A Characteristic Change in Fractal Dimension Prior to the 2003 Tokachi-oki Earthquake ($M_J = 8.0$), Hokkaido, Northern Japan

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Changes in form of hypocenter distribution preceding the 2003 Tokachi-oki Earthquake ($M_J = 8.0$) were investigated by using the analysis of temporal variation in spatial fractal dimension D. In this study, it was found that the D value began to decrease in 1998, and had been very small for about one year before the main shock occurrence. Such a D decrease before the main shock occurrence is a characteristic of some recent large earthquakes. Therefore, the D decrease may be an earthquake precursor. The D value decrease is yielded by both of seismic activation and quiescence which have often been reported as an earthquake precursor, due to a property of the calculation method. Therefore, the D change can be detected, even if the seismic activation and quiescence occur simultaneously in which case the number of earthquakes does not change significantly. On account of this property, using the D value is advantageous to detect the precursory change of seismic activity before a large earthquake.

Key words: The 2003 Tokachi-oki Earthquake, hypocenter distribution, fractal dimension, precursory change.

1. Introduction

Generally, the form of hypocenter distribution has a fractal structure. Therefore, hypocenters are distributed heterogeneously. That is, in hypocenter density, dense portions and sparse portions are intermixed. The degree of heterogeneity of fractal hypocenter distribution can be expressed in a fractal dimension D. When seismic activity in part of an analysis area becomes active or quiescent, the degree of this heterogeneity will change. Therefore, it is expected that the D of hypocenter spatial distribution is an indicator of the seismic activation or quiescence.

Currently, it is often reported that unusual variation of hypocenter distribution, such as the seismic activation or quiescence, appears before a large earthquake occurrence. Then, D may change prior to a large earthquake occurrence. Actually, it was reported that the phenomena which resembled such D changes had appeared before some other large earthquakes, for example the 1995 Hyogoken-Nanbu Earthquake and the 2000 Tottoriken-Seibu Earthquake, etc (e.g. Enescu and Ito, 2001; Murase, 2002).

On September 26, 2003, "the 2003 Tokachi-oki Earthquake ($M_J = 8.0$)" occurred in Hokkaido region, Northern Japan. It is expected that this earthquake had the same D variation as the preseismic changes of the 1995 Hyogoken-Nanbu Earthquake and the 2000 Tottoriken-Seibu Earthquake, because this was one of the largest earthquakes in recent Japan. Therefore, in this study, the author investigated whether there was a D change prior to this earthquake occurrence.

2. Data and Method

In this study data of the Japan Meteorological Agency Earthquake Catalog was used. Figure 1 shows the map of the study area and the hypocenter distribution. In order to obtain a homogeneous data set, the lower limit of magnitude of earthquakes was determined by applying the Gutenberg-Richter relation. It is expected that the frequency of detected earthquakes does not change temporally when the data set is homogeneous. In Fig. 2, magnitude-frequency plot and temporal changes in monthly frequency of earthquakes are shown. It seems that $M_J \geq 3.4$ earthquakes satisfied the Gutenberg-Richter relation (Fig. 2(a)). And, as illustrated in Fig. 2(c), the frequency of $M_J \geq 3.4$ earthquakes seems to be stable through the whole period. Therefore, $M_J \geq 3.4$ earthquakes are used as a homogeneous data set in this analysis. The number of picked earthquakes was 1427, and 1111 earthquakes among them occurred before the main shock occurrence.

The fractal dimension D of hypocenter distribution was calculated by the correlation integral method (Kagan and Knopoff, 1980; Grassberger and Procaccia, 1983). The correlation integral $C(r)$ is defined as follows;

$$C(r) = 2N(R < r)/N(N-1) \tag{1}$$

where N is the total number of points analyzed and $N(R < r)$ is the number of points separated by a distance R less than r (the distance between two events). If the hypocenter distribution has a fractal structure, the following relation will be obtained.

$$C(r) \sim r^D \tag{2}$$

The fractal dimension is defined as D (Grassberger, 1983). In Eq. (2), the upper limit of r is limited by the size of the study area. Usually, the upper limit of r is 1/3∼1/2 of length

