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Statistical Forecast of the Next Miyagi-Oki, Northeast Honshu Earthquake

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Abstract: We found that large earthquakes of magnitude 7.4-7.5 have repeatedly took place at an interval of 26 to 42 years in the Miyagi-Oki region, northeast Japan, where the Pacific plate subducts beneath the Honshu Island. Based on the recurrence intervals of past earthquakes, conditional probability of the occurrence of next earthquake is calculated. By fitting a lognormal distribution to the intervals of five large earthquakes of the past two hundred years, we obtain very high values of the probability ; 35%, 82% and 97% for the next 10, 20 and 30 years. The quasi-periodic occurrence of large earthquakes with similar magnitude indicates that the Miyagi-Oki region behaves as an asperity on the plate interface, where characteristic earthquakes of magnitude 7.4-7.5 are repeatedly released. If the large earthquakes ruptured the same fault plane on the plate interface, the seismic coupling at the Miyagi-Oki region is estimated at about 60%. We presume that the remaining part of relative plate motion may be accommodated by afterslips following coseismic slips for the most part.

1. Introduction

Patterns of earthquake occurrence at a plate boundary are not simple but much complicated both in space and time. In favorable cases, however, we recognize some regular patterns of seismicity including seismic gap of large earthquakes, precursory seismic quiescence and change in b-value. Among such regularities, quasi-periodic recurrence of large earthquakes is of particular importance for the long-term forecast of earthquake occurrence. In fact, statistical forecasts based on the recurrence interval have been attempted by many authors for various regions of different tectonic environments (*e.g.*, Bakun and McEvilly, 1984 ; Bakun and Lindh, 1985 ; Wyss, 1986 ; Nishenko and Buland, 1987 ; Working Group on California Earthquake Probabilities, 1988, 1990, 1995 ; Ohtake, 1993 ; Clague, 1997).

For the statistical forecast, probability of earthquake occurrence is calculated by fitting a statistical model to observed recurrence intervals. Nishenko and Buland (1987), by testing several models, concluded that the lognormal distribution surpasses normal and Weibull distributions in expressing observed earthquake intervals. This conclusion was followed by Working Group on California Earthquake Probabilities (1988, 1990, 1995). On the other hand, Utsu (1984) showed that significant difference is not seen in the adaptability among the lognormal, gamma, Weibull, and double-exponential distributions, which was later confirmed by Subcommittee for Long-Term Evaluations (SLE) (1998). It was also shown that the exponential distribution (Poisson's process) is inappropriate for a sequence of large earthquakes. Accumulation of observation data is needed to finally conclude which model is the best, but the SLE report recommended to use the lognormal model for the simplicity of probability density function.

Schwartz and Coppersmith (1984, 1986) proposed a hypothesis that a fault and fault segment generate *characteristic earthquakes* having a relatively narrow range of magnitudes near the maximum size inherent to the fault or fault segment. By assuming constant rate of tectonic loading and constant rupture strength of fault plane, periodic recurrence is expected for those earthquakes so that quasi-periodic occurrence of similar-sized earthquakes is a basic nature of characteristic earthquakes. Wesnousky (1994), Stirling *et al.* (1996) and others pointed out that the moment release by characteristic earthquakes is much larger than that expected from the Gutenberg-Richter relation for smaller earthquakes of the same fault segment. The characteristic earthquake model apparently oversimplifies complicated patterns of actual earthquake occurrence (see *e.g.*, Wallace, 1987 ; Kagan, 1993, 1996). Nevertheless, the recognition of characteristic earthquakes may provide a first-order information for evaluating the risk of future large earthquakes. In fact, the model has been used as a basic component for long-term evaluation of seismic hazard in California (Working Group on California Earthquake Probabilities, 1988, 1990, 1995), and in Japan (Subcommittee for Long-Term Evaluations, 1998 ; Earthquake Research Committee, 2000).

