Bull. Disas. Prev. Res. Inst., Kyoto Univ., Vol. 39, Parts 1, 2, No. 339, June, 1989

On the Duration Time of Aftershock Activity

By Kunihiko WATANABE

(Manuscript received on March 25, 1989)

Abstract

In order to discriminate between a period of aftershock activity and a period of usual seismic activity, it is important to know how long the aftershock activity continues. The aftershock activity of the Fukui earthquake (M7.1) which occurred in 1948 was compared with the present microearthquake activity in the Fukui plain, which was summarized by the Hokuriku Microearthquake Observatory of Disas. Prev. Res. Inst. of Kyoto University. As a result, the present seismicity is supposed to be not only the aftershock activity of the Fukui earthquake, but also the composite seismic activity of both the aftershock sequence and various other kinds of activities related to the pre-existing active faults. On the other hand, the aftershock activity of the Tottori earthquake (M7.2) in 1943 was analyzed by the same method as that of the Fukui earthquake. Nevertheless, it is not so clear whether the present seismicity in the Tottori region is the aftershock sequence of the Tottori earthquake or not.

The duration times of aftershock activities were estimated by investigating the present microearthquake activities in and around the aftershock areas of the past big earthquakes. The results are as follows:

a) After one hundred years or more have passed since the occurrence of the main event of M8 class, the aftershock activity becomes unrecognizable at the level of detectability of the present microearthquake networks.

b) Concerning earthquakes of M7 class, the aftershock activity becomes unrecognizable after fifty to one hundred years.

c) Concerning earthquakes of M6 class, the aftershock activity becomes unrecognizable after about thirty years.

1. Introduction

Large inland earthquakes are said to repeat with recurrence intervals of one to several thousands of years. On the other hand, little information concerning the whole cycle of a big inland earthquake has been obtained. In spite of this paucity of information, we have been making much effort to know the totality of large earthquake activity.

There are various seismological networks throughout the Japanese islands, and various seismicity maps have thus been obtained. If a period of seismic activity could be classified into foreshocks, swarms, aftershocks or usual activity, our perception about seismic activity would be much improved. If the seismic activity in some area is an aftershock sequence, this activity should decrease over time, and a subsequent big earthquake in and around this area will not likely occur in near future. On the contrary, if this activity is not an aftershock sequence, we should pay much attention to the nature of this activity, especially from the standpoint of earthquake prediction.

Omori presented a famous formula about the time dependent attenuation of the aftershock activity, the so-called "Omori's formula[1)]",

$$n(t)=K/(t+c), \qquad (K,\ c;\ \text{parameters}) \tag{1}$$

where $n(t)$ is the frequency of aftershocks per unit time interval at time t. Utsu (1957)[2)] made further investigations about aftershocks and presented a modified version of Omori's formula,

$$n(t)=K/(t+c)^{p}, \qquad (K,\ c,\ p;\ \text{parameters}) \tag{2}$$

where $n(t)$, K and c are the same as those in formula (1), while p concerns the degree of attenuation. Definition of the aftershock, however, is a fundamental problem. Yamakawa et al (1965)[3)] presented a method to distinguish usual activities from the aftershock sequence by evaluating the degree of deviation from the attenuation curve of aftershocks.

In order to ascertain whether a particular seismic activity is an aftershock sequence or not, two methods will be presented. One is to study the seismic activity in question precisely: Spatial distribution of hypocenters, applicability of the modified Omori's formula and the values of those parameters, Gutenberg-Richter's b-values, earthquake generating stress and some other parameters are to be synthetically investigated. It follows that much data would be necessary for this synthetic study. In many cases, this precise investigation can not be applied to historical earthquakes, because of insufficient data.

The other method is a statistical one which reveals the general tendency of the attenuation of aftershock activities by collecting many examples of aftershock sequences. In other words, if we can know the present aftershock activity of a certain big historical earthquake, it can be said that we can get individual datum about the attenuation of an aftershock activity at each time point after a lapse of time has passed since the occurrence of the historical earthquake in question. By superposing many examples of this kind of data with different lapse times, the nature of aftershock activity over a long interval is obtainable.

In this paper, whether the present microearthquake activity in the Fukui plain is an aftershock activity of the Fukui earthquake or not was investigated precisely as a test case of the first method. The seismic activity in the Tottori region was then investigated from the same standpoint, and was compared with that of the Fukui plain. Next, a criterion was defined, which concerns duration time of aftershock activity. The criterion is available to decide whether the present microseismic activity is the aftershock activity of a certain big earthquake or not.

2. Classiffication of seismic activities

With respect to time, seismic activities can be classified into the following four types,

a) usual activities,

b) earthquake swarms,

c) temporary activities related to big earthquakes, namely, foreshocks, the main shock and aftershocks,

d) usual aseismicity.

The purpose of this paper is to estimate the duration time of aftershock activity. If a certain seismic activity is an earthquake swarm or a foreshock sequence, the duration interval of such activity is usually relatively short and the frequency of earthquakes does not decrease monotonically with time. Furthermore, there should not be any main shock at the beginning of such activity. Thus, it is easy to distinguish earthquake swarms and foreshock activities. On the contrary, it is difficult to distinguish usual activity and an aftershock sequence without sufficient time series data.

For this distinction, we propose two kinds of conditions by which an earthquake activity can be regarded as an aftershock sequence. The first one is that aftershocks should occur in and around the fractured region of the main shock after its occurrence. The hypocenter distribution area in a relatively short interval after the main shock can be considered as the fractured area by the main shock. Regarding the Japanese inland earthquakes, Utsu (1969)[4] presented a formula,

$$\log A(\mathrm{km}^2) = M - 4.1 \tag{3}$$

which explains the relation between the magnitude (M) of the main shock and the aftershock area A (km^2). Precisely speaking, it is sometimes recognized that the aftershock area does not reach a constant level in a short interval. On the contrary in some cases, it is also recognized that the aftershock area does not expand finally to the size which is expected by formula (3). Generally speaking, as aftershocks are directly connected with the fracture of the main shock, they ought to occur in and around the fractured region. In this paper, the size of an aftershock area is assumed to be expressed by formula (3). Therefore, an earthquake which occurs far from the fractured region is not regarded as a direct aftershock, even though the earthquake can be considered to have been excited by the main shock. Although it is very attractive to investigate this type of earthquake, off-fault aftershocks[1], this problem is excluded from the present study.

