Macro-Anomalies Precursory to the 1984 Naganoken Seibu, Japan, Earthquake of Magnitude 6.8 —Possibility of Assessing the Epicenter, Magnitude and Occurrence Time—

Tsuneji Rikitake* and Ichiro Kayano

Association for the Development of Earthquake Prediction,
Chiyoda-ku, Tokyo 101, Japan

Macro-anomalies preceding the 1984 Naganoken Seibu earthquake of magnitude 6.8 are analyzed in relation to maximum detectable distance, $D_{\max}$, from the epicenter and to precursor time, T , between anomaly appearance and main shock occurrence. These anomalies are anomalous animal behavior, strange detonation, change in underground water and the like. Making use of the previously-obtained relation between main shock magnitude, M , and $D_{\max}$, the probable epicentral area is assessed from the area for which all the $D_{\max}$ circles, that are drawn centering at each observation spot, overlap. When $M=6.8$ is assumed, the area includes the actual source fault and epicenter. The areas determined are too wide or narrow if $M=7.0$ or 6.6 are assumed, respectively. When an anomaly appears, it is possible to evaluate the probability for an earthquake occurring within a specified time-span as shown in the previous study. Such an evaluation is based on the frequency distribution of precursor time. It is proved for the Naganoken Seibu earthquake that the synthetic probability increases as time goes on and multiple macro-anomalies appear one by one reaching a value close to 1 immediately prior to the main shock occurrence.

1. Introduction

Kayano (1991) made an extensive enquiry survey about various features related to the 1984 Naganoken Seibu earthquake ($M=6.8$) that occurred on Sept. 14. He was able to collect precursor-like macro-anomalies amounting to 86 in number. These are anomalies in animal behavior, underground water, and so on, with exact location of observation spot and precursor time. Data for anomalous weather and supernatural intuition are omitted.

As it appears that even macro-anomaly data precursory to an earthquake can be used for assessing the earthquake magnitude, epicentral area and occurrence time of main shock as shown by Rikitake *et al.* (1993) provided an appropriate processing is completed, it is in this paper planned to apply the technique developed by Rikitake *et*

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* To whom correspondence should be addressed.

al. to the data of Naganoken Seibu earthquake.

In Section 2, the data obtained through the enquiry survey are presented in a summarized form along with the brief account of seismic source. Section 3 describes the so-called " $D_{\max}$ method" (Rikitake *et al.*, 1993) applied to the data and shows that the epicentral area is assessed reasonably accurately. Even the earthquake magnitude can be approximately guessed from the spacial extent of the area.

Section 4 is reserved for evaluating earthquake occurrence probability in a specified time-span as time goes on. It is demonstrated that the probability becomes high as the number of macro-anomaly increases reaching almost 100% immediately before the main shock occurrence.

2. Naganoken Seibu Earthquake and Precursory Macro-Anomalies

A magnitude 6.8 earthquake occurred in the western part of Nagano Prefecture on Sept. 14, 1984. The hypocenter is located at 35.82°N, 137.56°E. The focal depth is estimated as 2 km. Twenty-nine people were killed, mostly by debris avalanche. According to the source mechanism analyses (e.g., Takeo and Mikami, 1987), it is likely that a subsurface fault of 12 km in length and 6 km in width was activated slipping 1 m or so in an ENE direction, the slip plane being almost vertical.

Enquiry sheets of paper were distributed by Kayano (1991) mostly through elementary and middle schools in Nagano and Gifu Prefectures. Enquiries were made about precursory macro-anomaly along with seismic intensity, earthquake damage and so on. Although many replies were collected mostly from parents of school student, only precursory data, in which precursor time and location of the observation spot are clearly shown, were used in the present analysis. The number of such data amount to 86 in total as given in the Appendix. The names of reporters are omitted from the table for the sake of brevity.

Looking at examples presented in the Appendix, one may raise a question such as the following. "Is it really anomalous if a dog barks?" As it is quite usual to see a dog barking, such a phenomenon cannot be regarded as an anomaly in the usual sense. But it is apparent that the observer felt it unusual for the dog to be barking in such a way.