In the present paper, we will show that the Miyagi-Oki region in the northeast part of Honshu has been repeatedly ruptured by large interplate earthquakes that indicate the nature of characteristic earthquakes. Based on the observed recurrence intervals, time-dependent probability of the next large event is estimated.

2. Regional Seismicity and Miyagi-Oki Earthquake of 1978

Figure 1 shows the epicenter distribution in and around the northeast part of Honshu, Japan. In the figure, shallow earthquakes ($H \leq 70$ km) with magnitude 4.0 or larger are plotted for the past 74 years based on the earthquake catalog of Japan Meteorological Agency (JMA). The high seismicity between the Honshu Island and the Japan Trench reflects the westward subduction of the Pacific plate beneath the Okhotsk plate, which involves northeast Honshu and Hokkaido (Seno *et al.*, 1996). According to the latest plate model (Wei and Seno, 1998), the plate convergence rate in this region is estimated at 7.8 cm/year.

The rectangle area in Figure 1 is enlarged in Figure 2, where only large earthquakes of $M \geq 7$ are plotted together with historical large events. For the earthquakes prior to 1926, epicenter coordinates and magnitude are taken from the earthquake catalogs of Utsu (1982), Usami (1996) and Watanabe (1998). In Figure 2, we recognize a small region where large earthquakes cluster including the Miyagi-Oki earthquake of June 12, 1978 (solid circle). The fault plane of this earthquake is shown by a shaded rectangle after Aida (1978). The earthquake cluster is enclosed by a $1^{\circ} \times 1^{\circ}$ rectangle area covering 37.8°-38.8°N and 141.6°-142.6°E, which we refer to as the "Miyagi-Oki region" hereafter.

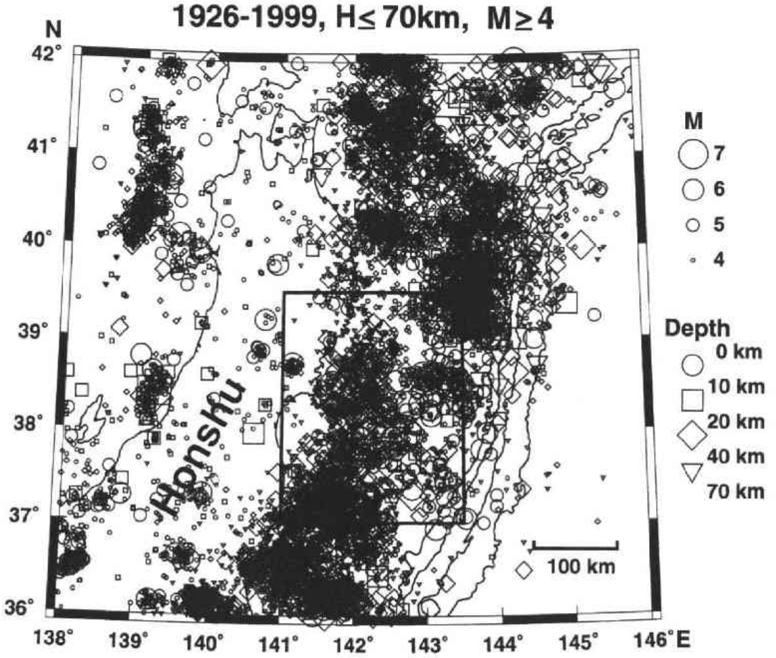

Figure 1 Epicenter distribution of shallow earthquakes in and around the northeast part of Honshu for 1926-1999 after JMA ($H \leq 70$ km, $M \geq 4.0$). A rectangle shows the map area of Figure 2.