The second condition is that the frequency of aftershocks should decrease with time. The decrease process of the aftershock frequency is usually examined by applying the modified Omori's formula, $n(t) = K/(t+c)^p$. The parameter p of this formula is considered to express the degree of attenuation of the aftershock activity. If the recent earthquake sequence in a certain area can be considered as the aftershock sequence of a historical big earthquake which had occurred in the area, the p-value obtained for this recent sequence might be the same as that obtained for the aftershock sequence immediately after the main shock. In other words, if both p-values are different from each other, the recent sequence might be a different one from the aftershock sequence immediately after the main shock.

For many cases, aftershocks satisfy these two conditions. In other words, whenever the seismic activity starts deviating from these two conditions, it can be said that other kinds of seismic activities have overlapped the aftershock sequence.

Some other ideas of defining some activity as an aftershock are now presented. One may be the idea that the stress field of an aftershock estimated by the fault plane solution is not contradictory to that of the main shock. The system of earthquake generating stress is usually derived from fault plane solutions. Nevertheless, if we adopt the hypothesis that the occurrence of an earthquake is restrained by the pre-existing fault, the direction of principal stress obtained from the fault plane solution does not necessarily coincide with the tectonic stress at the region. If we can imagine that there are many minor fractures whose directions are considerably random, the obtained stress field does not necessarily coincide with that obtained for the main shock. Therefore, the agreement of the stress field obtained by fault plane solutions to that of the main shock can not be a necessary condition.

One more idea is based upon the hypothesis that the earthquake sequences which belong to the same major event must show the same Gutenberg-Richter's b-value. Against this hypothesis, many researchers contend that the b-value might change with time[5,6]. So we think that the examination of b-value is not a decisive factor but only a reference.

3. Recent big earthquakes and present microearthquake activity

3.1 The Fukui earthquake

The Fukui earthquake ($M7.1$) occurred on June 28th, 1948, near Maruoka town, eastern part of the Fukui plain. The epicentral distribution according to the J.M.A. catalogue of one year succeeding the main shock is shown in **Fig. 1**[7]. According to formula (3), the aftershock area comes to 1,000 km^2. If the area is represented by

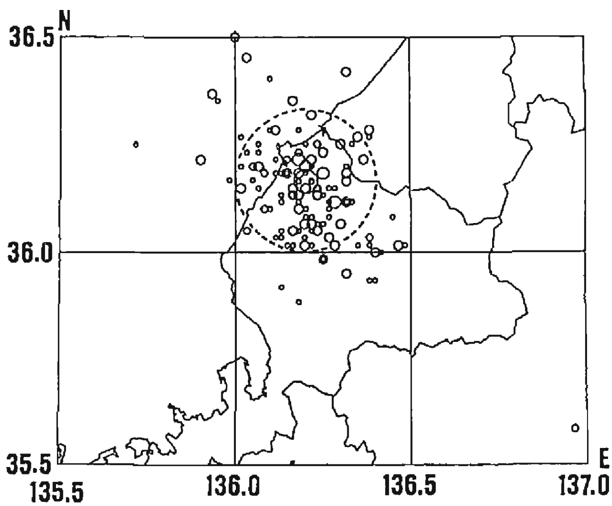

Fig. 1. Epicentral distribution by J.M.A. catalogue of two successive years to the Fukui earthquake of $M7.1$, which occurred in the eastern part of the Fukui plain in 1948. The aftershock area is calculated by using formula (3) and shown by a circle drawn with a dotted line.

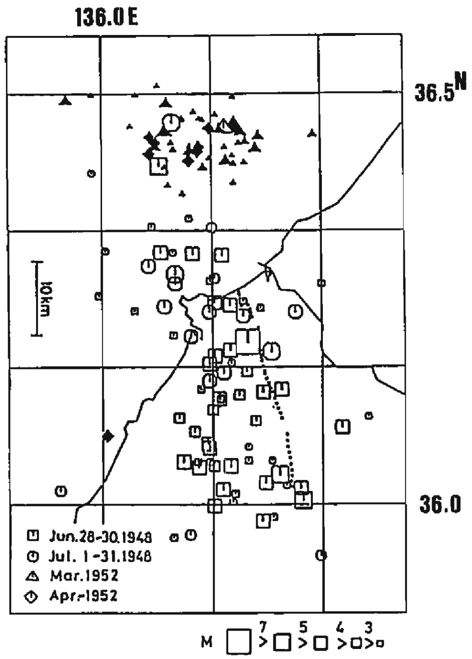

Fig. 2. Epicenters of the Fukui earthquake sequence (open symbols) and that of the Off Daishoji earthquake (solid ones). Both were relocated by Hamada (after Hamada (1987)[8]).

a circle, the radius comes to 17.8 km. In **Fig. 1**, the aftershock area is shown by a circle with center at the epicenter. Although the location of the hypocenters might involve considerable error, the epicenter distribution area in **Fig. 1** can be considered to amply denote the aftershock area. According to the hypocenters relocated by Hamada (1987)[8] (**Fig. 2**), the aftershock area is restricted between the southern edge of the Off Daishoji earthquake area to the north and the N36° line to the south.

Fig. 3 shows the epicentral distribution obtained according to the network of the Hokuriku Microearthquake Observatory from 1976 to 1985[9]. In the figure, the circle of the aftershock area drawn in **Fig. 1** is also shown. The active zone extending in north-south direction shown by a dotted parallelogram can be recognized in the eastern part of the Fukui plain. Near the northern end of this active zone, the Off Daishoji earthquake of $M6.5$ occurred in 1952. On the other hand, the southern part of this active zone has reached to the border zone between Fukui and Gifu prefectures, overstepping the southern end of the aftershock area of the Fukui earthquake shown by a circle. This southern active part seems to lie along a tectonic line which extends from the Fukui earthquake fault to the Neodani fault. Therefore, the microearthquake activity in the southern part of the present active zone is considered not to be the aftershock activity of the Fukui earthquake but some activity related to the pre-existing fault which had not moved at the Fukui earthquake.

The number of aftershocks will now be examined. The coefficient p of the

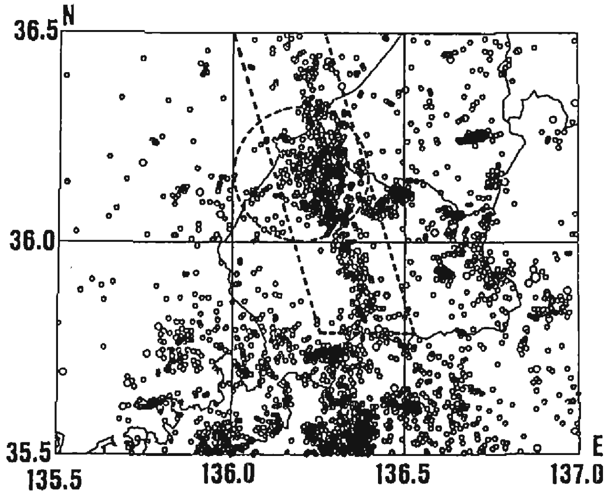

Fig. 3. Epicentral distribution in and around the Fukui plain from 1976 to 1985 obtained by the Hokuriku Microearthquake Observatory network. The aftershock area circle which is the same as in Fig. 1 is drawn with a dotted line and the present seismically active zone in the Fukui plain is shown by a parallelogram.