It is assumed in this paper that what was pointed out by an observer is all anomalous. There may be reports of considerable number that have nothing to do with the forthcoming earthquake even though the phenomenon reported looks anomalous. In order to cope with such spurious signals, a quantity called the reliability is introduced as can be found in the text.

3. Epicentral Area and Earthquake Magnitude

Rikitake *et al.* (1993), who analyzed 910 macro-anomaly data precursory to large earthquakes in Japan, showed that the maximum detectable distance, $D_{\max}$, of macro-anomaly is correlated to the earthquake magnitude, M , of main shock by an empirical relation such as

$$M = 1.86 + 2.6 \log D_{\max}, \quad (1)$$

in which $D_{\max}$ is measured in km. It is here assumed that Eq. (1) is applicable to earthquakes in general although the relation is deduced only from the data related to the six earthquakes, i.e. Ansei Tokai ($M=8.4$, 1854), Nobi ($M=8.0$, 1891), Kanto ($M=7.9$, 1923), Tonankai ($M=7.9$, 1944), Izu-Oshima Kinkai ($M=7.0$, 1978), and Miyagiken-Oki ($M=7.4$, 1978) earthquakes.

Supposing that a macro-anomaly is detected at an observation spot, we can draw a circle having a radius equal to $D_{\max}$ centering at the spot provided M is assumed. In that case it is clear that the epicenter of a coming earthquake must lie somewhere in the circular area as discussed by Rikitake (1988) in association with precursors observed by a geoscientific instrument. When a number of precursors are observed, the epicenter should be located in an area where all the $D_{\max}$ circles overlap.

Let us first assume $M=6.8$ for the Naganoken Seibu earthquake. $D_{\max}$ circles are then shown in Fig. 1(a) and (b) for the two periods respectively correspond to precursors No. 1–No. 51 and No. 52–No. 86. Denoting precursor time by T , these periods cover $T \geq 1$ day and $T < 1$ day, respectively. It is observed that the circle for precursor No. 72 does not overlap with most of other circles. It may therefore be right to omit this report in the same way as discussed by Rikitake *et al.* (1993) for data for which epicentral distance is too large.

Fig. 1. (a) $D_{\max}$ circles for macro-anomalies preceding the Naganoken Seibu earthquake. The circles for precursors No. 1–No. 51 are shown. The epicenter and fault model of the earthquake are shown by the double circle and thick straight line. $M=6.8$ is assumed. Small circles indicate the spots where anomalies are observed. (b) $D_{\max}$ circles for precursors No. 52–No. 86. Other symbols are the same as those for (a).

Fig. 2. Epicentral area inferred from macro-anomaly data for the Naganoken Seibu earthquake. The observation spots, epicenter and fault model are also shown. $M=6.8$ is assumed.

Fig. 3. Epicentral area inferred from macro-anomaly data when $M=7.0$ is assumed.

Figure 2 shows the area for which all the $D_{\max}$ circles except for No. 72 overlap. We see that the epicenter and source fault model are located in the area. Dambara (1979) presented an empirical relation between the extent of crustal deformation associated with an earthquake and the magnitude of main shock. According to the relation, the mean radius of the deformed area amounts to 16 km or so for $M=6.8$. It is surmised that the seismic energy is stored in the earth's crust covered by the area.

We see, therefore, that the mean epicentral area shown in Fig. 2 as determined by the macro-anomaly analysis is a few times wider than that directly connected to seismic energy. This is also the case for other large earthquakes in Japan (Rikitake *et al.*, 1993).

If we assume $M=7.0$ instead of $M=6.8$, the epicentral area due to macro-anomaly is determined as shown in Fig. 3 where all the troublesome $D_{\max}$ circles are not shown. The mean radius of the area amounting to 50 km or thereabout, the area is clearly too wide for an $M=7.0$ shock. On the contrary, an $M=6.6$ assumption results in an area that is much too small to be realistic. It is therefore concluded that the magnitude of coming earthquake seems likely to amount to 6.8 or so. It is interesting to note that the $D_{\max}$ analysis applied to the macro-anomaly data of the Naganoken Seibu earthquake leads us to a reasonable assessment of epicenter location and earthquake magnitude.