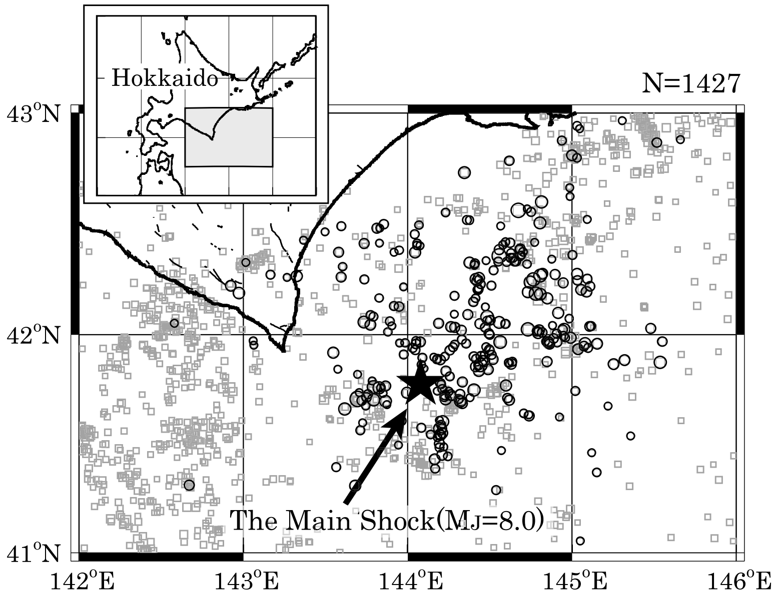

Fig. 1. Epicenter distribution map of study area. $M_J \geq 3.4$ earthquakes were plotted. Star and circle symbols show the main shock and aftershocks, respectively. Squares show the earthquakes which occurred before the main shock.

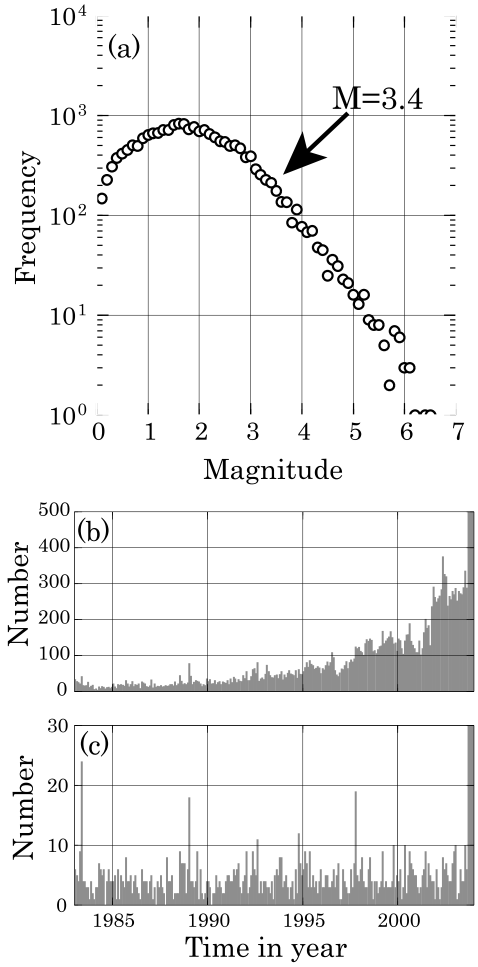

Fig. 2. (a) Magnitude-frequency relation. $M_J \geq 3.4$ earthquakes satisfied the Gutenberg-Richter relation. (b) Monthly frequency of $M_J \geq 0.0$ earthquakes. (c) Monthly frequency of $M_J \geq 3.4$ earthquakes. It is considered that the data set of $M_J \geq 3.4$ earthquakes is homogeneous, because the monthly number of them did not increase with time systematically.

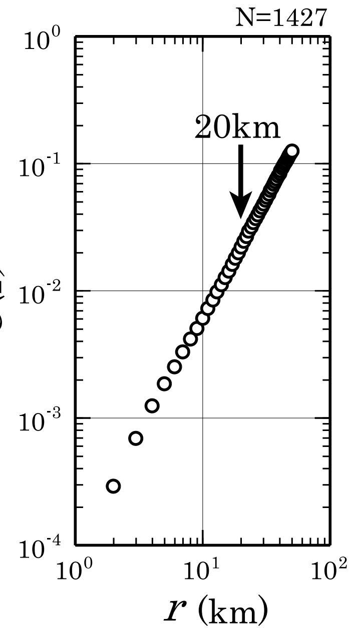

Fig. 3. $r - C(r)$ relation. It seems that equation (2) is satisfied even if the upper limit of r is 20 km which is 1/3 of length of the shortest side of study area.

