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# Seismicity in source regions of large interplate earthquakes around Japan and the characteristic earthquake model

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The occurrence rate of the characteristic earthquake (CE) was compared with seismicity in nine source regions of interplate earthquake (i.e., the regions off Shikotan Island, off Nemuro, off Tokachi, off Northern Sanriku, off Miyagi, far off Miyagi, and the Tonankai, Nankai, and Kanto regions) by combining instrumental data and the recurrence interval of CEs evaluated by the Headquarters for Earthquake Research Promotion (HERP) in Japan. The recurrence interval of the Nankai earthquake was estimated on the basis of long historical records and found to be one of the least uncertain ones. We used the unified catalog of earthquakes obtained by the Japan Meteorological Agency (JMA) on the basis of a recently improved seismic network, together with the old JMA catalog. Seismicity of all the interplate source regions indicated that the number of observed events was much less than the number of events predicted from the Gutenberg-Richter (G-R) relation and the occurrence rate of the CE. In all regions except for far off Miyagi, the CEs occurred during the interval of the earthquake catalog. Thus, our data set included the highest seismicity period during an earthquake cycle. In the region off Tokachi where the 1952 and 2003 Tokachi-Oki earthquakes occurred, the magnitude frequency distribution (MFD) during one seismic cycle exhibited a magnitude gap of 1.1 between the CE and the other events. Therefore, our results favored the CE model. Moreover, we conversely estimated an average recurrence interval of the CEs in each region, based on the assumption that the G-R relation holds. Most estimated recurrence intervals were far longer than the evaluation given by HERP.

**Key words:** Characteristic earthquake model, Gutenberg-Richter relation, interplate earthquake.

## 1. Introduction

The Gutenberg-Richter (G-R) relation ($\log n = a - bM$, where $n$ is the number of events with magnitude equal to $M$, and $a$ and $b$ are constant values) has been used to describe regional seismicity (Ishimoto and Iida, 1939; Gutenberg and Richter, 1944). However, a number of studies have reported that seismicity around a fault or a fault system does not satisfy the G-R relation across the entire magnitude range for a complete seismic cycle (Wesnousky *et al*., 1983; Schwartz and Coppersmith, 1984; Youngs and Coppersmith, 1985; Papadopoulos *et al*., 1993, 2003; Wesnousky, 1994; Stirling *et al*., 1996). In the characteristic earthquake (CE) model by Schwartz and Coppersmith (1984), only very few smaller events occur in the source region of the maximum-size events (MEs). The schematic illustration of the discrete and cumulative forms of the magnitude frequency distribution (MFD) described by the G-R relation and the CE model are displayed in Fig. 1. The MFD for the CE model exhibited a gap in magnitude between the largest and other events, though the G-R relation indicated continuous MFD up to the maximum magnitude.

Whether seismicity in a source region obeys the G-R relation or the CE model is an important question when exploring the possibility of earthquake prediction; therefore, much discussion has focused on this issue. The G-R power law of MFD is commonly found in regional seismicity and is sometimes generated by numerical simulations. This is often taken as evidence that earthquake occurrence is a critical phenomenon when the magnitude of an individual earthquake is unpredictable (e.g., Bak and Tang, 1989). However, the CE model has been suggested mainly from geological and/or geomorphological observations, including trenching surveys.

If the extent of an individual rupture in a source region is mostly determined by stochastic factors, a great earthquake is thought to be a rupture that accidentally did not stop halfway. In this case, the occurrence of great earthquakes would be difficult to predict. In contrast, if the seismicity in a source region were inactive during the inter-seismic period and the CE ruptures the entire segment more or less periodically, knowledge and comprehension of the physical conditions would help to determine the behavior.

A simple way to judge whether the G-R relation or the CE model more effectively describes the seismicity in a source region is to investigate directly the shape of the MFD during one complete seismic cycle. However, statistical fluctuation is large because the frequency of large earthquakes is basically low. Discussion of the magnitude gap also suffers from this statistical fluctuation. Therefore, some researchers have insisted that the observed MFD is consistent with the G-R relation within the limits of statistical fluctuation (e.g., Kagan, 1993, 1996).

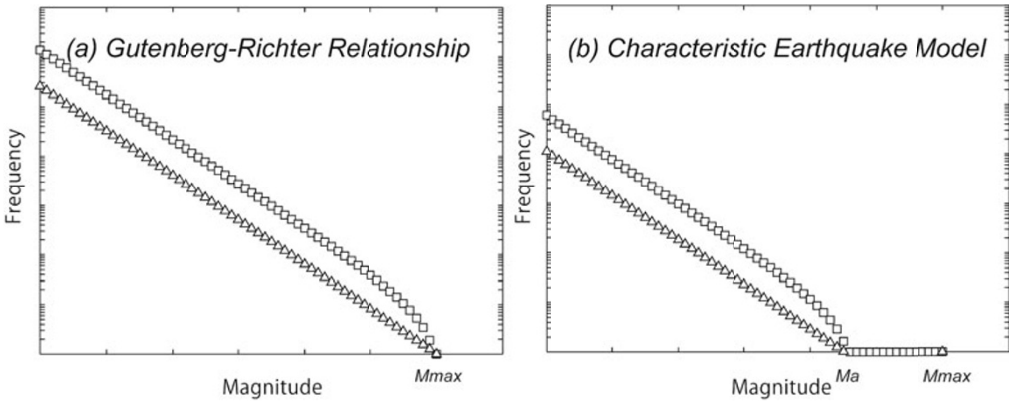


Fig. 1. Schematic illustration of the discrete and cumulative forms for the MFD of earthquakes described by (a) the G-R relation and (b) the CE model during one seismic cycle. For the CE model, a magnitude gap exists between the second-largest earthquake and the CE, while the G-R relation represents continuous distribution up to the ME.

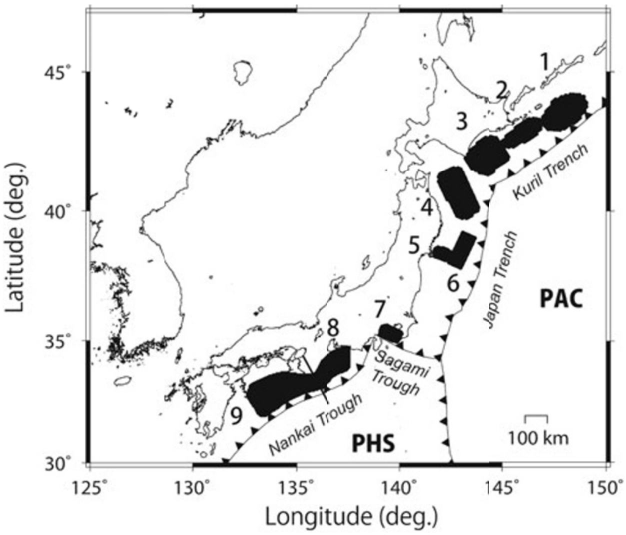


Fig. 2. Source regions of nine large interplate earthquakes from HERP. ID numbers in this figure correspond to those in Table 1. PAC and PHS indicate the Pacific Plate and Philippine Sea Plate, respectively.

We investigated interplate earthquakes around Japan (e.g., the Nankai earthquake) to settle this controversy. Japan is abundant in historical documents, and the records of historical large earthquakes during more than 1000 years have been stored (e.g., Usami, 2003). For example, at least nine Nankai earthquakes are recorded in historical documents; therefore, we can accurately estimate the average recurrence interval. Moreover, the Headquarters for Earthquake Research Promotion (HERP), affiliated with the Ministry of Education, Culture, Sports, Science and Technology, was established after the 1995 Kobe earthquake. It estimates the average recurrence interval for each source region of an interplate earthquake as several tens to several hundreds of years and evaluates long-term seismic hazard based on the renewal process from rich historical documents and geological and/or geomorphological information such as tsunami deposits (Earthquake Research Committee, 2000, 2001, 2004a, b, 2005). Discussion is based on the estimation of HERP for other source regions of large interplate earthquakes.