The hypocenter of the 1978 Miyagi-Oki earthquake was 38.15°N, 142.17°E, $H=40$ km, and magnitude was 7.4 after JMA. The earthquake brought about a severe damage with 28 deaths to Sendai City, the capital of Miyagi Prefecture, and surrounding areas. The focal mechanism was typical reverse-fault type with a fault plane dipping to the west at a low angle of 20°, indicating a rupture of the interface of the subducting Pacific plate. By using teleseismic waveforms, Seno *et al.* (1980) obtained a fault model that is composed of two sub-faults ; 37 km × 34 km, and 24 km × 34 km. Fault slip is 1.9 m and 2.4 m, respectively. This fault model is consistent with the model derived from tsunami data ; 2.0 m slip of a 26 km × 65 km fault plane (Aida, 1978). Total moment release is estimated as $3.1 \times 10^{\circ}$ Nm, corresponding to $M_W=7.6$. Source region of the 1978 Miyagi-Oki earthquake was located about 200 km to the west of the trench axis, and only deeper portion of the plate interface, roughly 25-50 km in the depth, was ruptured. This fault geometry is also confirmed by aftershock distribution (Takagi, 1980).

3. Past Seismicity of the Miyagi-Oki Region

Figure 3 shows the magnitude-time plot of the earthquakes that took place in the Miyagi-Oki region for the past 200 years, of which large earthquakes with $M \geq 7.4$ are listed in Table 1. The frequency of small-sized earthquakes reflects the change in detection capability ; in particular, earthquake smaller than M 6.0 are not reported from

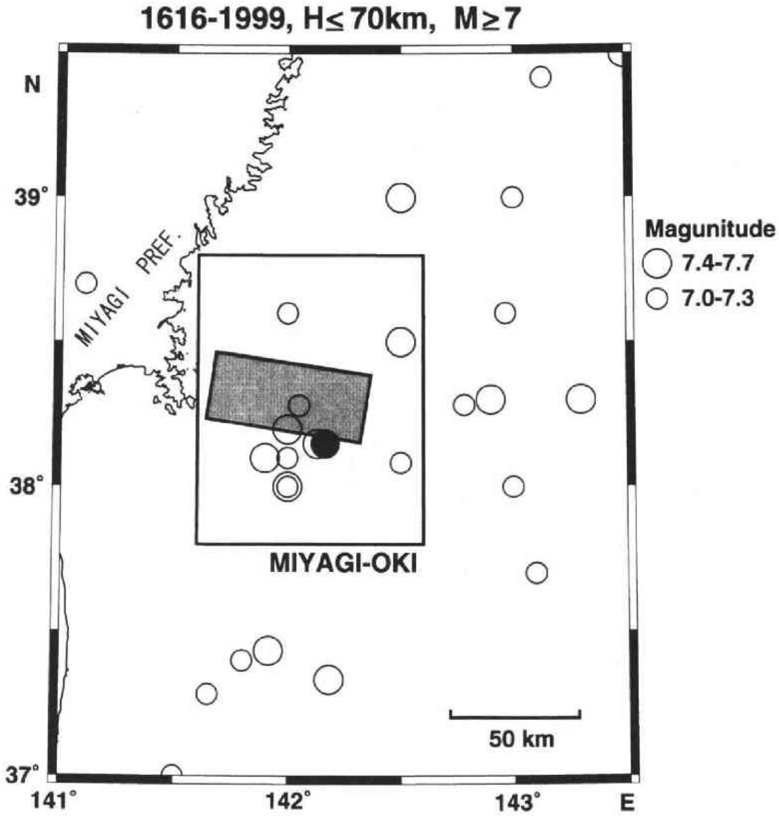

Figure 2 Epicenter distribution of $M \geq 7$ earthquakes in the rectangle of Figure 1. Historical earthquakes before instrumental observation are also included (see text for detail). Large rectangle indicates the Miyagi-Oki region (37.8°-38.8°N, 141.6°-142.6°E). The epicenter and fault plane of the 1978 Miyagi-Oki earthquake are shown by a solid circle and a shaded rectangle, respectively.

the Miyagi-Oki region before 1926, when nationwide observation of JMA (then Central Meteorological Observatory) started.

