Nature of Macro-Anomaly Precursory to an Earthquake

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Nature of macro-anomaly precursory to an earthquake such as anomalous animal behaviour, changes in underground water and hot springs and so on is studied based on an extensive data set related to a number of large earthquakes in Japan.

It turns out that the larger the magnitude of the main shock, the wider the area over which macro-anomalies are observed. Underground water and hot spring anomalies appear in an area where a marked crustal deformation can be expected to take place. The area for anomalous animal behaviour is slightly wider than that.

No dependence of precursor time of macro-anomaly on main shock magnitude is found for an individual earthquake. However, there is a certain regularity of precursor time distribution. The maximum frequency of precursor appearance occurs around one day before the main shock. The mean precursor time takes on a value amounting to 0.42 day.

It is likely that animals of smaller size such as rat, squirrel and so on become tumultuous earlier than those of larger size such as dog, pig, cow, and so on.

Much macro-anomaly precursor data is spurious. Changes in synthetic probability of the main shock occurrence with time when multiple signals appear are evaluated in two ways: one is assuming the reliability, r , which is defined by the ratio of genuine data to the total (genuine and spurious) data, for all the actual data. The other is obtained from a computer simulation of random appearance. Comparing the two evaluations, it seems appropriate to assume that r amounts to 0.05 or thereabouts.

1. Introduction

Many precursor-like data have been collected in Japan through geophysical and geochemical observations conducted under the national earthquake prediction programme (Rikitake, 1986; Seismology and Volcanology Research Division, 1990). These data are certainly useful for clarifying the nature of earthquake precursors of various geoscientific disciplines (Rikitake, 1987).

On the other hand, macro-anomaly precursor data, that can be sensed by humans without relying on a precise instrument, have also been collected in Japan notably by Rikitake (1986, 1989) and his group. Rikitake *et al.* (1993) showed that even macro-anomaly precursors can be applied, at least to some extent, to actual prediction of magnitude, epicentral area and occurrence time of an earthquake provided an appropriate processing is made.

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Since the nature of macro-anomaly has not as yet been clarified, however, the aim of this paper is to investigate the appearance mode of a macro-anomaly precursor in relation to its precursor time and detectability mainly based on an extensive data set collected for six large earthquakes in Japan. The data for two earthquakes collected by Kayano (1991) are also used.

In Sec. 2 will be outlined the macro-anomaly data analyzed in this paper. The analysis will be made from the following two standpoints. Section 3 is reserved for examining the sites where we observe a macro-anomaly precursor. Most typically, the relation between earthquake magnitude of the main shock and epicentral distance will be studied. The fact that larger magnitudes are associated with larger distances will be brought to light.

Next, it will be shown in Sec. 4 that no clear dependence of precursor time on main shock magnitude is found for an individual macro-anomaly. It will be brought out, however, that there is a tendency for the maximum precursor time for a larger magnitude earthquake to become longer than that for an earthquake of smaller magnitude. Comparative study of the distribution of precursor time for various anomaly disciplines will be presented in the same section.

As it is highly likely that macro-anomaly is contaminated with much noise, evaluation of the reliability of a macro-anomaly will be attempted in Sec. 5 comparing time change of earthquake occurrence probability as evaluated for actual data of multiple precursor appearances using a specified reliability to that for the case of computer-simulated random appearance.

What the writer intends to present in this paper is different from the points stressed in the previous paper (Rikitake *et al.*, 1993) in which the practical way of applying macro-anomaly data to actual prediction is dealt with. In contrast to such an approach, the main concern of this paper is the general character of the macro-anomaly.

2. Macro-Anomaly Data

Countless macro-anomalies have been reported from many countries since ancient times. For the purpose of choosing anomalies of equal scientific level, however, the writer relies on the data newly collected by Rikitake (1986, 1989) and his group. These data are for the six large Japanese earthquakes, i.e. Ansei Tokai ($M8.4$, 1854), Nobi ($M8.0$, 1891), Kanto ($M7.9$, 1923), Tonankai ($M7.9$, 1944), Izu-Oshima Kinkai ($M7.0$, 1978) and Miyagiken-Oki ($M7.4$, 1978) earthquakes. The data are supplemented by those for the Ibarakiken Nanseibu ($M6.0$, 1978) and Naganoken Seibu ($M6.8$, 1984) earthquakes (Kayano, 1991). The epicenters of these earthquakes are shown in Fig. 1 along with those supplementarily used for underground water and hot spring anomalies.