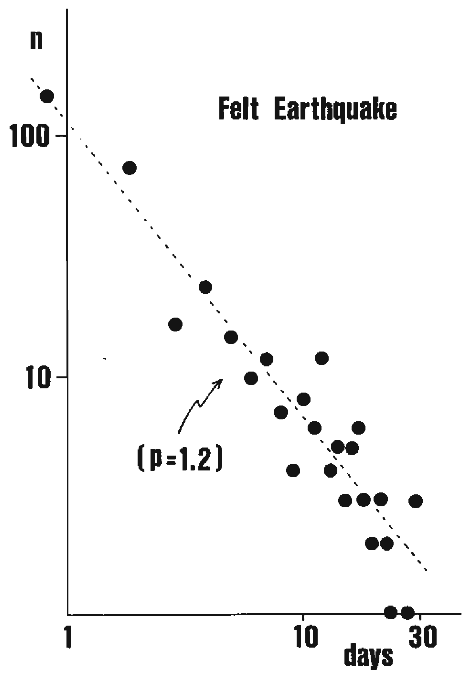

Fig. 4. The number of felt earthquakes versus lapsed time for the data of one month successive to the Fukui earthquake. The p-value of the modified Omori's formula was estimated at about 1.2 from this figure.

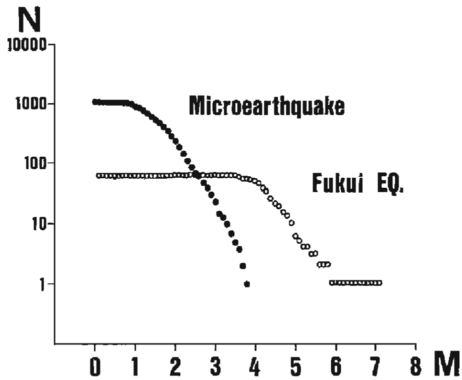

Fig. 5. Magnitude-frequency relations of the Fukui earthquake sequence (open circles) and the present microearthquake activity (solid circles). The *b*-value of the Fukui aftershock sequence without the main shock was estimated at 0.9 and that of the recent microearthquakes, 1.1.

modified Omori's formula was about 1.2 (**Fig. 4**) which was derived by using felt aftershock data within one month after the Fukui earthquake[10]. By adopting this *p*-value, the number of felt earthquakes expected in the Fukui plain at present, forty years after the main shock, becomes only once in 3.5 years. Utsu (1969)[4] and Ogata (1983)[11] obtained $p=1.3$ and $p=1.36$ respectively. By adopting these values, the expected number of felt earthquakes may be less than mentioned above. This rate of felt earthquakes is a little smaller than the real rate, so the present seismic activity can be supposed as a composite of the aftershock sequence and some other kinds of activities.

Next, the magnitude-frequency relation for the Fukui earthquake sequence and that for the present microearthquake activity will be discussed. Gutenberg-Richter's *b*-value calculated for the aftershocks of two years successive to the main shock is about 0.9 by using J.M.A. catalogue. In contrast, that calculated for the north-south active zone shown in **Fig. 3** by using microearthquake data obtained by the Hokuriku Observatory for these ten years is about 1.1 (**Fig. 5**). From **Fig. 5**, these two activities seem to be apparently different, but the difference of 0.2 between these two *b*-values is not significant by a statistical examination[12,13] because of the small quantity of aftershock data of forty years ago. Therefore, we could not distinguish these two activities by examining *b*-values.

In summary, it may be reasonable to consider that the active microearthquake activity recognized today is not only the aftershock activity of the Fukui earthquake but the overlapping composite activity by other kinds of seismic activities.

3.2 The Tottori earthquake

The Tottori earthquake ($M7.2$) occurred on September 10th, 1943 in the eastern part of Tottori Prefecture. The epicenters of aftershocks relocated by Hamada (1987)[8] are shown in **Fig. 6**. In the figure, the aftershock area which Hamada

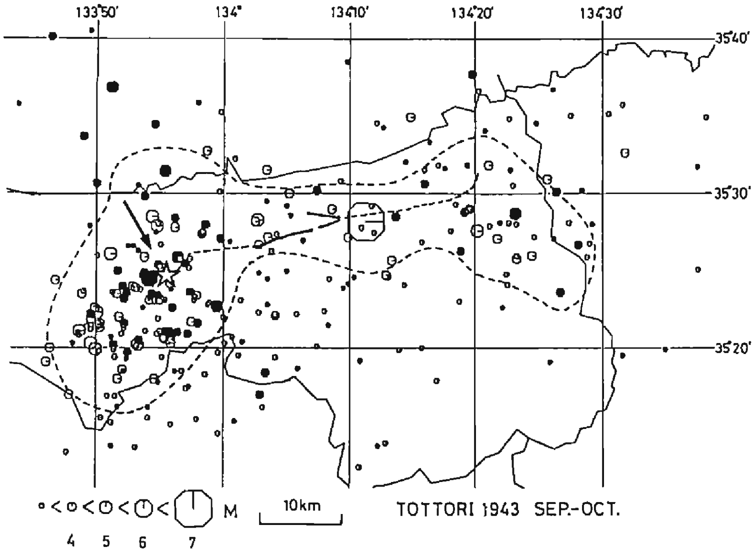

Fig. 6. Relocated epicenters of the Tottori earthquake sequence by Hamada (1987). Solid symbols indicate aftershocks within twenty four hours after the main shock, and open symbols, aftershocks by the end of October, 1943. The aftershock region defined by Hamada (1987)[8] is bounded with a dotted line. The epicenter of the Central Tottori Pref. earthquake in 1983 is also denoted by an open star with an arrow.

indicated is shown by a dotted line. A vigorous aftershock activity was recognized apart westward from the epicenter of the main shock. Forty years later, the Central Tottori Pref. earthquake of $M6.2$ occurred just in this area in 1983, which is shown by a star mark with an arrow in the figure. The fault strike of this earthquake was estimated to be almost perpendicular to that of the Tottori earthquake[14]. As a similar example to this fault strike relation, the fault strike of the biggest aftershock of the Western Nagano Pref. earthquake in 1984 was almost perpendicular to that of the main shock[15]. In this case, the biggest aftershock occurred one day after the main shock. But the Central Tottori Pref. earthquake occurred about forty years after the Tottori earthquake. Whether the earthquake in 1983 is an aftershock of the Tottori earthquake or not is a future problem.