4. Synthetic Probability of Earthquake Occurrence

Rikitake *et al.* (1993) showed that the frequency distribution of macro-anomaly precursors of the large earthquakes cited in the last section can be approximated by a Weibull distribution having two parameters, K and m . These parameters are determined as

$$K/(m+1)=0.172, \quad m+1=1.64 \quad (2)$$

from the actual data. Denoting s by

$$s=\log T+c,$$

the probability for s to take on a value between 0 and s is given by

$$P(s)=1-\exp[-Ks^{m+1}/(m+1)], \quad (3)$$

where c is a constant. For the convenience of numerical work, c is here chosen as 3, while T is measured in units of day.

When an anomaly is observed, therefore, cumulative probability of earthquake occurrence is obtained as given in Eq. (3). On the condition that no earthquake occurs during a period between 0 and s_1 , conditional probability of an earthquake occurring between s_1 and s_2 is obtained as

$$p(s_1, s_2)=[P(s_2)-P(s_1)]/[1-P(s_1)]. \quad (4)$$

It should be borne in mind, however, that some of macro-anomalies are spurious. They are probably connected with some processes other than a coming earthquake. In order to deal with such a noise factor, Maeda and Yoshida (1990) introduced a reliability parameter r which is defined by the ratio of the genuine precursor numbers to the total (genuine and spurious) ones. In that case it is proved that (4) is modified as

$$p(s_1, s_2) = [P(s_2) - P(s_1)] / [1/r - P(s_1)], \quad (5)$$

which can be rewritten as

$$p(t, t + \tau) = [P(t + \tau) - P(t)] / [1/r - P(t)], \quad (6)$$

on the assumption that t and $t + \tau$ correspond to s_1 and s_2 . This is the conditional probability of an earthquake occurring between t and $t + \tau$ on the condition that no earthquake occurs before t .

Supposing that n independent precursors are observed and that the probabilities of respective precursors are given by $p_1, p_2, \dots, p_n$, Utsu (1977) showed that synthetic probability p is given by

$$p = 1 / [1 + \left\{ \prod_{i=1}^n (1/p_i - 1) \right\} / (1/p_0 - 1)^{n-1}], \quad (7)$$

where p_0 is the probability of success when a prediction is made at random. It is customary to estimate p_0 from the seismicity in the area to be studied.

When a number of precursors are observed at the i -th epoch, p_i should be replaced by p_i^j which is given by

$$p_i^j = 1 - (1 - p_i)^j, \quad (8)$$

where j is the number of precursors observed at that epoch.

In the western part of Nagano Prefecture and Gifu Prefecture, where the Naganoken Seibu earthquake occurred, it is reported that earthquakes having a magnitude equal to 7.0 or over occurred in 1586, 1715, 1858, 1891, and 1961. As the time-interval between the 1858 and 1891 earthquakes is unusually small, we assume that the activity took place at an epoch represented by the averaged one of the two shocks. In that case it is estimated that an earthquake of the magnitude in question occurs once in 125 years. We may thus presume $p_0 = \tau / (125 \times 365)$.

Fig. 4. Changes in daily number of macro-anomaly forerunning the Naganoken Seibu earthquake of which the main shock (M.S.) occurs on the 100th day.

As can be seen in the Appendix, we have the first report on macro-anomaly precursor 100 days before the main shock. The change in precursor numbers for the following period is shown in Fig. 4. Only the data for which the precursor time is equal to or longer than 1 day are shown. It is apparent that the increasing rate of precursor number becomes remarkable since several days before the main shock.