The Japan Meteorological Agency (JMA) instrumental catalog of earthquakes is available from January 1923, and its duration is more than 80 years, which is comparable with the average recurrence interval of an interplate earthquake in Japan. Fortunately, MEs (the maximum-size earthquakes) occurred in almost all source regions of the interplate earthquake examined in this study. Therefore, the source region of an interplate earthquake in Japan is a good test field to examine whether the G-R relation or the CE model more adequately describes the MFD for one complete seismic cycle in an individual source region.

In this study, the occurrence rate of a ME estimated by HERP was compared with instrumental records in nine source regions of large interplate earthquakes (Fig. 2). Additionally, we found that seismic activity during the interseismic period was unusually quiescent.

## 2. Data Set and Methodology

We used the old JMA catalog from January 1923 to September 1997 and the unified JMA catalog from October 1997 to October 2006. We set the threshold magnitude at 5.0 for the old JMA catalog and 4.0 for the unified JMA catalog from the MFD (Fig. 3). Though earthquake observation data was unified by JMA in October 1997 and the earthquake detection capability has recently improved with the installation of new Hi-net stations (Obara *et al.*, 2005), detection capability was still insufficient in offshore regions. The regional $b$-value of the G-R relation was estimated by the maximum likelihood method described in Eq. (1) (Aki, 1965; Utsu, 1965; Hamilton, 1967; Page, 1968; Bender, 1983; Frohlich and Davis, 1993). The standard error of the estimated $b$-value is described in Eq. (2) (Shi and Bolt, 1982).

$$b = \frac{\log e}{E[M] - M_z} \tag{1}$$

$$\delta b = 2.3b^2 \sqrt{\frac{\sum_{i=1}^{N} (M_i - E[M])^2}{N(N-1)}} \tag{2}$$

where $b$ is the $b$-value estimated by the maximum likelihood method, $E[M]$ is the average magnitude, $N$ is the

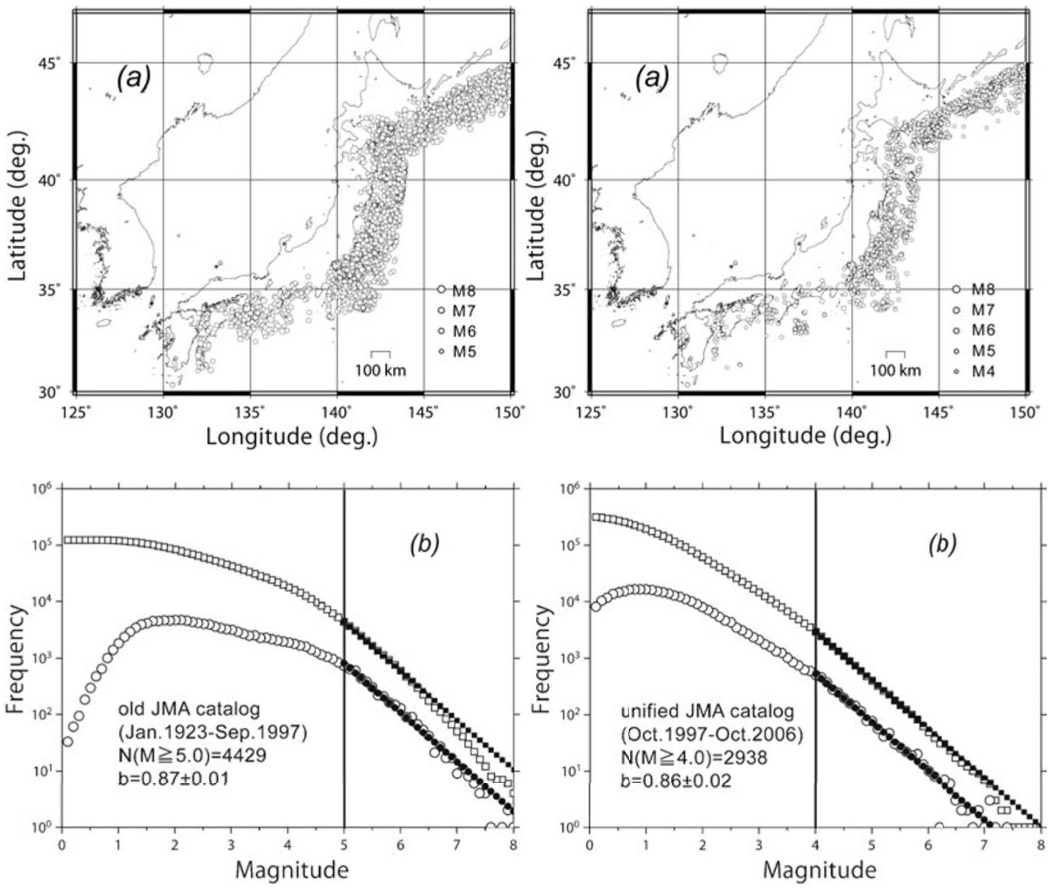


Fig. 3. (a) Epicentral distribution of offshore earthquakes used to estimate the regional *b*-value. The left figure plots the epicentral distribution from the old JMA catalog ($M \geq 5.0$, hypocentral depth $\leq 70$ km). The right figure plots the one from the unified JMA catalog ($M \geq 4.0$, hypocentral depth $\leq 70$ km). (b) MFD. The open circles represent the discrete number of events, and the squares represent the cumulative number of events. The vertical solid line indicates the minimum magnitude of completeness. The closed circles represent the discrete number of synthetic events, and the squares represent the cumulative number of synthetic events. The estimated *b*-values and associated ranges with one standard deviation are 0.87 and 0.86 to 0.89 for the old JMA catalog, and 0.86 and 0.85 to 0.88 for the unified JMA catalog.

Table 1. Nine interplate earthquake source regions and the parameters used in this study.

| ID number | Region | Recurrence interval (years) | Date of the most recent event | Magnitude | Minimum depth (km) | Maximum depth (km) |
|---|---|---|---|---|---|---|
| 1 | Off Shikotan Island | 72.2 | Aug. 1969 | 7.8 | 0 | 70 |
| 2 | Off Nemuro | 72.2 | June 1973 | 7.9 | 0 | 70 |
| 3 | Off Tokachi | 72.2 | Sep. 2003 | 8.1 | 0 | 70 |
| 4 | Off Sanriku North | 97 | May 1968 | 8.0 | 0 | 70 |
| 5 | Off Miyagi | 37.1 | June 1978 | 7.5 | 0 | 75 |
| 6 | Far Off Miyagi | 105 | Aug. 1897 | 7.7 | 0 | 40 |
| 7 | Kanto | 200∼400 | Sep. 1923 | 7.9 | 0 | 40 |
| 8 | Tonankai | 86.4 | Dec. 1944 | 8.1 | 0 | 40 |
| 9 | Nankai | 90.1 | Dec. 1946 | 8.4 | 0 | 40 |

number of events, and $M_z$ is the threshold magnitude.

The magnitude and average recurrence interval of the ME in each interplate earthquake source region were based on the HERP estimate. The recurrence interval, date of the most recent event, magnitude of the ME, and depth range we extracted earthquakes are indicated in Table 1. By combining instrumental observation with the HERP estimate, the occurrence rate of the ME was compared with observed seismicity in nine interplate earthquake source regions (i.e., off-Shikotan island, off-Nemuro, off-Tokachi, off-Sanriku north, off-Miyagi, far off-Miyagi, Tonankai, Nankai, and Kanto). Figure 4 presents a schematic illustration comparing the occurrence rate of the ME with the instrumental observation. If the G-R relation holds, the annual occurrence rates expected from the G-R relation (denoted by dotted lines) and the occurrence rate of the ME (denoted by diamond) should agree well with the observed ones (denoted by open squares). Conversely, the synthetic number of events per year (denoted by open and closed circles) should agree well with the annual occurrence rate of the ME.