In Figure 3, the data for 1926-1999 are taken from the JMA earthquake catalog. For the period from 1885 to 1925, focal parameters are instrumentally determined by Utsu (1982), but the detection capability is much lower than the following period. For the early period before 1885, the earthquake data are collected from earthquake catalogs of Usami (1996) and Watanabe (1998), both of which were edited based on historical documents. Although the catalogs are far from completeness for small-sized earthquakes, it is unlikely that a large earthquake of magnitude 7 or larger might have escaped documentation so far as recent 200 years are concerned. For some historical earthquakes, however, we find discrepancies between the earthquake catalogs, and a careful examination is needed. In Table 1, the focal parameters (location and magnitude) of Nos. 1 and 2 are taken from Watanabe (1998) judging from tsunami data. For

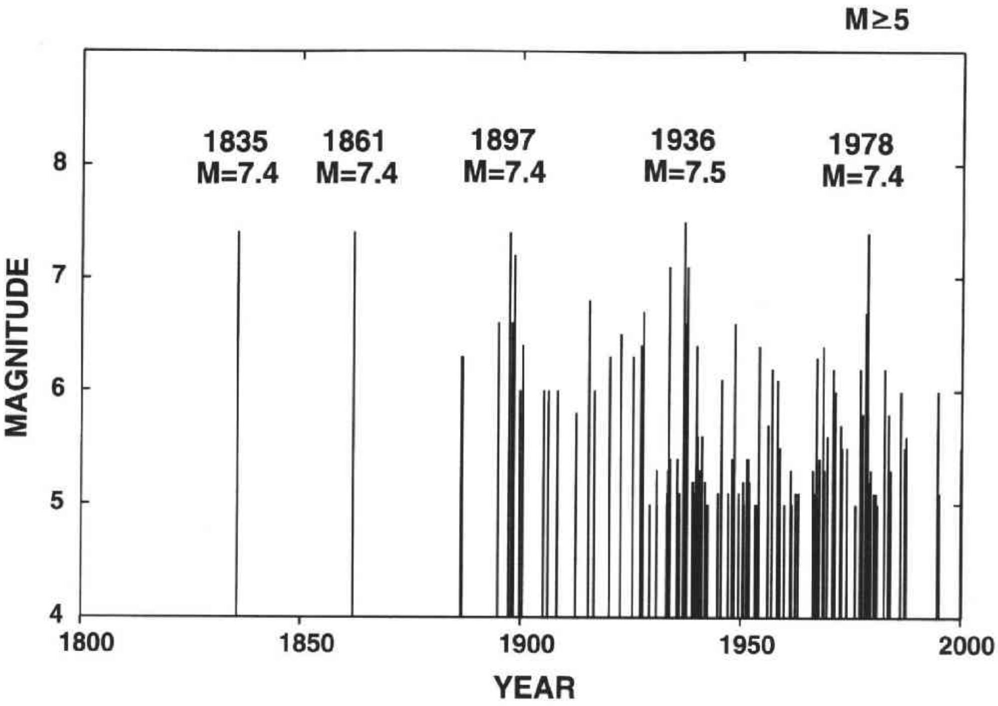

Figure 3 Magnitude-time plot of $M \geq 5$ earthquakes in the Miyagi-Oki region showing quasi-regular occurrence of large earthquakes of M 7.4-7.5.

Table 1. Large Miyagi-Oki earthquakes in the past 200 years ($M \geq 7.4$).

No.	Year	Date	Epicenter		M
			Latitude	Longitude	
1	1835	Jul. 20	38.0°N	142.0°E	7.4
2	1861	Oct. 21	38.2	142.0	7.4
3	1897	Feb. 20	38.1	141.9	7.4
4	1936	Nov. 03	38.15	142.13	7.5
5	1978	Jun. 12	38.15	142.17	7.4

the case of event No. 2, Usami's (1996) inland epicenter is not acceptable since large tsunamis are reported in historical documents. Other three events are instrumentally located by Utsu (1982) (No. 3), and JMA (Nos. 4 and 5). The 1855 earthquake listed in Usami (1996) is not included in Table 1, since it should have been an inland earthquake judging from no tsunami report. All the earthquakes listed in Table 1 were associated with tsunamis higher than 1 m.