The data are selected according to the guidelines which were put forward by Rikitake (1989). They are as follows:

- (1) Reported data are adopted as much as possible although those having an obvious mistake are omitted.
- (2) Although anomalous weather and human instinct are sometimes regarded as macro-anomaly, the writer feels that reports of this kind are too vague or anecdotal and so they are omitted from the analysis, so that only the data of the following

Fig. 1. Epicenters of earthquakes of which macro-anomaly precursors are analyzed. Large circles indicate the six large earthquakes that are associated with many macro-anomaly data. A: Ansei Tokai ($M8.4$, 1854), N: Nobi ($M8.0$, 1891), K: Kanto ($M7.9$, 1923), T: Tonankai ($M7.9$, 1944), I: Izu-Oshima Kinkai ($M7.0$, 1978), and M: Miyagiken-Oki ($M7.4$, 1978) earthquakes.

disciplines are studied: anomalous animal behaviour, strange detonation, unusual light in the sky and changes in underground water and hot springs.

(3) Anomalies that occur almost coseismically are rejected.

As for epicentral distance between the epicenter and the observation site, the numbers of available data amount to 67, 199, 222, 57, 129, 121, 19, and 46, respectively for the eight earthquakes. The underground water and hot spring data are supplemented by the data related to the Takada ($M7.2$, 1751), Kisakata ($M7.0$, 1804), Echigo ($M6.9$, 1828), Ansei Edo ($M6.9$, 1855), Tajima ($M6.8$, 1925), Tango ($M7.3$, 1927), Showa Sanriku Tsunami ($M8.1$, 1933), Shizuoka ($M6.4$, 1935), Hinomaki-Oki ($M6.8$, 1938), Tottori-Oki ($M6.2$, 1943), Tottori ($M7.2$, 1943), Nankai ($M8.0$, 1946), Fukui ($M7.1$, 1948), and Izu Hanto-Oki ($M6.9$, 1974) earthquakes. The numbers of these additional data amount to well over 30.

For the purpose of studying precursor times, the data amounting to 34, 201, 215, 66, 151, 118, 19, and 46 in number, respectively, for the eight earthquakes are available.

3. Where Do We Observe a Macro-Anomaly?

3.1 Detectability as a whole

In order to see where a macro-anomaly precursor appears, the writer first of all

examines the relation between earthquake magnitude (M) of the main shock and the epicentral distance (D) with respect to the data for the first six earthquakes in a fashion similar to the analysis for geoscientific precursors (Rikitake, 1987). Since the data are too numerous, the following approach is made to evaluate the overall tendency. Such an analysis has already been reported in Rikitake *et al.* (1993).

The percentages of anomaly number for each epicentral distance range of 20 km are estimated from the data for a particular earthquake. Circles, of which the radius is proportional to the percentage calculated, are shown on an M - $\log D$ graph in which D is measured in km, as can be seen in Fig. 2 for the six earthquakes in question. It appears in the figure that the larger the magnitude is, the larger is the maximum distance for which a precursor is observed. It is also observed, however, that there are a few cases for which an anomaly is observed at an unusually large distance. As these may be spurious, it is assumed, rather arbitrarily, that the maximum distance ($D_{\max}$) for precursor detection can be defined by the epicentral distance that covers 90% of the data. From the M - $D_{\max}$ relations thus obtained for the six earthquakes, we obtain the empirical relation

$$M = 1.8 + 2.6 \log D_{\max} \quad (1)$$

by use of the least squares method.

It is known that the M - $D_{\max}$ relation for geoscientific precursors can be approximately expressed by an equation similar to Eq. (1) (Rikitake, 1987). In obtaining Eq. (1), the writer assumes that the inclination of straight line A that represents Eq.