The epicentral distribution in this region for these twenty years obtained by the Tottori Microearthquake Observatory[16] is shown in **Fig. 7**. This activity almost coincides with the aftershock activity of the Tottori earthquake indicated by Hamada. Only a small portion of the activity reaches westward beyond the aftershock region. The b-value of the aftershocks recorded by J.M.A. for two successive years after the main shock and that of the microearthquakes observed by the Tottori observatory for the past twenty years are illustrated in **Fig. 8**. Apparently, not so much difference is recognized between them, in comparison with the case between the aftershocks of the Fukui earthquake and the recent microearthquakes there.

Utsu (1967)[17] precisely investigated the attenuation of the number of felt after-

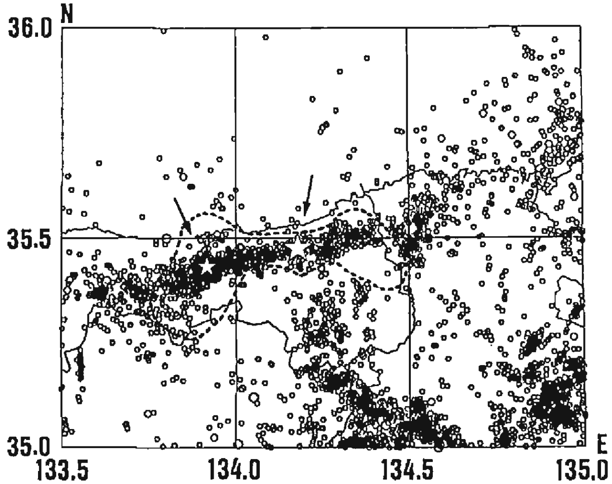

Fig. 7. Epicentral distribution in and around the Tottori plain from 1969 to 1987, obtained by the Tottori Microearthquake Observatory. The epicenter of the Tottori earthquake in 1943 is denoted by a big star with an arrow and that of the Central Tottori Pref. earthquake in 1983, by a small star with an arrow. The aftershock region of the Tottori earthquake defined by Hamada (1987)[8] is also shown by a dotted line.

shocks of the Tottori earthquake, and pointed out that the attenuation process could be explained by the modified Omori's formula even though fifteen years had already passed. The relation between magnitudes and occurrence time is shown in **Fig. 9**, including the data from 1885. From this figure, it may be recognized that the seismic energy has decreased monotonically in time, with the exception of the central Tottori earthquake sequence of 1983.

In summary, we could not resolve the problem whether the present microearthquake activity in the Tottori plain is the aftershock activity of the Tottori earthquake

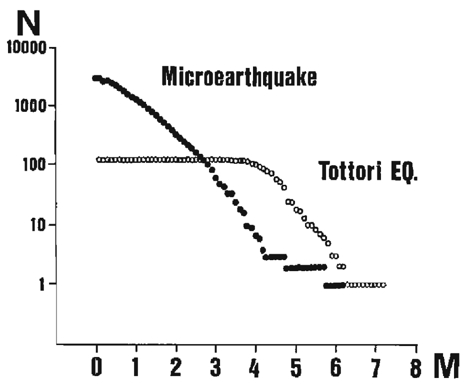

Fig. 8. Magnitude-frequency relations for the Tottori earthquake sequence (open circles) and for the present microearthquakes (solid circles). No significant difference between these two sequences could be recognized from this figure.

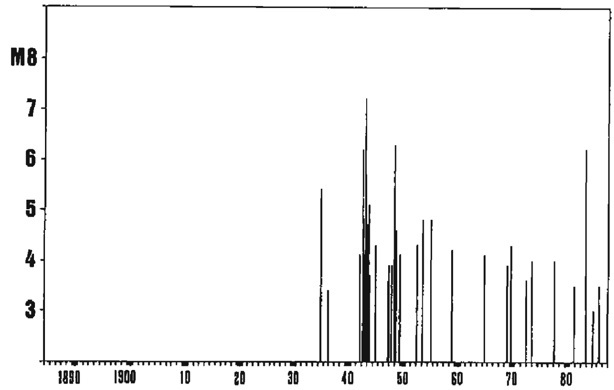

Fig. 9. Time series of the occurrence of the earthquakes greater than or equal to $M3.0$ in and around the Tottori plain.

or not. On the other hand, we could not find any evidence negating the idea that the present microearthquake activity is the aftershock activity of the Tottori earthquake.

4. Duration time of a past large earthquake

The Fukui earthquake occurred about forty years ago and the Tottori earthquake, about forty five years ago. As these two big earthquakes occurred in the modern seismological era, much modern seismological data are available to analyze these sequences. However, historical earthquakes can not be analyzed in the same way as the Fukui or the Tottori earthquake because we do not have sufficient modern seismological data about historical earthquakes to analyze their aftershock activities. In many cases, we only know the epicenters and the magnitudes of those historical earthquakes which have been estimated from the intensity distribution maps derived from paleographic survey. Other information we can use is the present seismic activity in and around the estimated aftershock area.

The purpose of this section is to determine the general relation between the duration time of the aftershock sequences and magnitudes of those main shocks by superposing many examples of present seismic activity on the estimated aftershock areas of various large historical earthquakes, including large ancient shocks which are known only through paleography.

4.1 Analyzed region and data

The analyzed regions are inside the two rectangles, namely central Japan and southwestern Japan, respectively. In these regions, historical seismic activity has been much investigated. Furthermore, there are so many microearthquake networks attached to universities that the microearthquake activity in these regions is known well. The bounds of these areas are as follows:

a) central Japan : 34°N–37°N, 135°E–140°E

b) southwestern Japan: 33°N–36°N, 131°E–136°E.