Figure 3 clearly indicates that magnitude 7.4-7.5 earthquakes have repeated at a nearly constant interval of several decades. Those large earthquakes took place five times in the past two hundred years, and the recurrence interval is 26.3–41.6 years (see Table 1). It is of particular interest that magnitude of the largest earthquakes is limited to a very narrow range, and earthquakes with $M \geq 7.6$ are not reported in the Miyagi-Oki region even in earlier historical time (see Usami, 1996 ; Watanabe, 1998). The east off Honshu segment of the Pacific-Okhotsk plate boundary is known by great earthquakes of magnitude 8 class such as the 1896 and 1933 Sanriku-Oki earthquakes ($M_W = 8.0$, 8.4, respectively) and the 1968 Tokachi-Oki earthquake ($M_W = 8.2$). However, the focal areas of those great earthquakes were adjacent to the trench, and the hypocenters were separated by 200–300 km from the Miyagi-Oki region.

4. Statistical Forecast

Figure 3 suggests that next large earthquake is approaching in the Miyagi-Oki region within a few decades. Based on the recurrence intervals of past large earthquakes, we estimate the conditional probability for the occurrence of the next Miyagi-Oki earthquake following the 1978 event. For the statistical model, we use a lognormal distribution of recurrence intervals as was adopted by Working Group on California Earthquake Probabilities (1988, 1990, 1995) and Subcommitte for Long-Term Evaluations (1998).

From Table 1, the interval of successive large earthquakes τ is obtained as 26.3, 35.3, 39.7 and 41.6 years, respectively. The mean and standard deviation of $\ln \tau$ are $\mu = 3.5606$ and $\sigma = 0.2069$, respectively (geometrical mean of τ is 35.2 years). When $\log \tau$ obeys a normal distribution (lognormal distribution), the probability density function of τ is

$$f(\tau) = \frac{1}{\sqrt{2\pi}\,\sigma\tau} \exp[-(\ln \tau - \mu)^2 / 2\sigma^2]. \tag{1}$$

The probability that the recurrence interval is shorter than τ is

$$F(\tau) = \int_0^{\tau} f(\tau')\,d\tau'. \tag{2}$$

Figure 4 plots $f(\tau)$ and $F(\tau)$ as a function of recurrence interval for the Miyagi-Oki earthquakes. By using $F(\tau)$ in Eq.(2), the conditional probability that the next earthquake will occur within the period from T_0 to $T_0 + T$ is calculated by

$$P(T, T_0) = \frac{F(T_0 + T) - F(T_0)}{1 - F(T_0)} \tag{3}$$

where T_0 is the time that already elapsed without occurrence of the target earthquake.

At the beginning of 2001 year, 22.6 years have passed since the last Miyagi-Oki earthquake of 1978. By inserting $T_0 = 22.6$ years into Eq.(3), the conditional probability of the occurrence of next large earthquake, $P(T, T_0)$, is calculated as is shown in Figure 5. Table 2 lists the probability for some typical time intervals, $T = 10$ to 50 years. As is seen from Figure 5 and Table 2, the conditional probability is as high as 35% even for