Since nothing is known about r , changes in synthetic probability are evaluated for $r=0.1$ and 0.02 assuming $\tau=1$ and 10 days, respectively. Figure 5(a) and (b) are the changes in the probability for $r=0.1$ with $\tau=1$ and 10 days, while Fig. 6(a) and (b) are those for $r=0.02$ with $\tau=1$ and 10 days.

It is seen in the figures that the synthetic probability jumps up when a precursor is observed although it decreases fairly quickly as time goes on if we have no earthquake. As the main shock occurrence approaches and the number of precursors increases, the probability tends to increase taking on a value close to 1 several to a couple of days before the main shock depending upon r . The probability for $\tau=10$ days is in general higher than that for $\tau=1$ day although the difference is not large.

It is interesting to note that the synthetic probability takes on a value close to 1 toward the last stage of precursor appearance even for a small value of r such as 0.02 . This means that a high probability can be obtained even for the data involving fairly many false ones provided the number of data is large. It is difficult, however, to see the right value of r from the present study. This is also the case for the six large earthquakes analyzed in the previous paper (Rikitake *et al.*, 1993).

Fig. 5. (a) Changes in synthetic probability of earthquake occurrence within 1 day ($\tau=1$) for the Naganoken Seibu earthquake. $r=0.1$ is assumed. (b) Changes in synthetic probability of earthquake occurrence within 10 days ($\tau=10$). $r=0.1$ is assumed.

Fig. 6. (a) Changes in synthetic probability of earthquake occurrence within 1 day ($\tau=1$). $r=0.02$ is assumed. (b) Changes in synthetic probability of earthquake occurrence within 10 days ($\tau=10$). $r=0.02$ is assumed.

5. Discussion and Concluding Remarks

It is demonstrated in this paper that the epicentral area and earthquake magnitude of the 1984 Naganoken Seibu earthquake can be assessed fairly accurately from the $D_{\max}$ analysis of macro-anomaly precursors. It is also proved that the occurrence probability increases as we observe many macro-anomaly precursors taking on a value close to 1 immediately prior to the main shock occurrence even if we assume that fairly many false signals are involved.

In light of the present result along with those for the six large earthquakes in Japan as studied in the previous paper (Rikitake *et al.*, 1993), it may be concluded that macro-anomaly observation precursory to an earthquake occurrence is useful, at least to some extent, for earthquake prediction.

It should be pointed out, however, that all the precursor data used in the present analysis were collected after the earthquake, so that what are discussed here is not a true prediction. For an actual prediction, it is required to make real-time data acquisition. The writers hope that a well-equipped data collecting and processing system is developed in the future in order to achieve earthquake prediction discussed in this paper.

Since most of macro-anomaly precursor data are anecdotal, it is possible that reported precursor times are influenced by time constant of human memory. At the moment, the writers cannot deal with such psychological effect. This point should be improved in the future, probably with the help of a psychologist.

The probabilities of earthquake occurrence are evaluated on the assumption that all the precursors are mutually independent. In that case it is clear that a high synthetic

probability is necessarily reached when multiple precursors are simultaneously observed even though the probability of single precursor is low. The high probabilities immediately before the main shock occurrence as shown in Figs. 5 and 6 may have something to do with such an effect. This is one of the points to be examined in future work.

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APPENDIX

Macro-anomalies precursory to the Naganoken Seibu earthquake arranged according to precursor time. Most data are from Nagano Prefecture except those denoted by (G) which are from Gifu Prefecture.

No.	Observation spot	Epicentral distance in km	Precursor time in day	Anomaly description
1	Higashi-Shirakawa Village (G)	27	100	Underground water is usually cold in summer. However, the water was not so cold this year.
2	Okuwa V.	18	70	No snakes were seen this year.
3	Okuwa V.	18	50	No bees came to the flowers which had been visited by them every year.
4	Okuwa V.	18	50	Few insects came to flowers.
5	Okuwa V.	18	50	No earthworms were seen.
6	Okuwa V.	18	50	Fairly many animal bodies that had been run over by cars were observed on highways.
7	Iida City	42	50	Few wasp nests this year.
8	Agematsu Town	11	30	Water in a tank became full although we had no rainfall.