Fig. 2. The relation between main shock magnitude, M , and epicentral distance, D , of macro-anomalies for the six large earthquakes in Japan. D is measured in km. The meaning of various circle sizes, that indicate the percentages of anomaly numbers for respective distance ranges, as shown in the inset, is given in the text. For the Kanto and Tonankai earthquakes, both having magnitude of 7.9, thin and thick circles are used for making the distinction. Straight line A represents the maximum epicentral distance, $D_{\max}$, given by Eq. (1).

(1) is the same as that for the geoscientific precursors. Line A is shown in Fig. 2.

Essentials of Fig. 2 having been already presented in Rikitake *et al.* (1993), nothing new about the M - $D_{\max}$ relation is added here. It seems appropriate, however, to repeat the general relation so far obtained to make the readers understand the situation.

According to Eq. (1), we see that the maximum detectable distances from the epicenter for a macro-anomaly precursor amount to 39, 95, and 230 km, respectively, for $M=6$, 7, and 8. As pointed out by Dambara (1981), the mean radius of an area over which crustal deformation directly associated with an earthquake takes place amounts to 6.3, 20.4, and 60.1 km, respectively for $M=6$, 7, and 8. It is interesting to note that the epicentral distance for which we may expect appearance of a macro-anomaly precursor is a few times as large as that for the area where the seismic energy is stored and so most aftershocks occur. It has been shown by Rikitake (1987), however, that a geoscientific precursor sometimes appears at a much greater distance depending upon precursor disciplines.

3.2 Difference in $D_{\max}$ between anomaly disciplines

Next, it is planned to look into the point whether there are differences in $D_{\max}$ between various disciplines of macro-anomaly. In Fig. 3 are shown the M - $\log D$ relations for underground, hot spring and animal behaviour anomalies based on the data for the eight earthquakes. No such a relation has been tried to study the strange detonation and unusual light in the sky because it is not quite certain that the distance between epicenter and observation site represents the correct epicentral distance for the site where the anomaly appears. As mentioned in Sec. 2, more than 30 data are added to those for the underground water and hot spring data of the eight earthquakes. Anomalous animal behaviour data are classified into four groups: mammal, bird, fish, and snake, insect, worm...etc.

Straight lines A, B, and C in the figure represent the M - $D_{\max}$ relations for respective anomaly groups. A is the straight line expressed by Eq. (1) which corresponds to the M - $D_{\max}$ relation for macro-anomaly as a whole. B is that for overall geoscientific anomaly (Rikitake, 1987). Meanwhile, C represents the same relation for the geoscientific precursor revealed by geodetic work only. It is interesting to see that most underground water and hot spring anomalies are located at a distance smaller than $D_{\max}$ defined by line A. Looking at Fig. 3, it may be said that an underground water and hot spring anomaly appears in an area over which crustal deformation that can be detected by geodetic work prevails.

Such a fact can be understood by assuming that changes in level, temperature, muddiness and/or chemical composition of underground water and hot springs are stimulated by crustal movement precursory to an earthquake. According to Rikitake (1987), who examined ground deformation precursors, the crustal strain expressed by line C amounts to the order of 10^{-7} – 10^{-6} ; therefore, it may be that a crustal deformation precursor of this order is monitored as a macro-anomaly signal of said discipline.

The four M - $\log D$ plots for anomalous animal behaviour shown in Fig. 3 are distributed in a way similar to the underground water and hot spring anomalies although plots of certain numbers appear to the right of lines A and C. This means that some of these precursors may reflect a crustal strain of the order of 10^{-7} or smaller. As it is

Fig. 3. M - $\log D$ graphs for macro-anomaly. D is measured in km. Graphs for anomalous animal behaviour are classified into four groups. Meanings of straight lines A, B, and C are given in the text.

hard to think that animals can directly sense the crustal strain of the said order, it is surmised that they probably react to some changes in microshock, weak change in electric and magnetic fields, change in underground water level and so on that are possibly associated with a small crustal deformation. However, nothing definite can be proposed for an exact mechanism of anomalous behaviour anomaly of animals.

4. When Do We Observe a Macro-Anomaly?

4.1 Comparative study on precursor time for various disciplines

It is important for earthquake prediction to see when a macro-anomaly precursor makes an appearance. Figure 4 illustrates the $\log T$ - M relations for various groups of macro-anomaly. T represents the precursor time, that is the time interval between the precursor appearance and main shock occurrence, measured in days. The $\log T$ - M plots in the figure are obtained from the data of the eight earthquakes in Japan as mentioned in Sec. 2.