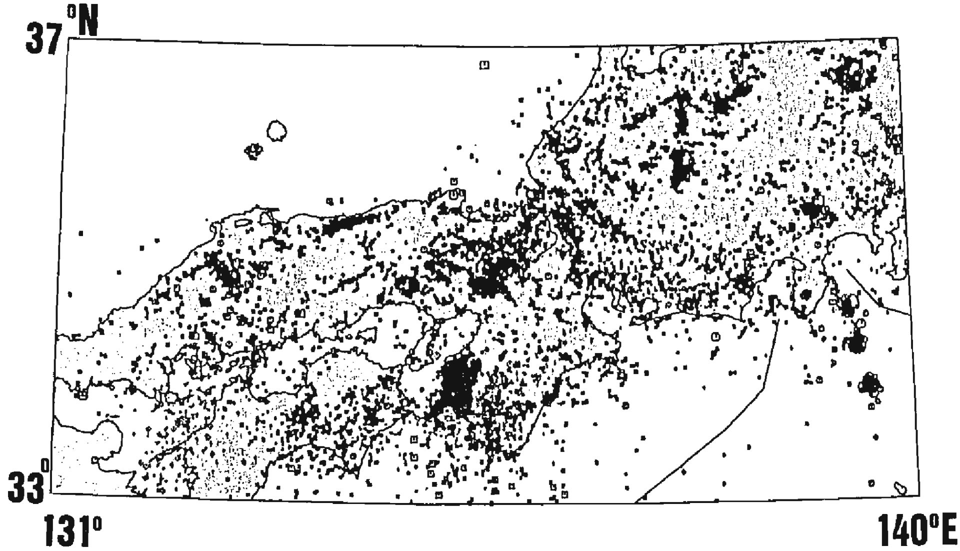

Fig. 10. Epicentral distribution of microearthquakes in 1983 in the concerned area compiled by E.R.I. of the University of Tokyo (after the pamphlet published by E.R.I., 1986)[19].

Aftershock activities of the large historical earthquakes which occurred in these two rectangles were investigated. More precisely, the historical disastrous earthquakes of $M \geqq 7$ listed in Usami's table[18] and the earthquakes of $M \geqq 6$ and $H \leqq 30$ km listed in the J.M.A. catalogue (from 1926 to 1982) were examined. The epicentral distribution of microearthquakes in 1983 (illustrated in the pamphlet published by E.R.I., 1986)[19,20] was adopted as a standard of the recent microearthquake activity (**Fig. 10**). The reason for this adoption is that the map is relatively homogeneous in the whole area, especially in the boundary zones between microearthquake networks. The J.M.A. data were utilized to decide whether the microearthquake activity in the region concerned is prevailing or temporary.

4.2 Analyzing method and results

The method of the analysis is as follows. Concerning a certain big historical earthquake, we calculated its aftershock area by using formula (3) and drew the circle of equivalent area with center at the epicenter. By repetition of this procedure, many circles of aftershock areas were drawn on a map. If several large earthquakes were closely located to one another with much overlapping, the aftershock activity that we could examine was assumed to be that of the most recent earthquake. When an actual aftershock area had been determined by observation, this knowledge was added in defining the aftershock area. The circles of aftershock areas are illustrated in **Fig. 11**.

Next, we will classify the degree of the present microearthquake activities in the aftershock areas. For this procedure, we need an epicentral distribution map of microearthquakes, which had been compiled homogeneously over the region con-

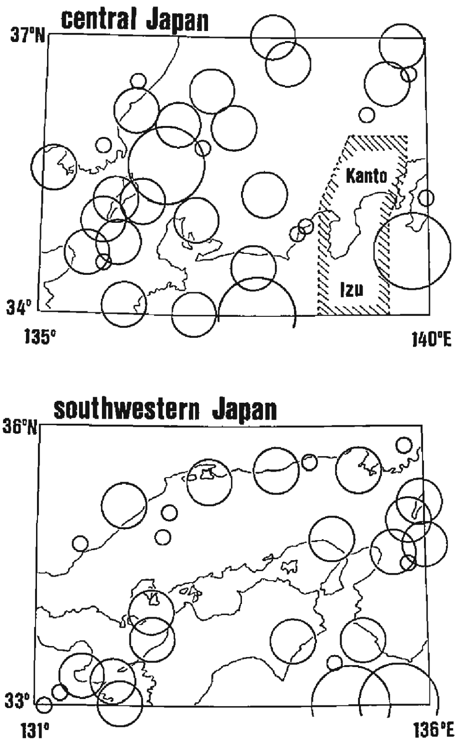

Fig. 11. Aftershock areas of the historical big earthquakes of $M \geqq 7$ listed on Usami's table[18] and those of the recent big ones of $M \geqq 6.0$ and $H \leqq 30$ km listed in the J.M.A. catalogue. All these earthquakes were roughly classified into three groups depending on their magnitudes. The size of each circle corresponds to the aftershock surface area of an earthquake of $M6.5$, $M7.5$ and $M8.0$, respectively.

cerned. For this standard microseismicity map, we used two kinds of microseismicity maps of 1983 mentioned above which were compiled by E.R.I.. Then, by superposing them on **Fig. 11** which is the map containing the aftershock area circles, we classified the present microearthquake activity in each aftershock area circle into three classes, namely,

a) more active than the surrounding areas,
b) as equal or slightly more active than the surrounding areas,
c) inactive or calm area.

The classification was made by visual judgment. After classifying the microearthquake activities in each aftershock area circle, we attempted to classify the present microearthquake activity (both (a) and (b)) into four types, namely: aftershocks, usually high or slightly high activity, swarm or foreshocks. Among these, most earthquake swarms and foreshocks could be easily distinguished by the reason given in Chapt. 2, but it was difficult to distinguish aftershock sequences from usually high activity.

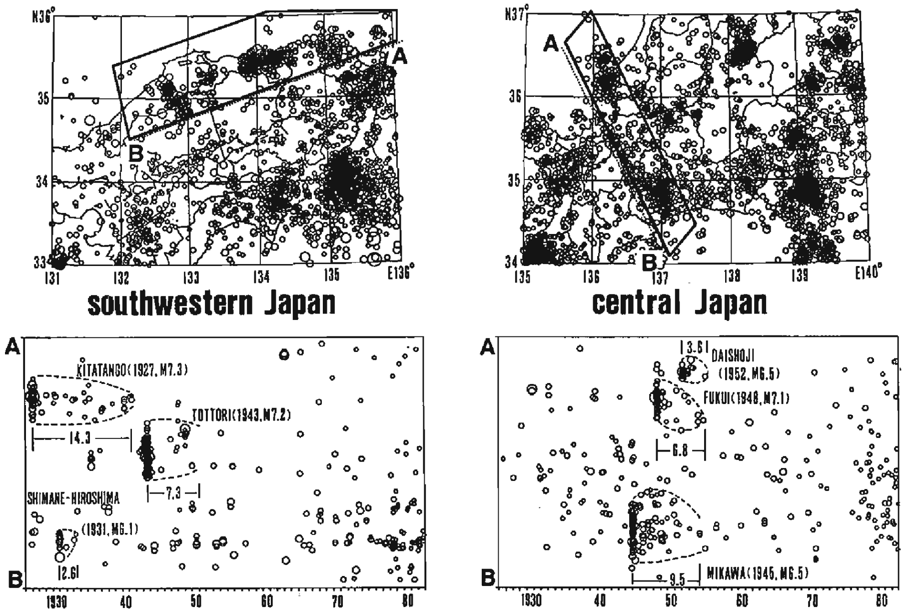

Fig. 12. The upper figures are the epicentral distributions by using J.M.A. catalogue. The lower figures are the time-space distributions of the earthquakes which occurred in the surrounding regions in the upper maps. The aftershock activities were estimated from these figures and surrounded by dotted lines.