Intraplate earthquakes also occurred near interplate earth-

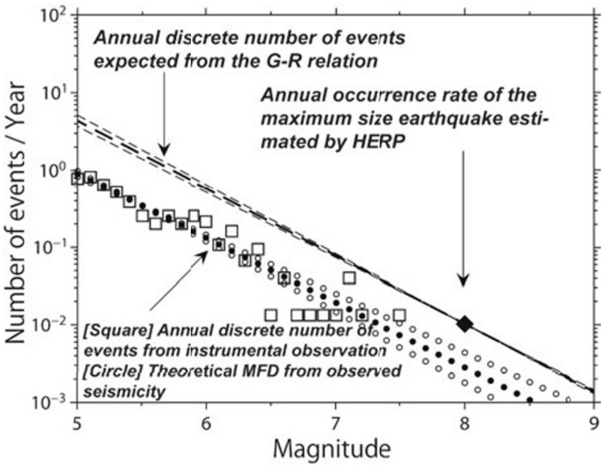


Fig. 4. Schematic illustration comparing the occurrence rate of the ME with observed seismicity. The horizontal axis is the magnitude, and the vertical axis is the annual occurrence rate (i.e., an inverse of the average recurrence interval). The open squares denote the number of observed events per year from instrumental observation. The solid circles denote the average, and the open circles denote its probable range of seismicity estimated from the observation using the maximum likelihood method. The magnitude and annual occurrence rate of the ME listed in Table 1 are represented by the closed diamond. The dotted lines have a slope of the regional $b$-value estimated from instrumental observation and represent the annual number of events expected from the G-R relation. The bold line represents the preferred number of events, and the thin lines represent the minimum and maximum ones.

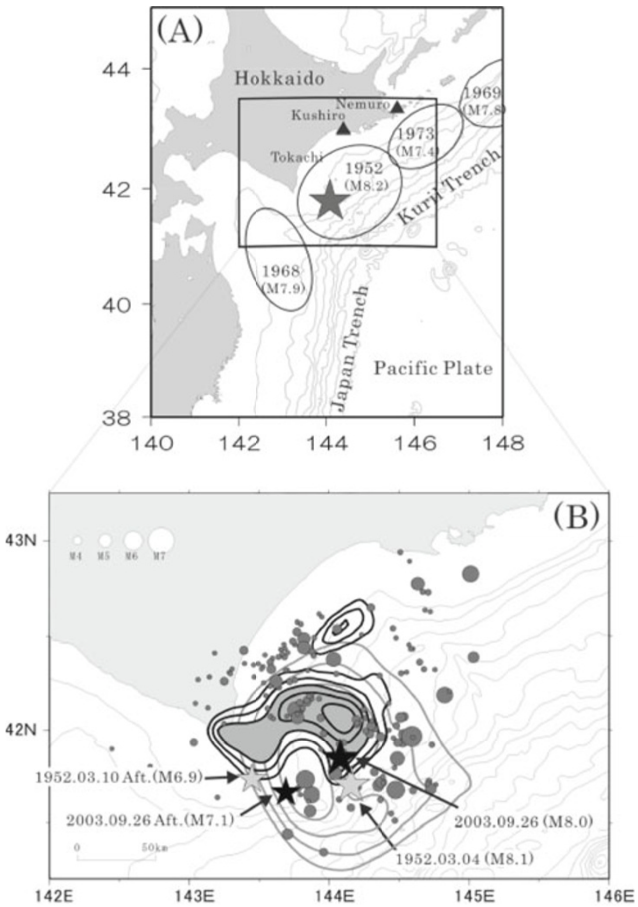


Fig. 5. (a) Location map of the epicenter of the 26 September 2003 Tokachi-Oki earthquake (black star) and source regions of the great interplate earthquake along the northern Japan Trench and the southern Kuril Trench. (b) Distribution of the mainshock (large black star), the largest aftershock (small black star), and aftershocks within 10 hours after the mainshock (gray circles). The black contours (1 m interval) indicate the fault slip distribution of the 2003 Tokachi-Oki earthquake. The area with a slip larger than half of the maximum slip was defined as an asperity and hatched. Gray stars indicate the mainshock and the largest aftershock of the 1952 Tokachi-Oki earthquake. The gray contour (0.3 m interval with the minimum of 1 m) is the slip distribution of the 1952 earthquake (from Yamanaka and Kikuchi, 2003).

quakes, although it was difficult to separate them properly because of the uncertainty in hypocentral location. Therefore, in this study we did not distinguish interplate earthquakes from intraplate ones, and all earthquakes in the source regions were included.

## 3. Result

### 3.1 Seismicity during one complete seismic cycle for the off-Tokachi source region

The 2003 Tokachi-Oki earthquake ($M$ 8.0) occurred close to the epicenter of the 1952 Tokachi-Oki earthquake ($M$ 8.2) on 26 September in the southern Kuril Trench southwest of Hokkaido, Japan, where the Pacific Plate is subducting beneath the North American Plate. From seismic wave and geodetic data, the source rupture process has been estimated for both the 1952 and 2003 Tokachi-Oki earthquakes (e.g., Yamanaka and Kikuchi, 2003). In recent years, it has been widely accepted that the dominant moment release occurs recurrently on the same asperity, and the spatial distribution of asperities within the subduction zone has been estimated (Nagai *et al*., 2001; Yamanaka and Kikuchi, 2004). It has been reported that the asperities of both earthquakes almost overlap (Fig. 5) (Yamanaka and Kikuchi, 2003), though the source rupture process of the 1952 Tokachi-Oki earthquake could not be determined in detail because of the poor quality of the observed waveform data. It has also been reported that aftershock regions were almost the same for both Tokachi-Oki earthquakes, based on the distribution of relocated aftershocks and the fact that the distributions of seismic intensity were similar (Hamada and Suzuki, 2004).

Instrumental observation records by JMA are now available from January 1923; both the 1952 Tokachi-Oki earthquake and the 2003 Tokachi-Oki earthquake occurred during instrumental observation. Therefore, the instrumental records cover one complete seismic cycle for this source region. Figure 6 depicts the MFD and magnitude-time diagram of earthquakes occurred in the source region off Tokachi during one complete seismic cycle (i.e., from the occurrence time of the 1952 Tokachi-Oki earthquake to just before the 2003 Tokachi-Oki earthquake). The magnitude of the second-largest interplate earthquake was 7.1, with a magnitude gap of 1.1 between this event and the mainshock. The MFD during one seismic cycle was remarkably closer to the CE model than to the G-R relation.

### 3.2 Comparison of observed seismicity with predicted seismicity

The results for nine interplate earthquake source regions for the unified JMA catalog are plotted in Fig. 7. The estimated regional $b$-value obtained from 2741 events with magnitudes equal to and above 4.0 was 0.86, and its range

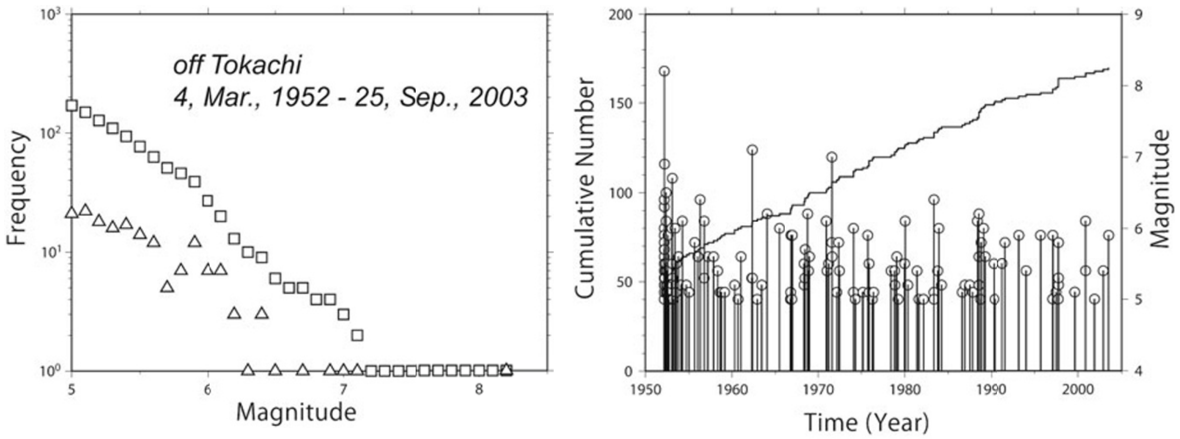


Fig. 6. MFD and magnitude-time diagram for the region off Tokachi from the occurrence of the 1952 Tokachi-Oki earthquake to just before the 2003 Tokachi-Oki earthquake. The squares denote the cumulative number of events, and the triangles represent the discrete number of events.