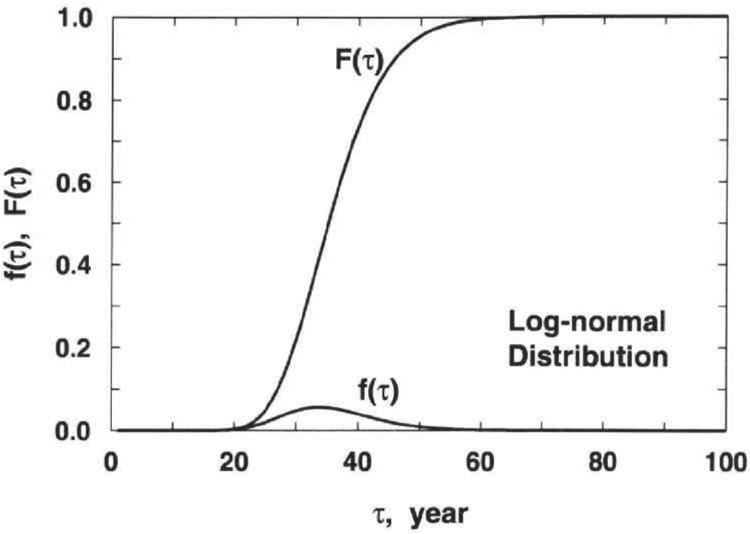

Figure 4 Probability density function $f(\tau)$, and cumulative probability $F(\tau)$ as a function of recurrence time τ for the Miyagi-Oki earthquakes.

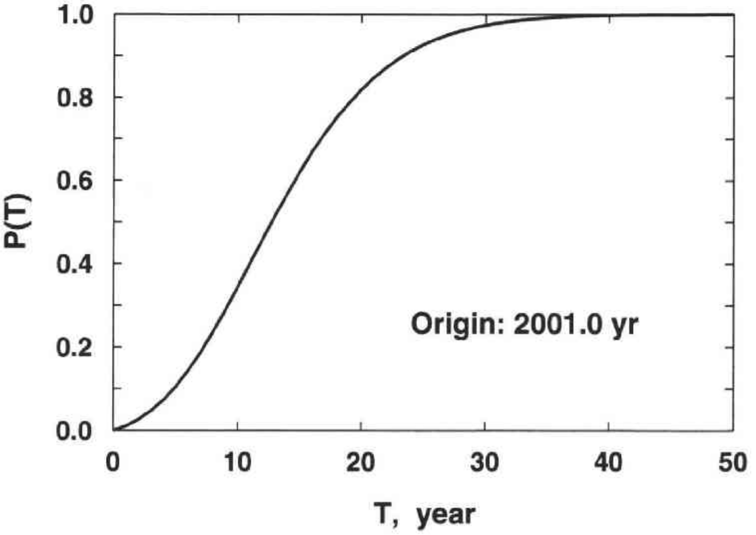

Figure 5 Conditional probability of the occurrence of next Miyagi-Oki earthquake $P(T)$ as a function of lapse time since 2001.0 year, T. The probability is calculated under the condition that the target earthquake has not occurred until 2001.0 year.

the next ten years, and it rapidly increases to 82% and 97% for coming twenty and thirty years, respectively. The result shows that the occurrence of next Miyagi-Oki earthquake is almost inevitable in the early 21st century.

Table 2. Conditional probability of the occurrence of next Miyagi-Oki large earthquake.

Period*	Probability
within 10 years till 2011.0	34.6%
within 20 years till 2021.0	81.9
within 30 years till 2031.0	97.4
within 40 years till 2041.0	99.7
within 50 years till 2051.0	100.0

*Origin time is 2001.0 year.

5. Discussion

The quasi-periodic occurrence and very similar magnitude of past Miyagi-Oki earthquakes may indicate that those earthquakes are characteristic earthquakes generated by repeated rupture of a strongly coupled asperity on the plate interface. In Figure 6, we show magnitude-frequency plot of shallow earthquakes ($H \leq 70$ km) that occurred in the Miyagi-Oki region for the recent 74 years from 1926 to 1999 (closed circles). The number of $M \geq 5$ earthquakes totals 107, and Gutenberg-Richter's b-value is 0.72. By extrapolating the relation to larger earthquakes, we obtain 0.01/year (once in a hundred years) for the occurrence rate of great earthquake of $M \geq 8.0$. However, such a great earthquake is not known in the Miyagi-Oki region in the past two hundred years we examined. It is most probable that the observed magnitude of M7.4-7.5 may represent the size of inferred Miyagi-Oki asperity.