As can be seen in Fig. 4, precursor times are distributed over a broad range of time from a few minutes to several hundred days. Such a fact can be observed even more clearly in histograms of $\log T$ frequency, as shown in Fig. 5, for respective disciplines of macro-anomaly precursor. The frequency maximum appears around $\log T=0.0-0.5$ for all the disciplines. It appears that no definite relationship exists between M and T .

A histogram of $\log T$ for all the macro-anomaly disciplines is then drawn as can be seen in Fig. 6 for which the 910 data for the first six Japanese earthquakes cited in Sec. 2 are used. Although this diagram has already been published in the previous paper (Rikitake *et al.*, 1993), the writer believes that it is better to reproduce it here for developing further argument. It is clearly demonstrated in the figure that the number of macro-anomaly precursors tends to increase beginning about 100 days before the earthquake. The increasing rate becomes appreciably high at about 10 days preceding the main shock and the maximum of appearance number occurs around the day before the earthquake day.

A Weibull distribution analysis of the histogram (Rikitake *et al.*, 1993) has concluded that the mean precursor time takes on a value of 0.42 day, so that it may be said that macro-anomaly precursor is essentially a short-term one. The precursor time distribution, as revealed in Fig. 6, can be used to evaluate the probability of an earthquake occurring in a specified time span after a macro-anomaly is observed (Rikitake *et al.*, 1993).

4.2 Relation between the longest precursor time and main shock magnitude

Going back to Fig. 4, we observe that the longest precursor time, $T_{\max}$, seems to be controlled by the main shock magnitude, M , although no regularity can be seen in the T - M relation for individual signals. It seems likely that the larger M is, the larger is the $\log T_{\max}$ for each discipline.

To see the overall tendency, an M - $\log T$ graph for the six Japanese large earthquakes cited in Sec. 2 is shown in Fig. 7 in which the percentages of $\log T$ for respective ranges of 0.5 interval are indicated with circles of different radius in a fashion similar to Fig. 2.

Based on the data thus obtained, the most probable $\log T_{\max}$ - M relation is deduced

Fig. 4. $\log T$ - M graphs for macro-anomaly. Precursor time, T , is measured in days.

UNDERGROUND WATER & HOT SPRINGS

MAMMAL

BIRD

FISH

SNAKE, INSECT, WORM, ---etc

Fig. 5. Frequency histograms of $\log T$ for macro-anomaly. T is measured in days.

as

$$\log T_{\max} = -6.2 + 1.14M \quad (2)$$

by means of the least squares method. The relation defined by Eq. (2) is shown by a straight line A in Fig. 7.

Hiraga *et al.* (1985), who studied precursory changes in underground water, pointed out that they observed the tendency that the larger the main shock magnitude is, the longer is the maximum precursor time. Ma *et al.* (1990) also claimed a similar M - $T_{\max}$ relation on the basis of ample data relevant to large Chinese earthquakes. It is interesting to note that the present analysis reveals that such an M - $T_{\max}$ relation holds true not only for ground water anomaly but also for animal behaviour anomaly.

Relying on Eq. (2), one can suppose that an $M=6$, 7, and 8 earthquake would occur within 4.4, 60, and 830 days' time when a macro-anomaly is observed. When a plausible magnitude can somehow be known by means of the so-called $D_{\max}$ method (Rikitake *et al.*, 1993; Rikitake and Kayano, 1993) or some other means, we may guess

Fig. 6. Overall histogram of $\log T$ for macro-anomalies for the six earthquakes cited in Sec. 2.

Fig. 7. The relation between main shock magnitude, M , and precursor time, T , of macro-anomalies for the six large earthquakes in Japan. T is measured in days. The meaning of various circle sizes, that indicate the percentages of anomaly numbers for respective time ranges, as shown in the inset, is given in the text. For the Kanto and Tonankai earthquakes, both having a magnitude of 7.9, thin and thick circles are used for making the distinction. Straight line A represents the maximum precursor time, $T_{\max}$, given by Eq. (2).

the upper limit of the date of the coming earthquake.