of the shortest side of a study area. In this study, the range of r which satisfied Eq. (2) was examined by using the $r - C(r)$ log-log plot. Figure 3 shows the $r - C(r)$ log-log plot. For this examination, all of the picked 1427 earthquakes were used. In Fig. 3, though the upper limit of r is hard to find, it seems that the linear relation is satisfied in the range of $r \leq 20$ km which is 1/3 of length of the shortest side of the study area. Therefore, it was decided that the upper limit of r was 20 km. The lower limit of r essentially depends on the accuracy of a location in an earthquake catalog. In Fig. 3, however, it seems that the linear relation is not satisfied in the range of $r \leq 3$ km. Because most of the hypocenters were in

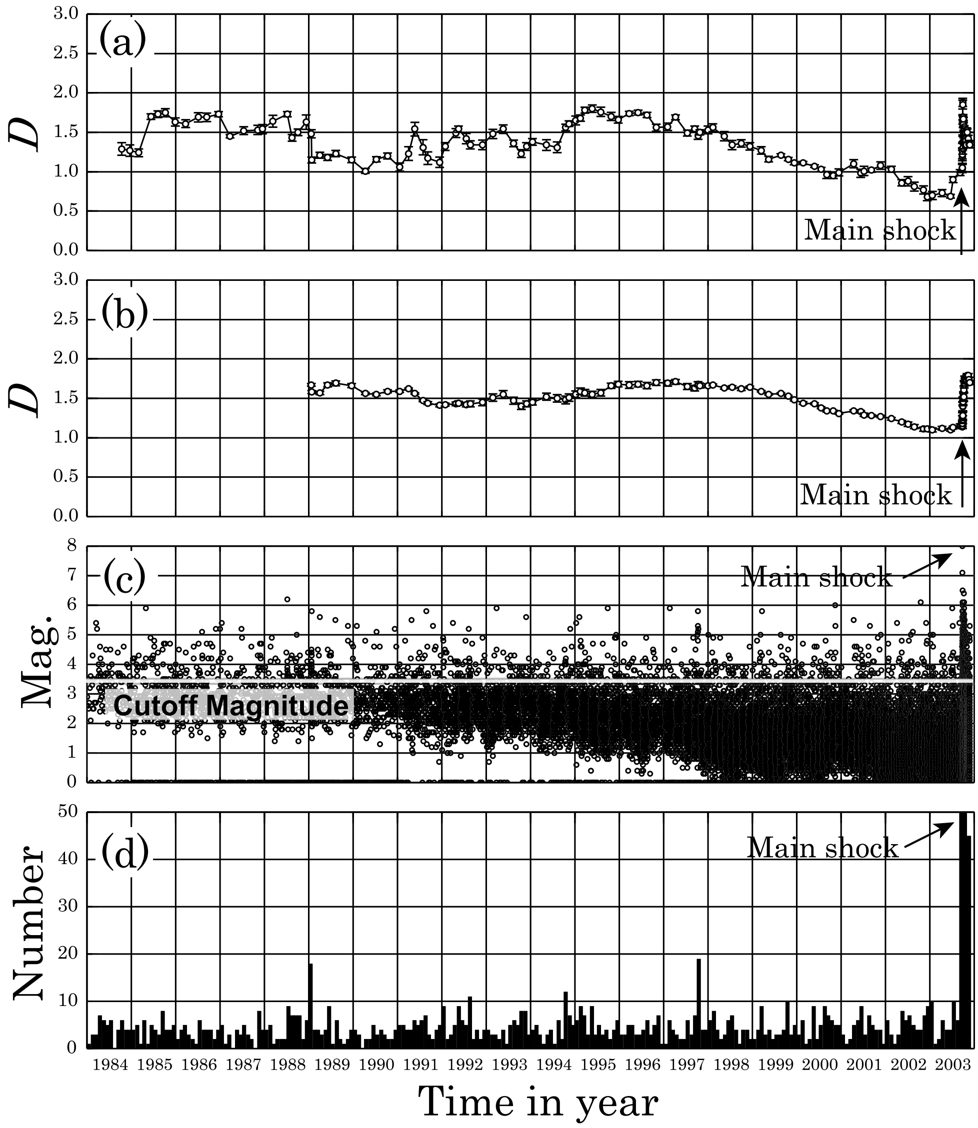

Fig. 4. Temporal changes in the D value, M-T diagram and monthly frequency. (a) D changes with 100 events time-windows. (b) D changes with 300 events time-windows. In comparison with (a), the D values are stable. (c) M-T diagram. The white line indicates the cutoff magnitude. (d) Monthly frequency of $M_J \geq 3.4$ earthquakes. In (a) and (b), error bars indicate the range of the standard deviation.

the sea area, those locations may not be very accurate. As a result, it was decided that the lower limit of r is 5 km.