No.	Observation spot	Epicentral distance in km	Precursor time in day	Anomaly description
9	Otaki V.	3	20	Many crows were seen. They disappeared a few days prior to the earthquake.
10	Gero T. (G)	24	20	Rats raged about in the attic every night
11	Agematsu T.	13	14	No birds were seen since the beginning of September.
12	Osaka T. (G)	24	14	A well tended to dry up toward the end of this summer. The well has never been in such a state.
13	Kiso V.	24	10	Well water decreased and got muddy. No rain on that day.
14	Kashimo V. (G)	20	10	Underground water decreased. It dried up after the earthquake.
15	Okuwa V.	18	10	A dog barked continually since about 10 days before the earthquake.
16	Agematsu T.	13	7	A flock of many birds was seen on the way to school.
17	Agematsu T.	13	7	A house dog barked since a week before the earthquake. The dog did not enter the kennel during night.
18	Agematsu T.	16	7	Crows cawed anomalously since a week before the earthquake.
19	Tsukechi T. (G)	21	7	Crows made a fuss since a week before the earthquake.
20	Gero T. (G)	28	7	A house dog kept unusually quiet since a week before the earthquake. It usually barks when a family member comes back from outside. But it did not bark this time.
21	Kashimo V. (G)	20	7	A carp swam around in a pond.
22	Otaki V.	6	5	No fish on a river nearby on Sept. 9. This is quite unusual.
23	Okuwa V.	19	5	A neighbor's dog barked in a strange way since 4-5 days before the earthquake.
24	Higashi-Shirakawa V. (G)	27	5	Many crows were seen.
25	Gero T. (G)	27	5	Many hairy caterpillars were seen on the road 4-5 days before the earthquake. They disappeared after the earthquake.
26	Gero T. (G)	27	5	Many hairy caterpillars were seen by weeds.
27	Gero T. (G)	27	4	A small tortoise was found in the garden at about 10 o'clock on the morning of Sept. 10.
28	Gero T. (G)	28	3	Rats moved about violently in the ceiling a few days prior to the earthquake.
29	Gero T. (G)	27	3	Carp and other fish swam in a pond in a strange way.
30	Gero T. (G)	27	3	Snakes were often observed on a road before the earthquake.

No.	Observation spot	Epicentral distance in km	Precursor time in day	Anomaly description
31	Tsukechi T. (G)	21	3	Well water became whitish about 3 days before the earthquake.
32	Kashimo V. (G)	20	3	A cow became so nervous that it almost ran out from the cowshed.
33	Kiso-Fukushima T.	12	2	A dog tended to cease barking 2 days before the earthquake.
34	Agematsu T.	13	2	Insects stopped chirping since 2 days before the earthquake.
35	Takagi V.	45	2	Unusually many river fish were caught on Sept. 12.
36	Chino C.	57	2	Many crows gathered on a small mountain and cawed at dusk.
37	Osaka T. (G)	24	2	Pheasants often cried out 2 days before the earthquake.
38	Kashimo V. (G)	20	2	A house dog barked out in the presence of family members even at midnight since about 2 days before the earthquake.
39	Otaki V.	5	1	Animals moved away toward the evening on Sept. 13.
40	Agematsu T.	13	1	A house dog climbed to a high place and kept barking since a day before the earthquake.
41	Okuwa V.	18	1	A cat became restless since a day before the earthquake.
42	Okuwa V.	18	1	A carp moved about violently in a pond on the day before the earthquake.
43	Agematsu T.	13	1	Contrary to normal time, only one swamp crab was caught on Sept. 13.
44	Gero T. (G)	27	1	A snake was found at the porch. This was the first time to see a snake since this summer.
45	Gero T. (G)	27	1	Crows cawed in a strange way the day before the earthquake.
46	Gero T. (G)	24	1	Rats made a fuss the day before the earthquake.
47	Gero T. (G)	24	1	Many birds made a fuss the day before the earthquake.
48	Gero T. (G)	24	1	Water became muddy the day before the earthquake.
49	Tsukechi T. (G)	21	1	Color and smell of Tsukechi river were unusual on the morning of the day one day before the earthquake.
50	Kashimo V. (G)	20	1	A bird, which had never been seen before, came to a mountain in front of the house one day before the earthquake.
51	Kashimo V. (G)	22	1	On the day before the earthquake, snakes were found in the bathroom and corridor for the first time during 10 years in the past.