One effective method for making this distinction is to compare the J.M.A. epicenter distributions over the course of time. Some examples of timespace distribution of J.M.A. epicenters are illustrated in **Fig. 12**. Six major earthquakes and their aftershock sequences can be recognized in the figures. The termination of the activities of the Tottori and Mikawa earthquakes do not seem to be clear. As for the Tottori earthquake, the seismic activity in the concerned region in southwestern Japan was relatively calm within a period of about five years before and after 1960. Therefore, the activity before this period has been somewhat emphasized visually in the figure. Taking account of this emphasis, we concluded that some earthquakes occurring after 1950 were not aftershocks, but usual activity. In the Mikawa region, the aftershock

Table 1. Duration times read from Fig. 12.

Year	Earthquake	Mag.	Duration time
1927	Kita-Tango	7.3	14.3 years
1931	Simane-Hiroshima	6.1	2.6
1943	Tottori	7.2	(7.3)
1945	Mikawa	6.8	(9.5)
1948	Fukui	7.1	6.8
1952	Off Daishoji	6.5	3.6

activity has been overlapped by the constant seismic activity caused by the Philippine Sea plate. Therefore, it is difficult to decide the end of the aftershock sequence. The duration times of aftershock activities of earthquakes of $M7$ class or less were taken directly from these figures and are listed in **Table 1.** These duration times are those which were defined on the earthquake detectability level of J.M.A. at that time.

From these results, concerning an earthquake of $M7$ class or less, a few years to more than ten years is needed for its aftershock activity to reach the same activity level as that of surrounding areas based on the J.M.A. catalogue. In other words, an activity that continues longer than dozens of years on the seismicity map of the J.M.A. catalogue can not be an aftershock activity of an earthquake of $M7$ class or less. By utilizing this detectability of the J.M.A. network, we tried to reject usual seismic activities. Namely, those activities which have continued for more than dozens of years in the J.M.A. catalogue are considered not to be the aftershock activities of earthwuakes of $M7$ class or less. Furthermore, microearthquake activity which is recognizedin that area is also considered not to be aftershock activity. However, we have yet no information about the duration time of aftershock activity for an earthquake of $M8$ class. There-

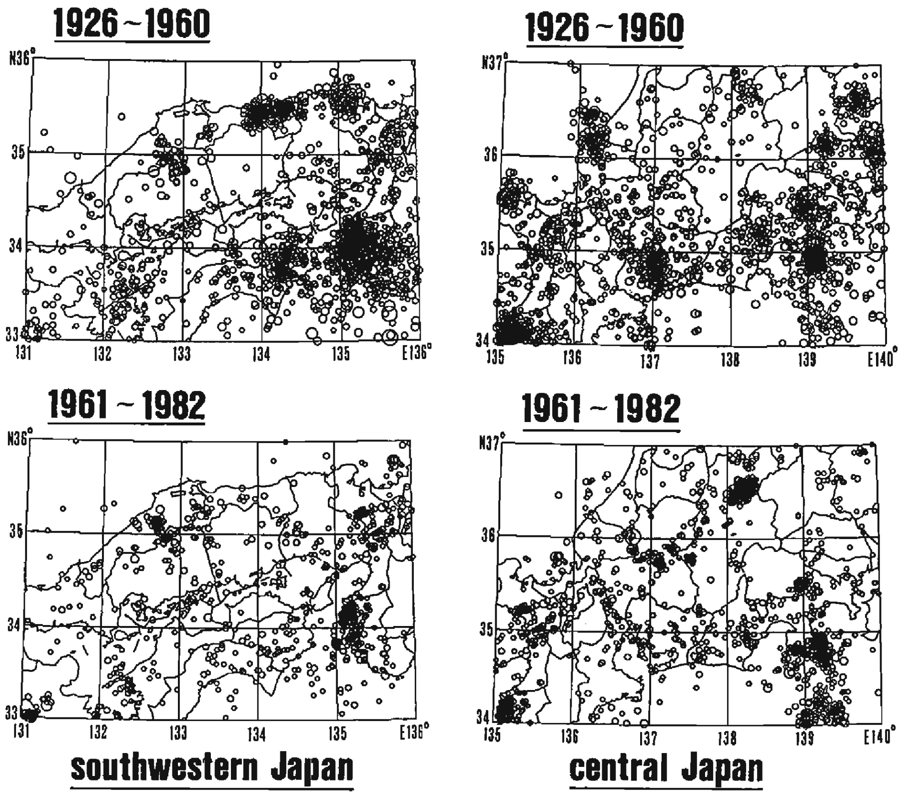

Fig. 13. The epicentral distributions for the two separated periods. Earthquakes of $M \geq 3.0$ and $H \leq 30$ km are plotted. Comparing these separated maps with the seismicity maps of Fig. 12, the seismic activity variation with time can be clearly recognized.

fore, if any earthquake of $M8$ class had occurred in the area earlier, the possibility that the present seismic activity is an aftershock sequence still remains.

In order to simply put this procedure into effect, we divided the J.M.A. catalogue into two periods of data sets. The former set consists of the data from 1926 to 1960 and the latter, from 1961 to 1982 (**Fig. 13**). Then, any activity which was recognized as existing through both periods was considered not to be an aftershock activity of an earthquake of $M7$ class or less because of too long a duration time. Consequently, present microearthquake activity can be considered not to be an aftershock sequence but usual activity. On the other hand, any activity which terminated within either one of these periods still has a possibility of being an aftershock activity. In this case, even if there is no seismic activity presently recognized in the J.M.A. catalogue, present microearthquake activity, if being recognized, has a possibility to be an aftershock sequence. For earthquakes which occurred near the end of the former