In order to examine the temporal variations in D, the running time-window method was used. Each time-window is composed of 100 or 300 consecutive earthquakes. The windows are advanced by 10 events between each calculation. These D values are plotted in the end time of each time-window. That is, each data point for D is obtained from 100 or 300 events which occurred before that moment, so that 10 events are included within the time length between two points. The accuracy of D is expressed with the ranges using the standard deviation of the residuals of each data point in the least squares method.

3. Temporal Changes in Spatial Fractal Dimension D

In Fig. 4, the temporal changes in fractal dimension D, time-magnitude diagram, and monthly frequency plots are shown. Figures 4(a) and (b) show temporal changes in D estimated by the time-window with 100 and 300 earthquakes, respectively. The occurrence time of the 2003 Tokachi-oki Earthquake is indicated by the arrow, in each plot. In Fig. 4(a), (b), D values were nearly 1.5, and did not have a systematic change before 1998. D began to decrease systematically in 1998, and reached a minimum in the middle of 2002. The value of D had been very small, for about one year before the main shock occurrence. In M-T diagrams and monthly frequency plots , unusual variation in seismicity was not detected. The progress of D after the main shock occurrence is unidentified, because this period is very short.

4. Discussion

Prior to the 2003 Tokachi-oki Earthquake, unusual D decrease appeared. This change style resembled the cases of other large earthquakes. Therefore, these D changes may be precursors of these large earthquakes.

Now, the D estimated by the correlation integral method is sensitive to the concentration of hypocenters. If most of