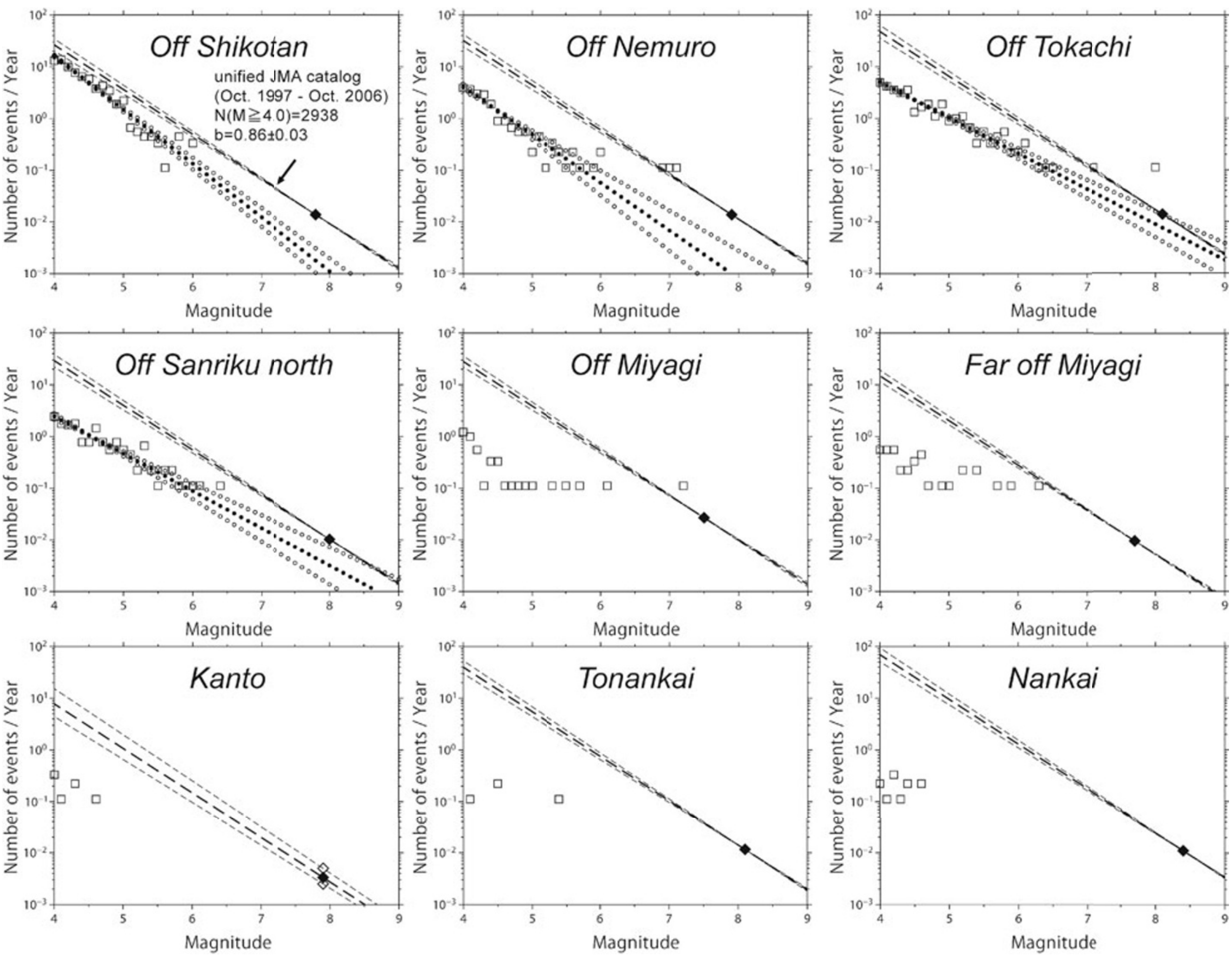


Fig. 7. Discrete number of events per year versus magnitude for the nine interplate earthquake source regions. The square represents the instrumental data of the unified JMA catalog from October 1997 to October 2006. The diamond represents the annual occurrence rate of the ME estimated by HERP. The dotted lines have slopes of the range of estimated *b*-values and denote the number of events predicted by the G-R relation. The circles and dots, indicating the synthetic MFD estimated from the observed seismicity, are also indicated for the source region where the total number of observed events was equal to and more than 50.

with one standard deviation was 0.02. The closed and open circles respectively, indicating the annual number of synthetic events estimated from the observed seismicity and its 95% confidence limit, are also indicated for source regions where the total number of observed events exceeded 50. The results for the old JMA catalog are presented in Fig. 8. The estimated regional *b*-value was 0.87, and its range with one standard deviation was 0.01. If the G-R relation held for each interplate source region, the number of observed events should agree well with the dotted lines indi-