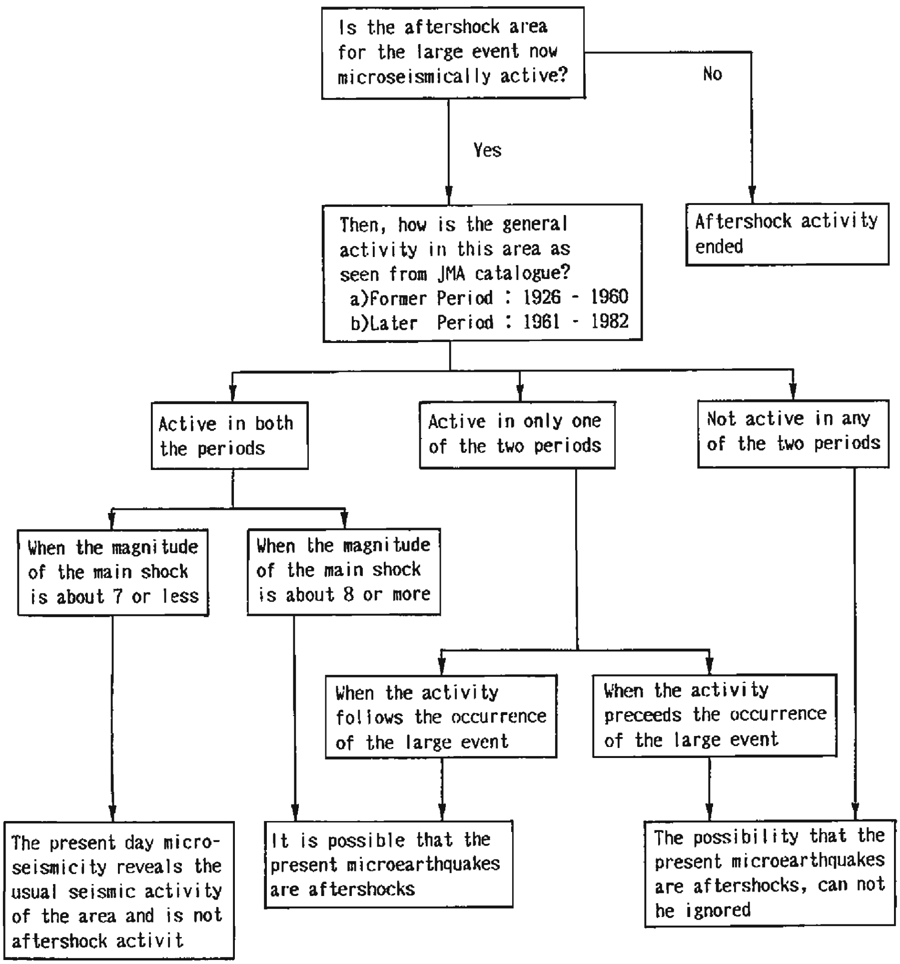

Fig. 14. Flow chart for the classification of earthquake activities.

Table 2. The results of the classification for central Japan (a) and southwestern Japan (b). The earthquakes with * are listed in both tables. Classified activity is shown by A, B and C according to the notation mentioned in chapt. 4.2 for the two periods of the J.M.A. catalogue and the microearthquake activity respectively. Following Fig. 14, the judgment was carried out and those results are shown by ○, △ and ×. The present microearthquake activity shown by (—) is judged as the usual. An arrow means that the seismic activity of the earthquake is related to the earthquake which occurred in the year shown by the arrow. [ ] means that the microearthquake activity in the related area has not been obtained so accurately, because the area is located outside of the networks.

(a) *Central Japan*

Year	before 1985	M	region	JMA former	JMA latter	micro-seismic activity	judge-ment	references
599*	1386	7.0	N Nara					→ 1854
715	1270	7.0	SW Shizuoka					→ 1718
745	1240	7.9	Shiga Gifu					→ 1891
762	1223	7.0	W Nagano	B	A	A	—	usually active
818	1167	7.5	Tochigi Gunma	A	A	A	—	usually active
841	1144	7.0	E Shizuoka					Izu
863	1122	7.0	SW Niigata	B	B	B	—	usually active
878	1107	7.4	Kanagawa					Izu
938*	1047	7.0	Kyoto Osaka					→ 1185
1096	889	8.3	S off Shizuoka					→ 1854
1185*	800	7.4	Kyoto Osaka	A	A	A	—	usually active
1241	744	7.0	Tokyo Bay					Kanto
1257	728	7.3	Sagami					Kanto
1293	692	7.0	Tokyo Bay					Kanto
1433	552	7.0	Sagaminada					Kanto
1498	487	8.3	S off Shizuoka					→ 1854
1586	399	7.8	Fukui Gifu					→ 1961
1596*	389	7.5	Osaka	C	C	C	×	
1633	352	7.0	Sagami Bay					Kanto
1648	337	7.0	Sagami Bay					Kanto
1649	336	7.0	Tokyo					Kanto
1662*	323	7.4	NW Shiga	A	A	A	—	usually active
1683	302	7.0	N Tochigi	B	B	B	—	usually active
1703	282	8.1	SE off Boso	C	C	[C]	[×]	
1718	267	7.0	S Nagano	C	C	C	×	
1782	203	7.0	Kanagawa					Izu
1819	166	7.3	SE Shiga	C	C	C	×	
1847	138	7.4	N Nagano	A	A	A	—	Matsushiro swarm
1854*	131	7.3	N Nara	C	C	C	×	
1854	131	8.4	SE off Kii	C	C	[C]	[×]	(Ansei EQ.)
1855	130	7.3	Enshunada	C	C	[C]	[×]	
1858	127	7.1	Toyama Gifu	C	C	B	△	
1891	94	8.0	SW Gifu	A	C	A	○	
1894	91	7.4	Mikawa Bay	A	A	B	—	usually active

