.

372 Toda, S., Ross, S., Lin, J. (2011) Widespread seismicity excitation throughout central
373 Japan following the 2011 M=9.0 Tohoku earthquake and its interpretation by Coulomb
374 stress transfer, *Geophys. Res. Lett.*, 38, L00G03,

<https://doi.org/10.1029/2011GL047834>.

Figure Captions

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Fig. 2. Cumulative number of events shown by red crosses in Fig. 1.

(a) M-T plot of events. (b) Cumulative numbers of the whole term with three thresholds of M . For the period around the occurrence time of the $M 9$ event (shown by gray

squares on each line) are expanded in (c), (d) and (e), respectively. The slope of five occurrence rates are shown by black lines as references to see rates from cumulative number lines.

Fig. 3. Occurrence rates and AIC at each T_c for $M \geq 2.5$.

(a) Daily occurrence rate of before T_c (Blue line) and after T_c (Red line) terms are shown at each T_c . Black line shows the average rate of the whole term.

(b) M-T plot of $M \geq 2.5$ for the same period.

(c) AIC values for each T_c are plotted at T_c . The black line shows the AIC for the model without T_c , i.e. the constant rate through the whole term. The part in the red broken square are expanded in (d).

Fig. 4

. Occurrence rates and AIC at each T_c for $M \geq 2.5$ without one month data after the M9 event.

T_c in July 2011 gives the smallest AIC. See the caption of Fig. 3.

407

408 Fig. 5. Occurrence rates and AIC at each T_c for $M \geq 3.0$ without one month data after the
409 M9 event.

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412 Fig. 6. Temporal changes of the isotropic strain due to the M9 event.

413 The vertical section of the isotropic strain changes along the line A-A' in Fig. 1 at $t=0$

414 (coseismic), 5, 10, 20, 30, 50, and 100 years after the M9 event are shown by color and

415 contours. The red and blue color scales represent expansion, and contraction,

416 respectively. Contours of 5×10^{-5} , $\pm 2 \times 10^{-5}$, $\pm 1 \times 10^{-5}$, $\pm 5 \times 10^{-6}$, $\pm 2 \times 10^{-6}$ are also shown by

417 thin lines. The thick solid line indicates the PAC plate interface shallower than 50km.

418 The thin horizontal line at 40km-depth indicates the interface between elastic and

419 viscoelastic layers. The analyzed area is shown by the blue dotted rectangle in the top

420 figure. The green star in the top figure shows the position of the point whose stress

421 change is plotted in Fig. 8. [made after Hashima et al. (2014)]

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427 2×10^{-5} , 1×10^{-5} , 5×10^{-6} , and, 2×10^{-6} . The black and white bars show the extension and

428 contraction directions with those magnitudes at each point, respectively. See the caption

429 of Fig. 6.

430

431 Fig. 8. Changes of the mean stress (extension positive), and the maximum shear stress

432 at the point of (422km-west from the trench axis, 10km-depth) shown in Fig. 6 due to

433 the M9 event, for 50 years.

434 Since the point is in the elastic layer, dilatation and the maximum shear strain are

435 proportional to the mean stress, and the maximum shear stress, respectively. With the

436 bulk and shear moduli in Table 3, these are converted to stresses. The values at $t=0$ are

437 coseismic values.

438

439 **Table Contents**

440 **Table 1.** List of the three largest earthquakes in the studied area during Oct. 1997-Dec.
441 2019.

Date (JST)	JMA M	Mw	depth (km)	type
1997/11/23 12:50	5.8	5.5	8	thrust
2011/3/12 4:46	6.4	6.1	5	strike slip
2019/6/18 22:22	6.7	6.4	11	thrust

442 Mw and depth are from F-net.

443 **Table 2.** List of Tc with three smallest AICs for each model

Tc in 2011	days after the M9	AIC _{2.5w/c}	AIC _{3.0w/c}	AIC _{2.5}	$\lambda_{\text{left}2.5w/c}$	$\lambda_{\text{right}2.5}$	$\lambda_{\text{left}3w/c}$	$\lambda_{\text{right}3w/c}$	$\lambda_{\text{right}2.5}$
July 3	113	<u>7176.4</u>	3563.4	<u>7354.8</u>	0.20	0.10	0.073	0.036	0.21
July 24	134	7176.5	3562.1	7355.0	0.20	0.10	0.073	0.035	0.21
Aug. 10	151	7178.4	<u>3561.9</u>	7357.1	0.20	0.10	0.073	0.035	0.21

444 Underlined value is the smallest AIC for each data set. A numerical subscript for AIC
445 and λ represents Mth of each data set. “w/c” represents that the data without a month
446 after the M9 event is used. All λ s are occurrence rates per one day.

447

448

449 **Table 3.** The structural parameter of the elastic-viscoelastic layered half-space model

450 used for the simulation (after Hashima et al., 2014).

Layer No.	Thickness (km)	Bulk modulus (10^{10} Pa)	Shear modulus (10^{10} Pa)	Density (10^3 kg/m ³)	Viscosity (10^{19} Pa s)
1	40	5.1	3.2	2.6	∞
2	∞	13	6.9	3.4	1

Figures

Fig. 1

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Figure 7

Deviatoric shear strain changes due to the M9 event. The vertical section of the deviatoric strain fields along the line A-A' in Fig. 1 at $t=0$ (coseismic), 5, 10, 20, 30, 50, and 100 years after the M9 event. The deviatoric maximum shear strain is shown by color, and contours of 5×10^{-5} , 2×10^{-5} , 1×10^{-5} , 5×10^{-6} , and 2×10^{-6} . The black and white bars show the extension and contraction directions with those magnitudes at each point, respectively. See the caption of Fig. 6.

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