In Figure 6, open circles show the earthquake frequency excluding the largest events of 1936 and 1978, and earthquakes within one year following these events. This plot represents the magnitude-frequency relation for background seismicity, which does not include mainshock-aftershock sequences of characteristic earthquakes. The total number of $M \geq 5$ earthquakes is 91 for the 72 years, and b-value is 0.79. The largest earthquake is M7.1. From this statistical result, occurrence rate of $M \geq 7.4$ earthquakes is predicted as 0.016/year. This value is nearly one-half of the observed rate, 0.028/year, which is calculated from the mean recurrence interval of 35.2 years in the past two hundred years. The difference between the observed and estimated rates may indicate the *magnitude gap* that characteristic earthquakes occur more frequently than expected from smaller earthquakes (*e.g.*, Singh *et al.*, 1983; Schwartz and Coppersmith, 1984; Papadopoulos *et al.*, 1993; Wesnousky, 1994; Stirling *et al.*, 1996).

Far east off the coast of Miyagi Prefecture, a great earthquake associated with large tsunami took place in 1793. Based on historical documents, the hypocenter is located near the trench axis; 38.3°N, 144.0°N (Utsu, 1999). The magnitude is estimated as 7.8 by Hatori (1987), 8.0-8.4 by Usami (1996), and 8.2 by Utsu (1999). Judging from the similarity of isoseismal pattern with the 1978 Miyagi-Oki earthquake, Earthquake Research Committee (2000) inferred that the rupture of 1793 earthquake involved the Miyagi-Oki region. For the future Miyagi-Oki earthquakes, it may be necessary to take account of

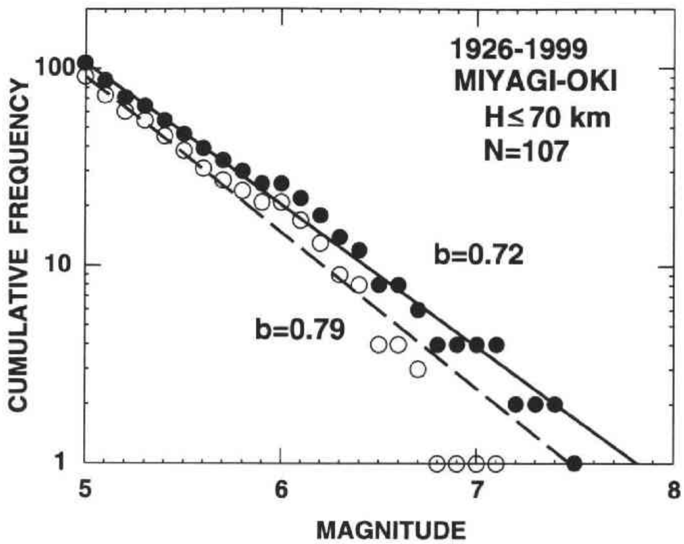

Figure 6 Magnitude-frequency plot of shallow earthquakes ($H \leq 70$ km) in the Miyagi-Oki region for 1926-1999 (solid circles). Large earthquakes of 1936 and 1978, and aftershocks within one year are excluded from the statistics for open circles. The b-value is 0.72 and 0.79 for closed and open circle, respectively.

the possibility that a rupture of the Miyagi-Oki asperity may trigger a rupture of surrounding larger area, and vice versa. However, the recurrence history of 1793-type earthquakes is not well known, and further discussion is difficult so far.