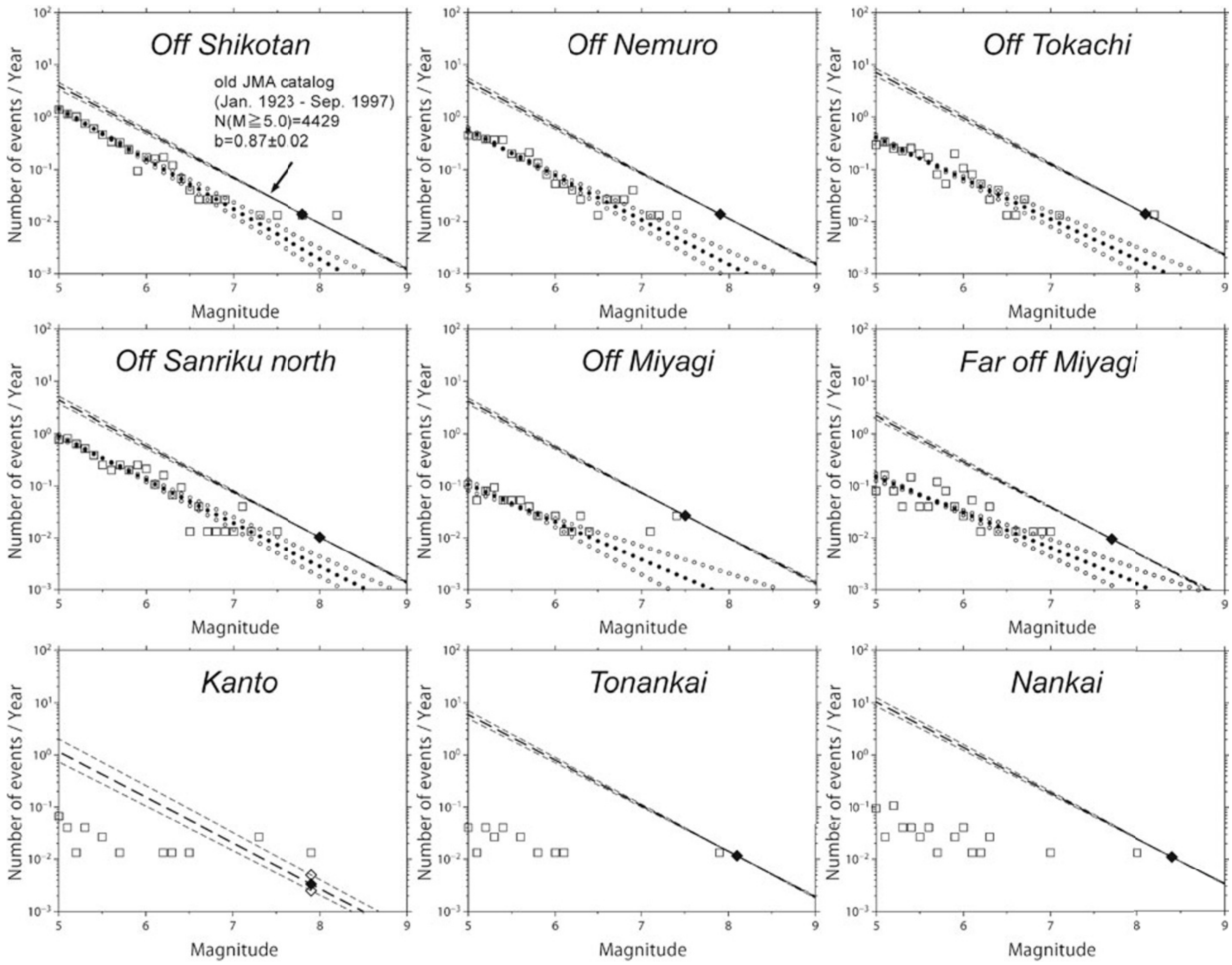


Fig. 8. Discrete number of events per year versus magnitude for the nine interplate earthquake source regions estimated from the old JMA catalog. The symbols are the same as those in Fig. 7.

cating the number of events expected from the G-R relation and the occurrence rate of the ME. However, these figures indicated that the number of observed events was much less than the expected number of events.

In most source regions, the MEs occurred during the instrumental observation period. Moreover, the observed seismic activity was overestimated because of the mixture of intraplate earthquakes. Nonetheless, the number of observed small-to-moderate size events was less than expected from the G-R relation and the observed MEs. These results implied that the G-R relation did not hold for the entire magnitude range and that the small-to-moderate earthquakes were much less frequent than the occurrence rate expected from the ME. Conversely, this finding implied that the MEs occurred more frequently than indicated by the G-R relation and the MFD in the focal region was consistent with the CE model.

Figure 9(a) depicts the frequency ratio of the number of observed events to that of events expected from the G-R relation and the occurrence rate of the ME for each interplate source region. The magnitude range for comparison was above the threshold magnitude for each catalog. As a result, the number of events was less than half of the number of events expected from the G-R relation for all nine interplate earthquake source regions. Figure 9(b) plots the ratio of the observation time length to the average recurrence interval of the MEs estimated by HERP. Except for the Kanto region (ID No. = 7), where the recurrence interval was estimated from 200 to 400 years, more than 80% of one seismic cycle was extracted from the old JMA catalog. With the unified JMA catalog, 10% of one seismic cycle was extracted for almost all source regions.

We compared the occurrence rate of the ME estimated by HERP with the instrumental records by calculating the number of events expected from the G-R relation. Here, we conversely estimated the annual occurrence rate of the MEs from observed seismicity, based on the assumption that the G-R relation held for the entire magnitude range. The magnitude of the ME estimated by HERP was assumed. The $b$-value of the G-R relation and its standard error were estimated by the maximum likelihood method from observed seismicity in each interplate source region. If the threshold magnitude $M_z$ and the cumulative number of earthquakes with magnitude equal to and above the threshold magnitude $s$ were known, the $a$-value of the G-R relation could be calculated by Eq. (3) (Utsu, 1978).

$$a = \log\left(s\beta \exp(\beta M_z)\right) \tag{3}$$

Here, $\beta = b \ln 10$. The annual occurrence rate of the ME, whose inverse represents the average recurrence interval,

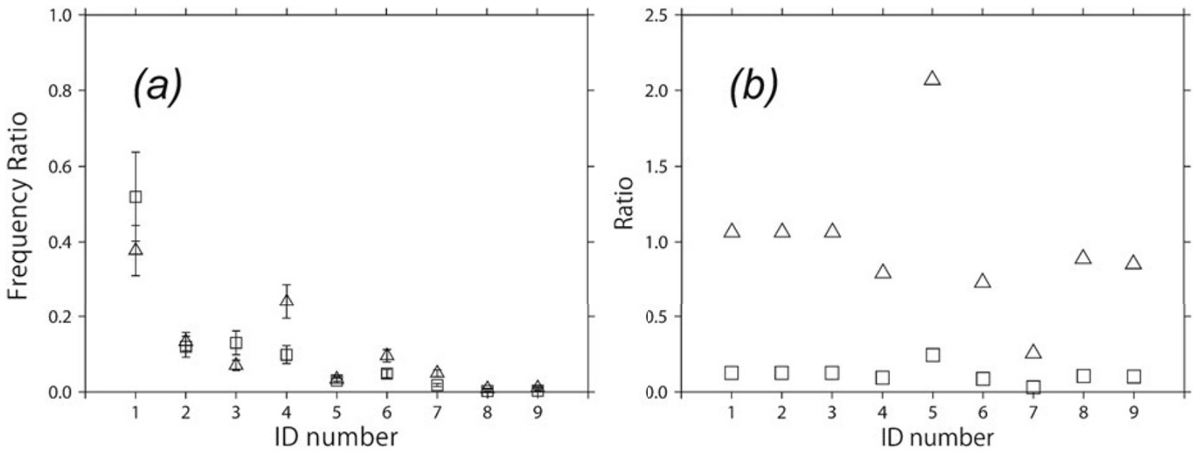


Fig. 9. (a) Ratio of the number of observed events to the number of events predicted by the G-R relation for each interplate source region. The ID numbers correspond to those in Table 1. The triangles denote the results of the old JMA catalog, and the squares denote the results of the unified JMA catalog. The error bar indicates the range of 95% confidence limit. (b) Ratio of the catalog interval to the average recurrence interval estimated by HERP in each interplate earthquake source region. Squares represent the ratio of the unified JMA catalog to the average recurrence interval, and the triangles represent the ratio of the old JMA catalog to the average recurrence interval.

Table 2. Recurrence interval of the ME predicted from observed seismicity during the old JMA catalog interval. $T_{pref}$ indicates preferred average recurrence interval. $T_{min}$ and $T_{max}$ indicate its range with one standard deviation, respectively. STD indicates a standard deviation of the $b$-value estimated from Shi and Bolt (1982). $T_{ref}$ indicates the average recurrence interval estimated by HERP.

| ID number | Region | Num of EQ. | $b$-value | STD | $T_{min}$ (yrs) | $T_{pref}$ (yrs) | $T_{max}$ (yrs) | $T_{ref}$ (yrs) |
|---|---|---|---|---|---|---|---|---|
| 1 | Off Shikotan Island | 538 | 0.958 | 0.041 | 216.6 | 337.7 | 530.3 | 72.2 |
| 2 | Off Nemuro | 233 | 0.858 | 0.051 | 312.7 | 551.4 | 986.2 | 72.2 |
| 3 | Off Tokachi | 184 | 0.780 | 0.048 | 367.9 | 649.3 | 1163.7 | 72.2 |
| 4 | Off Sanriku North | 383 | 0.835 | 0.038 | 229.6 | 357.1 | 560.1 | 97 |
| 5 | Off Miyagi | 52 | 0.724 | 0.096 | 266.0 | 604.7 | 1479.4 | 37.1 |
| 6 | Far Off Miyagi | 77 | 0.685 | 0.059 | 269.9 | 469.9 | 843.1 | 105 |
| 7 | Kanto | 21 | 0.583 | 0.150 | — | — | — | 300 |
| 8 | Tonankai | 18 | 0.752 | 0.207 | — | — | — | 86.4 |
| 9 | Nankai | 40 | 0.721 | 0.116 | — | — | — | 90.1 |

Table 3. Recurrence interval of the ME predicted from observed seismicity during the unified JMA catalog interval.

| ID number | Region | Num of EQ. | $b$-value | STD | $T_{min}$ (yrs) | $T_{pref}$ (yrs) | $T_{max}$ (yrs) | $T_{ref}$ (yrs) |
|---|---|---|---|---|---|---|---|---|
| 1 | Off Shikotan Island | 682 | 1.040 | 0.035 | 323.7 | 557.7 | 965.1 | 72.2 |
| 2 | Off Nemuro | 192 | 0.926 | 0.076 | 302.3 | 1003.5 | 3423.1 | 72.2 |
| 3 | Off Tokachi | 311 | 0.691 | 0.037 | 73.9 | 133.8 | 244.9 | 72.2 |
| 4 | Off Sanriku North | 144 | 0.722 | 0.052 | 139.2 | 316.0 | 732.8 | 97 |
| 5 | Off Miyagi | 42 | 0.877 | 0.181 | — | — | — | 37.1 |
| 6 | Far Off Miyagi | 36 | 0.701 | 0.111 | — | — | — | 105 |
| 7 | Kanto | 7 | 1.842 | 0.669 | — | — | — | 300 |
| 8 | Tonankai | 4 | 0.643 | 0.262 | — | — | — | 86.4 |
| 9 | Nankai | 11 | 1.346 | 0.264 | — | — | — | 90.1 |

could be estimated from the synthetic G-R relation.