It has often been reported in China (Ma *et al.*, 1990) that macro-anomalies tend to migrate gradually from the outside towards the epicenter, with a migration velocity of several km per day. No such tendency is seen in the present data set. If we express the relation on a TD -plane, the plotted points are scattered so randomly that we can

see nothing.

Because of a relation derived from Eqs. (1) and (2), however, it is likely that the maximum precursor time becomes longer when the area over which macro-anomalies appear is wider.

4.3 Animal size and precursor time

When the writer visited the earthquake area of Songpan-Pingwu earthquakes ($M7.2$, 6.7 , 7.2 , 1976) in Sichuan Province, China, he was told by Chinese colleagues at the Sichuan Seismological Bureau (personal communication, 1978) that small animals become tumultuous earlier than large animals. Rikitake (1982) also presented a data set indicating such a tendency basing on data other than those from China. In order to check the point again, histograms of animal anomaly are shown in Fig. 8 with respect to small and large mammals.

As can be seen in the figure, the data are classified into two groups: Group I includes the data for small-sized animals such as the rat, mole, hamster, and squirrel, while Group II includes the data for large-sized animals including the dog, cat, raccoon dog, rabbit, pig, deer, and cow. It is pointed out that the numbers of data having a precursor time shorter than 1 day are considerably smaller for Group I than those for Group II.

Fig. 8. Histograms of logarithmic precursor time for animal precursor divided into two groups according to animal sizes. The upper graph is for small-sized animals such as the rat, mole, hamster, and squirrel, while the lower one corresponds to that for dog, cat, raccoon dog, rabbit, pig, deer, and cow, of which the size is generally larger than that for animals in the upper graph.

Although the maximum peak frequency appears around 1 day or $\log T=0$ for both the groups, it is obvious that we hardly observe an animal anomaly in group I during the few hours before the main shock as far as the present data are concerned. This fact seems to support the Chinese view that smaller size animals tend to behave anomalously earlier than larger size animals. There may be a squirrel which is larger than a dog in size, so that the above classification is by no means strict. A small animal may grow eventually taking a large size. Because of such difficulties, therefore, no exact precursor time analysis can be made for the relation between animal size and precursor time.

5. How Reliable Is a Macro-Anomaly?

It is highly likely that macro-anomaly data often contain false signals which have nothing to do with an earthquake occurrence. For instance, an animal may make a fuss reacting to changes in environmental condition such as air temperature, atmospheric electric field and the like arising from some causes other than an earthquake. Strictly speaking, there is no clear-cut way of omitting such spurious data.

To cope with this situation, a reliability factor called r was introduced in the previous work (Rikitake *et al.*, 1993) in which r was arbitrarily chosen to evaluate changes in synthetic probability of earthquake occurrence. It was suggested for most earthquakes analyzed that a value around 0.05 may be appropriate for r judging from the increasing mode of synthetic probability toward the final period when the appearance number of precursory signals tends to notably increase.

Taking the macro-anomaly data preceding the Kanto earthquake, it is undertaken to herein evaluate changes in synthetic probability as time goes on when macro-anomalies, which are all genuine, appear randomly. It is assumed that signals amounting to rN in number occur, N being the total number of macro-anomalies actually reported. As $N=127$ for $T \geq 1$ day macro-anomaly precursors concerned and the first signal appears 270 days before the main shock, a computer-produced set of random numbers implies that only the 13 signals which appeared on the 8th, 18th, 33rd, 38th, 99th, 105th, 164th, 214th, 228th, 230th, 248th, 259th, and 261st days are genuine when $r=0.1$ is presumed. If we take $r=0.05$, a genuine signal appears on the 8th, 105th, 164th, 228th, 230th, 259th, and 261st days. Those days for a genuine signal become the 8th, 164th, and 259th corresponding to presumption $r=0.02$.