As was discussed above, it is most probable that the Miyagi-Oki earthquakes represent repeated rupture of a fixed asperity on the plate interface. If it is the case, the long-term rate of seismic fault slip is calculated as 4.8 cm/year from the slip of the 1978 Miyagi-Oki earthquake, 2 m (Aida, 1978; Seno *et al.*, 1980), and lapse time from the previous earthquake, 42 years. This slip rate implies seismic coupling of 62% by using the plate convergence rate of 7.8 cm/year that is predicted from the plate model of Wei and Seno (1998). The inferred seismic coupling is larger than the average seismic coupling in the northeast Honshu, 35-60% (Shen-Tu and Holt, 1996).

The 1978 Miyagi-Oki earthquake was followed by a significant afterslip on the plate boundary. According to Ueda *et al.* (2001), the afterslip, having lasted for several years, propagated from the coseismic slip region to deeper portion of the plate interface with time. Moment release by the afterslip amounted to 80-140% of coseismic slip in total. If such a large afterslip is common to all the Miyagi-Oki earthquakes, the relative plate motion may be almost completely accommodated by coseismic slips and following afterslips. Thus, aseismic slip in the interseismic period is expected to be negligibly small for the Miyagi-Oki region.

Prior to the occurrence of next large earthquake, temporal changes of seismicity may alarm the final stage of earthquake preparation. Before the occurrence of last

Miyagi-Oki earthquake of 1978, Takagi (1980) observed a remarkable concentration of seismicity along the fault plane of pending mainshock, which started with a magnitude 5.8 preshock of June 8, 1977. In contrast, shallow seismic activity in the continental plate just above the future rupture zone was significantly lowered for one year preceding the mainshock. For the case of the 1989 off-Sanriku earthquake ($M=7.1$), which took place roughly 250 km to the north of the Miyagi-Oki region, Wyss *et al.* (1999) showed that the large event was preceded by a precursory seismic quiescence lasting about 2.5 years. They also reported that extensive quiescence of high significance was not seen off the coast of Honshu between 36.5°N-42.0°N, involving the Miyagi-Oki region, as of 1997. These observations indicate the importance of continuous monitoring of micro-seismicity for predicting the pending Miyagi-Oki earthquake. Detailed analysis of observation data will provide important information on the time-space characteristics of precursory seismicity changes.

6. Conclusion

Carefully examining earthquake catalogs, we found that large earthquakes repeatedly took place in the Miyagi-Oki region (37.8°-38.8°N, 141.6°-142.6°E), off the east coast of Honshu, where the Pacific plate subducts from the Japan Trench. Five large events registered for the past two hundred years, including the 1978 Miyagi-Oki earthquake, are very similar in maginitude and recurrence interval; magnitude is $M=7.4$-7.5 by JMA scale, and interval is 26.3-41.6 years (geometrical mean is 35.2 years). This peculiar feature indicates that the large Miyagi-Oki events have a nature of characteristic earthquakes that are distinguished from smaller earthquakes occurring in this region.

Based on the above observation, we estimated the conditional probability for the occurrence of next Miyagi-Oki earthquake by assuming lognormal distribution of recurrence intervals. The calculated probability is 35%, 82% and 97% for coming 10, 20 and 30 years, respectively, under the condition that the next one has not occurred until 2000.1 year. Judging from those high probabilities, the occurrence of next Miyagi-Oki earthquake seems to be almost inevitable in the early 21st century.

The characteristic earthquake property of Miyagi-Oki earthquakes strongly suggests that those large earthquakes may have repeatedly ruptured the same asperity on the plate interface. If it is the case, seismic coupling of the Miyagi-Oki region is estimated at about 60%, which is higher than the average for the east-off Honshu segment of the plate boundary. The remaining 40% may be accommodated by an afterslip following the coseismic slip for the most part. This predicts nearly complete coupling of the Miyagi-Oki asperity during the interseismic period.

The result of present study, having been presented at the 1999 fall meeting of Seismological Society of Japan, partly contributed to revise the long-term evaluation of the Miyagi-Oki earthquake in Subcommittee for Long-Term Evaluations (1998). The revised version (Earthquake Research Committee, 2000) adopted the same earthquake list as Table 1 with one additional earthquake of 1793.

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