No.	Observation spot	Epicentral distance in km	Precursor time in day	Anomaly description
52	Matsumoto C.	60	0.5	A catfish went so mad that it jumped out of the tank and died in the evening before the earthquake.
53	Kiso-Fukushima T.	12	0.5	No chirping of insects in the evening before the earthquake.
54	Agematsu T.	13	0.5	A dog barked furiously in the night before the earthquake day.
55	Tajimi C. (G)	65	0.5	Earth sounds were felt in the night before the earthquake day.
56	Okuwa V.	18	0.4	Birds kept in the house warbled by 10-12 o'clock in the night before the earthquake day.
57	Agematsu T.	13	0.15	A macaw made a fuss at 5 o'clock on the earthquake day.
58	Otaki V.	4	0.1	A bird, which is rarely found, was seen near the dam.
59	Agematsu T.	13	0.1	Many newts were found dead on the earthquake day morning.
60	Agematsu T.	13	0.1	A house dog was afraid of something and stayed in the kennel without eating breakfast.
61	Okuwa V.	18	0.1	Carp jumped unusually high.
62	Okuwa V.	18	0.1	Carp gathered in the center of a pond. Usually they hide themselves under a stone.
63	Okuwa V.	19	0.1	A dog barked anomalously before the earthquake.
64	Okuwa V.	17	0.1	Crows anomalously cawed early in the morning.
65	Okuwa V.	17	0.1	Carp moved about in the morning.
66	Okuwa V.	17	0.1	Crows cawed in an unusual way early in the morning.
67	Seinaiji V.	38	0.1	Hens and cocks kept quiet in the morning.
68	Osaka T. (G)	30	0.1	A dog kept quiet.
69	Okuwa V.	18	0.05	A man of 46 years old said that it was unusually warm. Other family members did not notice.
70	Osaka T. (G)	30	0.05	Dogs were restless.
71	Osaka T. (G)	30	0.05	Birds were restless.
72	Nagano C.	100	0.04	A pheasant made a fuss on the road 30 min before the earthquake.
73	Kanayama T. (G)	39	0.03	Flocks of many birds flew about 1 h before the earthquake.
74	Otaki V.	5	0.01	A fisherman saw many fish jumping in the river.
75	Kiso-Fukushima T.	12	0.01	Dogs and ducks made a fuss furiously just before the earthquake.
76	Okuwa V.	18	0.01	A dog barked before the earthquake.
77	Okuwa V.	18	0.01	A dog was missed at 8:30 in the morning. It was found at a safe place near a school.

No.	Observation spot	Epicentral distance in km	Precursor time in day	Anomaly description
78	Okuwa V.	18	0.01	Carp in a breeding pond did not eat much before the earthquake.
79	Takato T.	43	0.01	Wild pheasants made a fuss just before the earthquake.
80	Takato T.	43	0.01	A budgerigar made a fuss just before the earthquake.
81	Ina C.	40	0.01	Carp jumped on the pond just before the earthquake.
82	Gero T. (G)	28	0.01	A flock of many birds was observed.
83	Mitake T. (G)	57	0.003	A catfish jumped out of a tank 5 min before the earthquake.
84	Okuwa V.	18	0.002	A pheasant cried violently a few minutes before the earthquake.
85	Osaka T. (G)	30	0.001	A cat ran about before the earthquake. This is also the case for aftershocks.
86	Gero T. (G)	21	0.001	A dog barked fiercely just before the earthquake.