The average recurrence interval of the ME for each interplate source region was estimated from the JMA catalogs. Table 2 presents one predicted from the old JMA catalog, and Table 3 presents one from the unified JMA catalog. For reference, these tables also list the average recurrence interval estimated by HERP (referred to as $T_{ref}$). The G-R relation would be helpful if the average recurrence interval estimated from instrumental observation record agrees with the estimates of HERP. However, it is readily evident that the average recurrence intervals predicted from the observed seismicity are much longer than the estimates of HERP, though some estimated average recurrence intervals had large uncertainty due to the small number of events. One possible exception was the estimated average recurrence interval for the region off Tokachi estimated from the unified JMA catalog, which was comparable to the HERP-estimated value, due to the aftershock activity of the 2003 Tokachi-Oki earthquake. However, the number of aftershocks per unit time decays in accordance with the Omori-

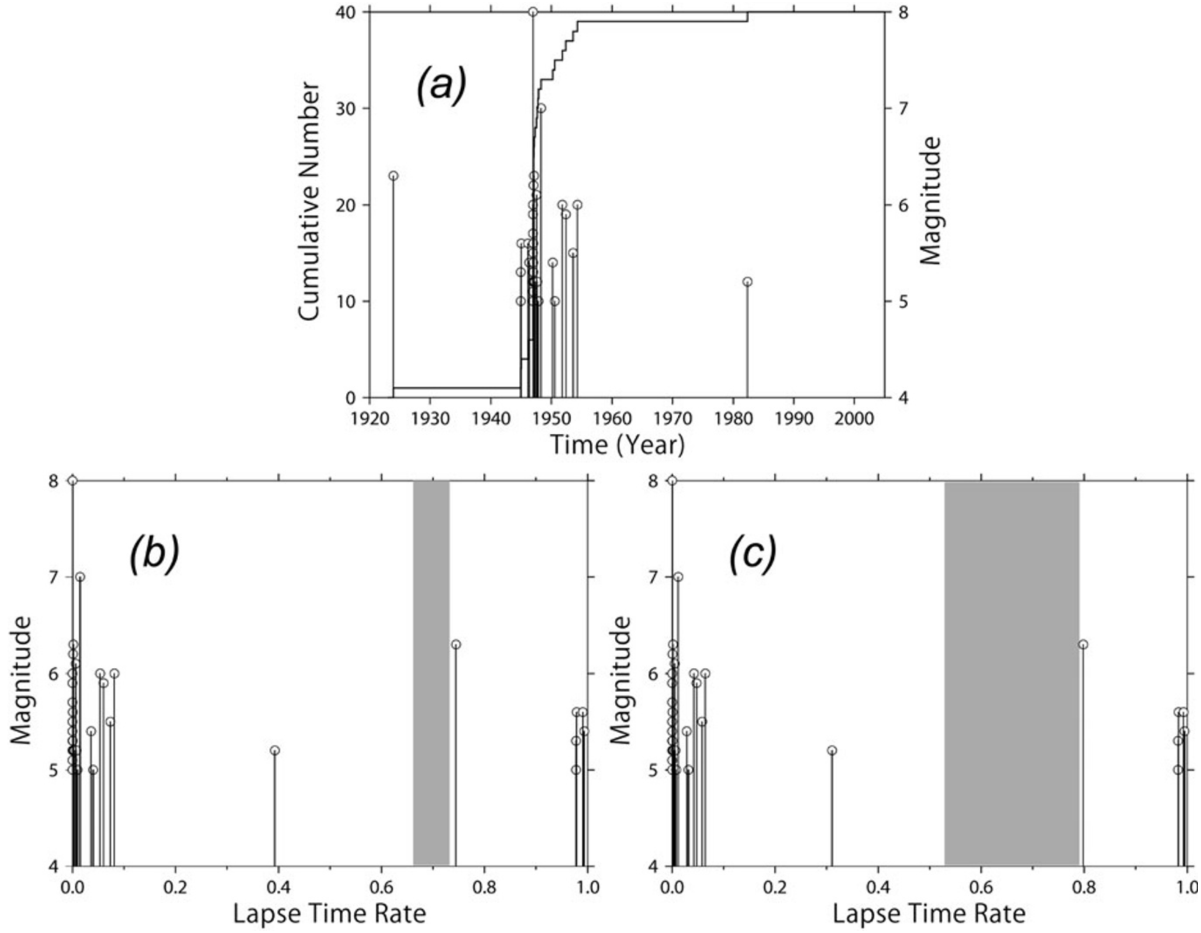


Fig. 10. (a) Magnitude-time diagram and cumulative frequency curve for the Nankai source region. (b) Normalized magnitude-time diagram (average recurrence interval is 90.1 years based on time-predictable model (Shimazaki and Nakata, 1980)) (c). Normalized magnitude-time diagram (average recurrence interval is 114 years from the occurrence histories of the Nankai events since the 1605 earthquake). Horizontal axis shows the time after the maximum-size event normalized by its average time interval. The grey zone corresponds to the interval of the seismic cycle when no instrumental record was available.

Table 4. Historical Nankai earthquakes.

| Year | Date | Name |
|---|---|---|
| 684 | 26, Nov. | Hakuho |
| 887 | 22, Aug. | Ninna |
| 1099 | 16, Feb. | Kowa |
| 1361 | 26, July. | Koan |
| 1498 | unknown | Meio |
| 1605 | 3, Feb. | Keicho |
| 1707 | 28, Oct. | Hoei |
| 1854 | 24, Dec. | Ansei |
| 1946 | 21, Dec. | Showa |

Utsu formula (Utsu, 1961, 1969), or its summation (e.g., Ogata and Shimazaki, 1984). Aftershock seismicity decays with increasing lapse of time, since the mainshock and the high seismicity during the mainshock–aftershock interval cannot be maintained for the entire seismic cycle. Comparison between the occurrence frequency of the ME and the number of observed events revealed that seismic activity of small-to-moderate earthquakes was much lower than the number of events expected from the G-R relation for most of the stages during one seismic cycle. Therefore, if the G-R relation held during one seismic cycle, much higher seismic activity compared to the one expected from the G-R relation would be necessary to fill the observed gap. However, analysis of the unified JMA catalog for the region off Tokachi indicated that seismic activity was at most equal to that expected from the G-R relationship even if the ME and its aftershock sequence are all included. The high seismic activity indicated by the unified JMA catalog should continue throughout the complete one seismic cycle in order to verify the G-R relation.