Fig. 9. (a) Changes in synthetic probability of main shock (M.S.) occurrence of the Kanto earthquake within 1 day as evaluated from macro-anomaly data. Thin line indicates the probability change when the reliability, r , is assumed to be 0.1. Meanwhile, the change for random appearance of genuine signal as evaluated by a computer simulation is shown by the thick line. (b) Changes in synthetic probability of main shock occurrence of the Kanto earthquake within 1 day. $r=0.05$ is assumed for the thin line curve, while the thick line indicates the probability change for random appearance of macro-anomaly. (c) Changes in synthetic probability of main shock occurrence of the Kanto earthquake within 1 day. $r=0.02$ is assumed for the thin line curve, while the thick line indicates the probability change for random appearance of macro-anomaly.

Fig. 9

How to evaluate changes in synthetic probability of earthquake occurrence within one day from a specified time when a number of precursory signals appear one by one having been given repeatedly in Rikitake *et al.* (1993) and Rikitake and Kayano (1993), no details of evaluation are described here. Figure 9(a) shows the changes in synthetic probability according as macro-anomaly precursors appear successively before the main shock (M.S.) of the Kanto earthquake. The thin line in the figure indicates the change in probability evaluated from all the data when $r=0.1$ is assumed. It is remarkable that the probability increases discontinuously when a precursor is observed, although the probability decreases subsequently if we have no earthquake. However, the probability tends to reach 1 as many precursors are observed.

In contrast to such a pattern of probability increase obtained from all the data assuming $r=0.1$, the random appearances of genuine precursory signals lead to an increase of probability at an earlier period as indicated by a thick line. The writer feels, however, that the probability takes on a value close to 1 too early in this case.

Similar graphs of probability increase are shown in Fig. 9(b) and (c) for $r=0.05$ and 0.02, respectively. It is observed in these figures that random occurrences of precursor signals lead to an appreciable increase of probability at an earlier period although the probability at that period decreases fairly quickly.

As the synthetic probabilities evaluated on the assumptions that precursors occur randomly and the reliability takes on a value ranging 0.02–0.05 agree with one another toward the final stage of precursor appearance several to a few tens of days prior to the main shock occurrence, it may be justified to assume that the reliability takes on a value around 0.05 in actual evaluation of probability although an exact appraisal of reliability is difficult to make.

6. Discussion and Concluding Remarks

Analysis of an extensive data set of macro-anomaly precursors related to eight large earthquakes in Japan leads us to conclude that an underground water and hot spring anomaly is observed in an area over which remarkable ground deformation is to be detected by a geodetic survey. The area for anomalous animal behaviour seems likely to be somewhat wider than the above one though it is considerably narrower than the area for a geoscientific precursor monitored by a highly sensitive instrument such as volume strainmeter or tiltmeter.

The precursor time of a macro-anomaly does not seem to depend on the earthquake magnitude of main shock. However, the frequency distribution of precursor time exhibits some regularity. Macro-anomalies begin to be observed about 100 days before the main shock, anomaly numbers tending to increase rapidly some 10 days prior to the earthquake occurrence. The maximum frequency of precursor time usually takes place around 1 day prior to the main shock. A Weibull distribution analysis indicates that the mean precursor time amounts to 0.42 days suggesting that a macro-anomaly is essentially a short-term one.

It appears that no systematic relation exists between main shock magnitude and individual precursor time of macro-anomaly. Close examination reveals a tendency for the maximum precursor time to become longer for an earthquake of larger magnitude

although such a tendency has little to do with actual earthquake prediction.

As has been reported in China, precursor time of anomalous animal behaviour anomaly seems to be controlled partly by animal size. The average precursor times for rat, squirrel, and so on are longer than those for dog, cat, pig, deer, and the like.

Although it is highly likely that macro-anomaly signal is contaminated with much noise, no effective way of eliminating false signals can readily be found. Comparing the probability change with time when multiple precursors, of which the reliability is prescribed, appear successively to that for random appearance as evaluated by computer simulation, it is tentatively surmised that the reliability may take on a value around 0.05. This suggests that one of 20 macro-anomaly signals may usually be genuine.

In spite of the detectability and precursor time examination as developed in this paper, no conclusive point about the cause of macro-anomaly excitation is presented. The area over which underground water and hot spring anomalies are observed suggests that these anomalies reflect crustal strain changes on the order of 10^{-7} – 10^{-6} or larger. It is still not clear why and how animals react to strain changes of such an order.

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