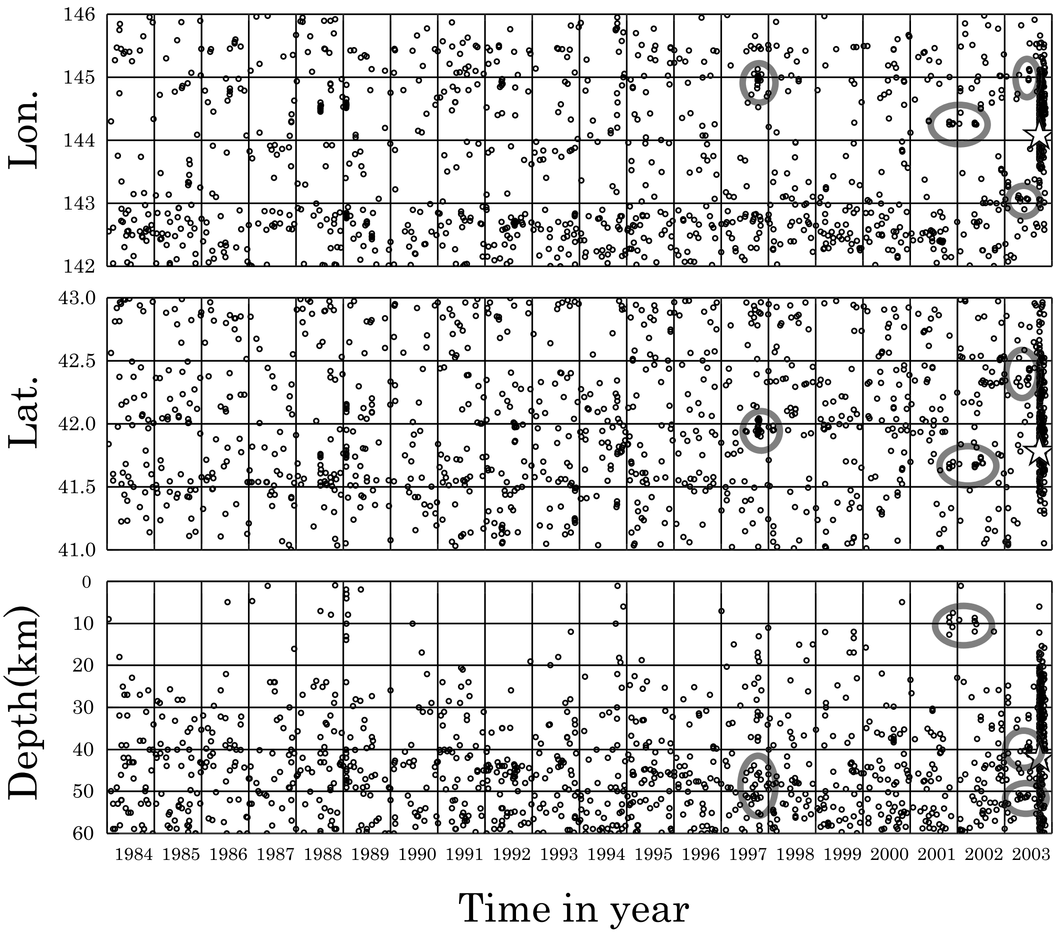

Fig. 5. Time-space diagrams of earthquakes which occurred in study area. The star symbols show the main shock. The encircled earthquakes show the hypocenter clusters which were formed just before the main shock occurrence. In this figure, earthquake clusters of about 10 km in diameter were marked. It seems that there were some clusters which occurred in the time in which D did not decrease. Seismic quiescence was not seen clearly.

earthquakes are in hypocenter clusters, the D will decrease effectively. It is considered that such a situation is caused by seismic activation and quiescence. First, as its cause, the hypocenter cluster is formed by swarm earthquake or aftershock activity which has a small activity area. In this case, it seems that seismic activity becomes active. Second, when a seismic gap is formed by seismic quiescence, such situation may be realized. In this case, it is expected that the earthquakes are isolated and compose clusters, since a seismic gap cuts the spatial connection of hypocenters. In conclusion, both seismic activation and quiescence are effective for D decrease. Currently, these phenomena, seismic activation and quiescence, are known as the precursor of a large earthquake (e.g. Odaka and Maeda, 1994; Wiemer and Wyss, 1994). Therefore, the unusual D decrease may be caused by these phenomena. As depicted in Fig. 5, which shows time-space diagrams, it seems that some hypocenter clusters were formed in the study area in the same period as D decreased. The clusters shown in Fig. 5 are small (about 10 km) enough to decrease D, because their size is smaller than the middle of range of r in Eq. (2). But, it was indistinguishable whether the seismic quiescence appeared. In addition, some hypocenter clusters were also formed in other times. However, these clusters were not associated with D decrease. This may mean that it is difficult to detect the bias of hypocenter distribution by only its appearance.

As the pattern mentioned above, we should consider a possibility that seismic activation and quiescence occur simultaneously. For example, it corresponds to earthquake swarms or moderate earthquakes which have aftershocks occurring in and around a seismic gap. In this case, detection of seismic activation or quiescence is difficult, because they cancel out each other in the number of earthquakes. In order to search seismic quiescence in this situation, the method of declustering is used frequently. But, when a lot of hypocenter clusters are formed simultaneously, the advantage of this method will be lost. Now, either of these unusual seismic activities decrease the D value. That is, the value of D will decrease more effectively, if both of them occur simultaneously.

A lot of unusual changes of seismic activity before a large earthquake have been reported. However, its detection before the main shock occurrence is very difficult, because of the complexity of seismic activity. That is, it may be uncommon that the unusual seismic activity appears with a simple pattern. In this study, the relation of these unusual seismic activity and decrease of D was made clear. In conclusion, it is considered that using the D change is advantageous in order to detect an unusual seismic activity before a large earthquake.

5. Conclusion

The temporal changes in fractal dimension D of hypocenter distribution before the occurrence of the 2003 Tokachi-oki Earthquake was analyzed in this study. The resulting characteristics found by this analysis are as follows:

(1) The value of D began to decrease in 1998, and had been very small, for about one year before the main shock occurrence. It is considered that this D decrease was a precursor of this earthquake.

(2) The value of D is decreased by both of seismic activation and quiescence which essentially cancel out each other in the number of earthquakes. It is often difficult to detect either of them simply based on the temporal change in the number of earthquakes. Therefore, the D change is advantageous in order to detect an unusual seismic activity preceding a large earthquake.

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