### 3.3 Seismicity in the Nankai source region

The Nankai source region provided one of the best-known recurrence sequences of great earthquakes in the world. Historical records indicate at least nine Nankai earthquakes (Table 4). Recurrence intervals of successive Nankai earthquakes ranged from 92 to 262 years and the average interval was estimated as 158 years. However, archaeological studies of liquefaction suggest two more Nankai earthquakes occurred during the historical period, one in the second half of the 10th century and another in the first half of the 13th century (Sangawa, 1997); therefore, the average interval would be 126 years. HERP adopted 114 years from the occurrence dates of the Nankai events since the 1605 earthquake. The average recurrence interval varied

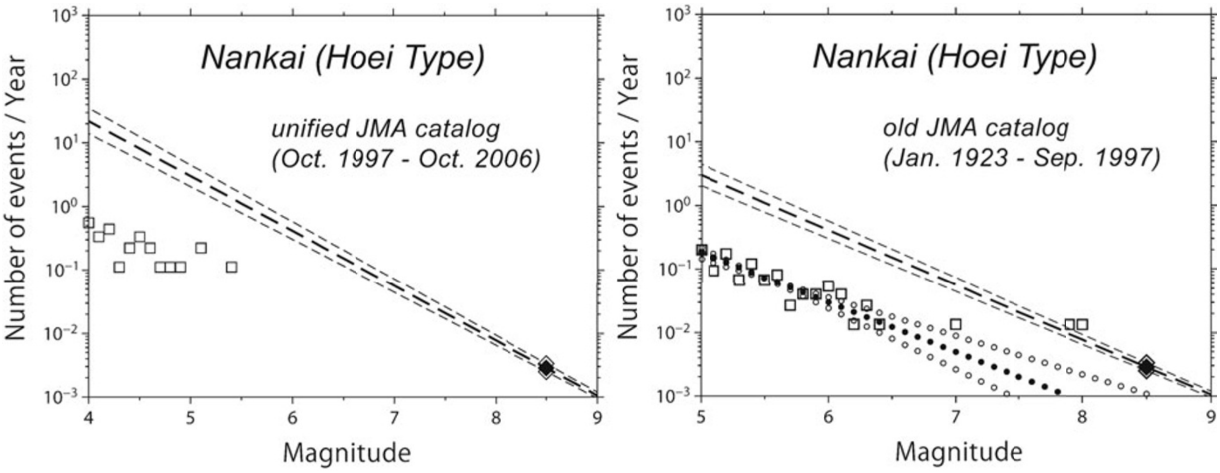


Fig. 11. Discrete number of events per year versus magnitude for the Hoei-type Nankai earthquake source region. The left figure is the result from the unified JMA catalog, and the right figure is that from the old JMA catalog. The symbols are the same as in Fig. 7.

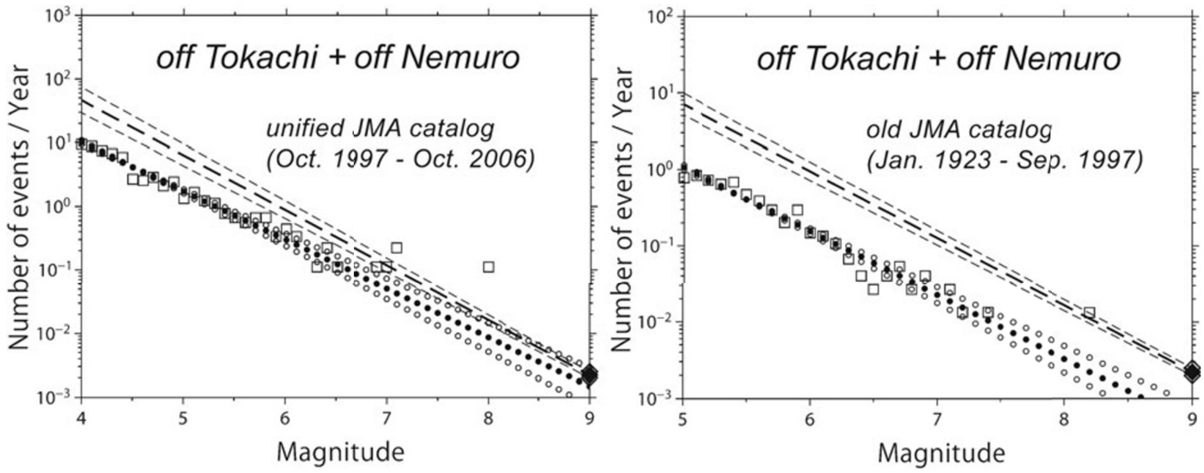


Fig. 12. Discrete number of events per year versus magnitude for the region off Tokachi–Nemuro. The left frame depicts the result from the unified JMA catalog, and the right frame depicts that from the old JMA catalog. The symbols are the same as in Fig. 7.

from 114 to 158 years, depending on the choice of data set. However, the conclusion did not depend on range of the estimated repeat time at all: the observed seismic activity was significantly lower than that expected from the occurrence rate of the ME and the G-R relation.

Some studies insist that evidence of the CE hypothesis could be explained by either statistical bias or statistical artifact (e.g., Kagan, 1993, 1996). However, rich historical documents clearly constrain the average recurrence interval of the Nankai earthquake as 114 to 158 years. The frequency of smaller earthquakes in the instrumental observation period was significantly lower than the value expected from the average interval of the MEs and the $b$-value; this result could be explained by neither statistical bias nor statistical artifact. Figure 10(a) represents the magnitude-time diagram for the Nankai source regions on an ordinary time scale. Figure 10(b) and (c), respectively, represent the magnitude-time diagrams normalized by the present recurrence interval of 90.1 years estimated by HERP (Table 1) and by the average recurrence interval of 114 years adopted by HERP. The grey zone corresponds to the interval of the seismic cycle when no instrumental record was available. An alternative average recurrence interval would change only the width of the grey zone. These figures indicate that few moderate-to-large earthquakes occurred except for foreshocks and aftershocks, and that the source region was significantly quiescent.

### 3.4 Simultaneous rupturing of neighboring source regions

Simultaneous rupturing of neighboring source regions has been reported along the Nankai Trough (e.g., Ando, 1975). Therefore, the previous analysis of seismicity in each source region may not be appropriate. For example, the 1707 Hoei earthquake simultaneously ruptured all the segments along the Nankai Trough; however, the 1944 Tonankai earthquake and the 1946 Nankai earthquake ruptured only a few segments. Therefore, we analyzed a combined source region.

The average recurrence interval of the 1707 Hoei-type event was estimated to be 300 to 400 years, assuming the huge Nankai earthquake tsunamis identified by Matsuoka *et al.* (2006) were associated with simultaneous rupturing of all the source regions along the Nankai Trough. The magnitude of the 1707 Hoei-type earthquake was estimated to

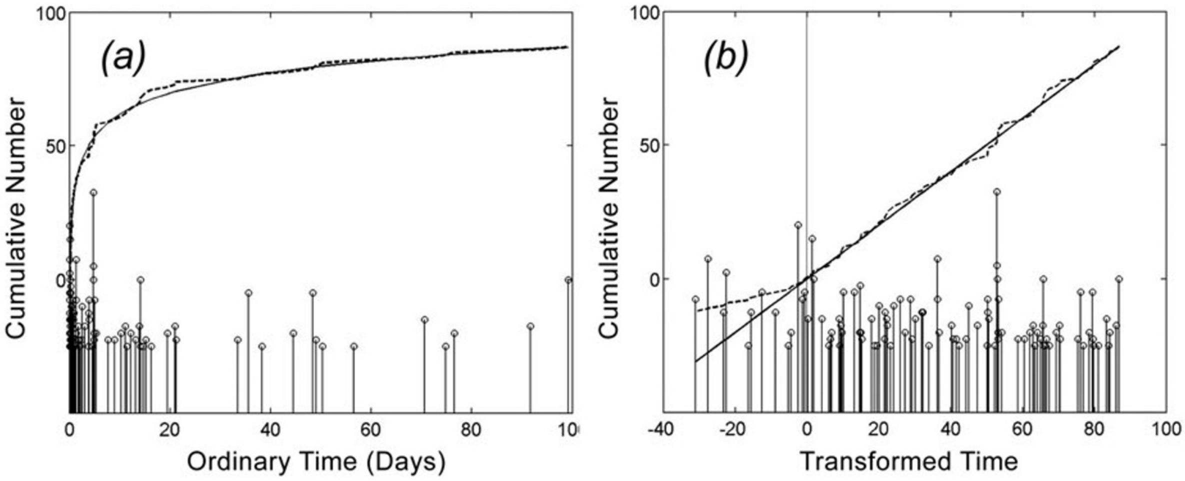


Fig. 13. (a) Cumulative number of aftershocks of the Hokkaido-Toho-Oki earthquake ($M$ 8.2), indicated by dotted lines; theoretical cumulative number following the Omori-Utsu formula, indicated by solid line and magnitude-time diagrams. Horizontal axis denotes the time after the occurrence of mainshock (days). (b) The cumulative number of observed (dotted line) and synthetic (solid line) events on a transformed time scale. The time started 0.1 days after the mainshock.

be 8.5 (Earthquake Research Committee, 2001). The magnitude and the occurrence rate of the 1707-type earthquake were compared with the observed seismicity (Fig. 11). The observed seismicity was remarkably quiescent compared to the one expected from the G-R relation, and the conclusion was not affected by any uncertainty in the spatial extent of the source region. One might argue that the CE model did not hold because the magnitude of the ME varied along the Nankai Trough (i.e., no characteristic size existed). However, the actual MFD is closer to the CE model than to the G-R relation. The observed data indicated that small-to-moderate-magnitude earthquakes were extremely infrequent in the Nankai source regions.

Simultaneous rupturing of regions off Tokachi and off Nemuro was also inferred (e.g., Hirakawa, 2000a, b; Nanayama *et al.*, 2003; Satake *et al.*, 2008). The recurrence period of the Tokachi-Nemuro earthquake was estimated as 400 to 500 years, and it is inferred that the most recent one occurred during the 17th century from the tsunami deposits along the eastern coastal line of Hokkaido. The tsunami magnitude of the Tokachi-Nemuro earthquake was estimated as 9.0 (Abe, personal communication, 2002) based on estimated tsunami inundation heights of 10–15 m, although Satake *et al.* (2008)'s estimate of $M_w$ was 8.5. The result (Fig. 12) led us to the same conclusion for each source region though the result was obviously contaminated by numerous intraplate earthquakes because the depth ranges of the all source regions are set to be significantly larger than source region estimated from HERP to take uncertainty of hypocentral location into consideration.

## 4. Discussion

### 4.1 Aftershock activity accompanying the 1994 Hokkaido-Toho-Oki earthquake

In the region off Shikotan Island, the number of observed events was slightly lower than the number of events calculated from the G-R relation for the unified JMA catalog as shown in Fig. 7. However, the Hokkaido-Toho-Oki earthquake ($M$ 8.2) occurred in this source region on 4 October 1994. Waveform inversion indicated that this earthquake was an intraplate earthquake (e.g., Kanamori and Kikuchi, 1995). The aftershock region dominantly overlapped the source region off Shikotan Island (e.g., Katsumata *et al.*, 1995); therefore, the seismic activity in this source region was thought to be significantly overestimated. Consequently, in this study we tried to remove this aftershock sequence, assuming that the temporal aftershock decay obeyed the Omori-Utsu formula. We estimated the parameter of the Omori-Utsu formula by the maximum likelihood method proposed by Ogata (1983) and obtained $K = 13.56$, $c = 0.059$ (day), $p = 1.06$, from 0.1 day to 100 days, with the threshold magnitude of 5.0. The cumulative number of observed and synthetic events estimated from the Omori-Utsu formula in the source region off Shikotan Island is plotted in Fig. 13(a). Figure 13(b) represents the same data as Fig. 13(a) on a transformed time scale, where the expected frequency of aftershocks became constant if the parameters were appropriately estimated (Ogata and Shimazaki, 1984). We first assumed two models; one model which includes the background seismicity term, and the other without it, and tested the two models against the observed catalogue data by using the Akaike Information Criterion value (AIC; Akaike, 1974). A comparison of these two models indicated that the one with no background seismicity was superior; and therefore, we neglected the background seismicity.

The cumulative number of aftershocks with magnitude 5.0 and above during the old JMA catalog interval predicted from the Omori-Utsu formula was 120, corresponding to 22% of the total number of observed events within the source region off Shikotan Island. The frequency ratio of the number of observed events to that of expected from the G-R relation became 0.26 when we subtracted the estimated number of aftershocks from the total number of observed events. Similarly the ratio of the observed number of events to the expected one from the G-R relation became

0.42 for the case of the unified JMA catalog, when the estimated number of aftershocks was subtracted. The cumulative number of aftershocks with magnitude 5.0 and above during the unified JMA catalog interval was estimated to be 14. The $b$-value of the source region off Shikotan Island was 0.96; accordingly, the cumulative number of aftershocks with magnitude 4.0 and above was estimated to be 130, corresponding to 19% of the observed events.

### 4.2 Relationship between the G-R relation and the CE model

What does it mean when the MFD in a source region obeys the CE model while the G-R relation effectively describes the MFD for regional seismicity? A possible answer to this question is tectonic development or maturity produced by repeating activities in a source region (Wesnousky, 1988, 1990; Sornette and Davy, 1991; Lockner, 1993; Cowie *et al.*, 1995; Stirling *et al.*, 1996). At the first stage, source areas with various scale lengths occupy a certain region of interest. Suppose the CE model holds for an individual source area, though the magnitude of the largest event in each area is small. If the size of the source area follows a power law, the MFD in this region follows an exponential relation such as the G-R relation. The entire tectonic region matures: the largest source area grows at the expense of surrounding smaller source areas, and finally becomes comparable to the size of the whole region. Its scale length then becomes dominant, and an earthquake with magnitude corresponding to this scale length becomes frequent. The inhomogeneity in such a mature or developed fault zone is low, and the fault plane becomes smooth. Additionally, seismic activity in such a source region usually becomes low, and accumulated strain tends to be released by a ME that decreases stored energy in virtually all parts of the source region. As a result, small-to-moderate magnitude earthquakes become relatively infrequent under the stable strain accumulation, and the MFD becomes close to the CE model. Shimazaki (1999) developed this idea and proposed the "Almighty Earthquake" concept that only one earthquake occurs on the earth. He regarded the G-R relation as a law at an original stage and the CE Model as a model at a stage halfway to the final stage of the Almighty Earthquake.

Yoshioka (2003) experimented with sand pile collapses on various sizes of disc and analyzed the shape of MFD of sand pile slides. He found a drastic change from the simple power law distribution to the distribution close to the CE model, depending on disc size and sand pile radius. This result implied the possibility that the MFD may obey a simple power law or the CE model, depending on the characteristic size (e.g., fault length or width of the largest event) and the extent of the region considered.

Seismic hazard estimates based on the CE model have been limited to large earthquakes in Japan. However, MEs repeating every five years off Kamaishi, Iwate Prefecture (e.g., Matsuzawa *et al.*, 2002) suggest that the CE model also holds for the relatively small magnitude range around $M$ 5.0, if a small source area exists without interference from the surrounding region. At least part of the G-R relation may be regarded as representing statistical populations of various sizes of MEs.

## 5. Conclusion

Seismicity of all the nine interplate source regions (i.e., off Shikotan Island, off Nemuro, off Tokachi, off Northern Sanriku, off Miyagi, far off Miyagi, and the Tonankai, Nankai and Kanto regions) indicated that the number of observed events was much less than the number of expected events estimated from the Gutenberg and Richter (G-R) relation and the occurrence rate of the maximum-size earthquake (ME). Our datasets included the highest seismicity period during an earthquake cycle because MEs occurred during the interval of the earthquake catalog in all regions except far off Miyagi. Nonetheless, the number of observed events was much less than the number of events expected from the G-R relation. Moreover, in the region off Tokachi where the 1952 and 2003 Tokachi-Oki earthquakes occurred, the MFD during one complete seismic cycle exhibited a magnitude gap of 1.1 between the ME and other events. The average recurrence interval of the ME was estimated by both rich historical documents and geological and/or geomorphological observations especially for the Nankai earthquake source region; therefore, this conclusion could not be explained by statistical fluctuation.

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