Year	before 1985	M	region	JMA former	JMA latter	micro-seismic activity	judge-ment	references
1894	91	7.0	Tokyo					Kanto
1899	86	7.0	S Mie	C	C	C	×	
1906	79	7.6	SE off Kii	A	C	[B]	[△]	
1923	62	7.9	Sagami Bay					Kanto
1924	61	7.3	Kanagawa					Izu
1926	59	6.3	S Boso Pen.	B	C	C	×	
1927*	58	7.3	N Kyoto	A	C	B	△	(Kita-Tango EQ.)
1927	58	6.3	N Kyoto					→ 1927
1927	58	6.0	N Kyoto					→ 1927
1927*	58	6.5	N Kyoto					→ 1927
1929	56	6.3	E Yamanashi					Kanto
1930	55	6.3	Fukui					→ 1948
1930	55	7.3	Izu					Izu
1931	54	6.3	W Saitama					Kanto
1931	54	6.3	E Yamanashi					Kanto
1931	54	6.9	W Saitama	A	C	B	△	
1934	51	6.3	SE Gifu					→ 1891
1935	50	6.4	central Shizuoka	B	B	C	?	
1936*	49	6.4	N Nara	A	C	C	×	
1936	49	6.3	near Niijima					Izu
1941	44	6.1	N Nagano					→ 1847
1944	41	6.1	SE off Kii					→ 1906
1944	41	6.3	near Niijima					Izu
1945	40	6.8	Mikawa Bay					→ 1894
1945	40	6.3	central Aichi					→ 1894
1948	37	7.1	Fukui	A	B	A	○	(Fukui EQ.)
1949	36	6.2	N Tochigi					→ 1949
1949	36	6.4	N Tochigi	A	C	B	△	
1952	33	6.5	NE off Hokuriku	A	B	B	△	(Off Daishoji EQ.)
1957	28	6.0	near Niijima					Izu
1961	24	7.0	Fukui-Gifu	C	A	A	○	
1963*	22	6.9	E Wakasa Bay	C	A	A	○	
1965	20	6.1	central Shizuoka	C	A	A	○	
1969	16	6.6	SE Gifu	B	A	A	—	usually active
1972	13	6.0	Fukui-Gifu					→ 1891
1974	11	6.9	S Izu					Izu
1978	7	7.0	Izu-oshima					Izu
1980	5	6.7	E off Izu					Izu

(b) *Southwestern Japan*

Year	before 1985	M	region	JMA former	JMA latter	micro-seismic activity	judge-ment	references
599*	1386	7.0	N Nara					→ 1854
868	1117	7.0	SW Hyogo	B	B	B	—	usually active
880	1105	7.0	W Tottori	B	A	C	?	
887	1098	8.3	S off Kii					→ 1854
938*	1047	7.0	Kyoto Osaka					→ 1185
1099	886	8.2	S off Kii					→ 1946
1185*	800	7.4	Kyoto Osaka	A	A	A	—	usually active
1331	654	7.0	Kii channel	A	A	B	—	usually active
1361	624	8.4	S off Kii					→ 1854
1408	577	7.5	S off Kii					→ 1946
1498	487	7.3	Bungo channel					→ 1769
1520	405	7.4	S off Kii					→ 1946
1596	389	7.0	Iyonada	C	C	[C]	[×]	
1596*	389	7.5	Osaka	C	C	C	×	
1605	380	7.9	SE off Shikoku					→ 1854
1614	371	7.3	S off Kii					→ 1946
1649	336	7.0	Iyonada	A	B	[C]	?	
1662*	323	7.4	NW Shiga	A	A	A	—	usually active
1686	299	7.2	Akinada					→ 1857
1707	278	8.4	S off Kii					→ 1946
1769	216	7.8	Bungo channel	B	B	[C]	[?]	
1789	196	7.0	Tokushima	A	A	A	—	usually active
1854*	131	7.3	N Nara	C	C	C	×	
1854	131	8.4	SE off Kii	C	C	[C]	[×]	(Ansei EQ.)
1854	131	7.4	Bungo channel	B	C	[C]	[×]	
1857	128	7.3	Akinada	B	C	[C]	[×]	
1872	113	7.1	Off W San'in	C	C	[C]	[×]	(Hamada EQ.)
1927*	58	7.3	N Kyoto	A	C	B	△	(Kitatango EQ.)
1927	58	6.3	N Kyoto					→ 1927
1927	58	6.0	N Kyoto					→ 1927
1927*	58	6.5	N Kyoto					→ 1927
1930	55	6.1	Shimane-Hiroshima	B	C	C	×	
1936*	49	6.4	N Nara	A	C	C	×	
1938	47	6.8	S off Kii					→ 1946
1941	44	6.2	Off W San'in	B	C	[C]	[×]	
1943	42	6.2	E Tottori					→ 1943
1943	42	6.2	E Tottori					→ 1943
1943	42	7.2	E Tottori	A	C	A	○	
1943	42	6.0	E Tottori					→ 1943
1943	42	6.2	E Tottori					→ 1943
1946	39	8.0	S off Kii	B	B	[A]	[○]	(Nankai EQ.)
1946	39	6.3	S off Kii					→ 1946

Year	before 1985	M	region	JMA former	JMA latter	micro-seismic activity	judge-ment	references
1946	39	6.0	S off Kii					→ 1946
1947	38	6.2	S off Kii					→ 1946
1947	38	6.2	SE off Shikoku					→ 1946
1947	38	6.1	S off Kii					→ 1946
1948	37	7.0	S off Kii					→ 1946
1948	37	6.7	S. Wakayama	A	A	A	—	usually active
1949	36	6.3	N Hyogo	A	C	B	△	
1950	35	6.7	SE off Shikoku	A	B	[C]	[×]	
1955	30	6.4	Tokushima					→ 1789
1963*	22	6.9	E Wakasa Bay	C	A	A	○	
1975	10	6.1	NE Kumamoto	A	A	[C]	?	
1975	10	6.4	northern Oita	A	A	[C]	?	
1978	7	6.1	Shimane-Hiroshima	B	A	A	—	usually active

period, the analyses were carried out as circumstances required. The flow of this consideration is illustrated in **Fig. 14**.

According to the detectability of microearthquake networks of universities, whether the aftershock activity is continuous or already finished was judged by this procedure. The results of this judgment are listed in **Table 2** and illustrated in **Fig. 15**. The horizontal axis denotes the lapse time in years from the occurrence of a big earthquake and the vertical axis denotes the magnitude of that earthquake. The judged results are illustrated by following symbols, namely, ○; possibility of being aftershock activity is high, △; the possibility can not be ignored, but the present microearthquake activity is not so high, ×; aftershock activity has already finished.

In both the Kanto and Izu regions, seismic activities are usually too high to investigate the duration time of aftershock activity by this method, so we excluded both regions from this analysis. The aftershock areas of the earthquakes with [ ] are located outside of any of the microearthquake networks and thus the microearthquake activities in those areas could not be grasped precisely, so that the results of this analysis are not so accurate.

4.3 Discussion

According to **Fig. 15**, there is a tendency revealed wherein the bigger the main shock is, the longer the duration time becomes. By this method of analysis, it is difficult to distinguish aftershock activities and some other kinds of seismic activities perfectly. Nevertheless, when there is no microearthquake activity recognized in the aftershock area, it is clear at least that the aftershock activity has already finished. Therefore, it can be said that × symbols are more significant than ○ and △ symbols in **Fig. 15**. This means that **Fig. 15** does not emphasize the duration time of aftershock activity but shows the period after which aftershock does not occur.

If the following three parameters are known, namely, the p-value of modified

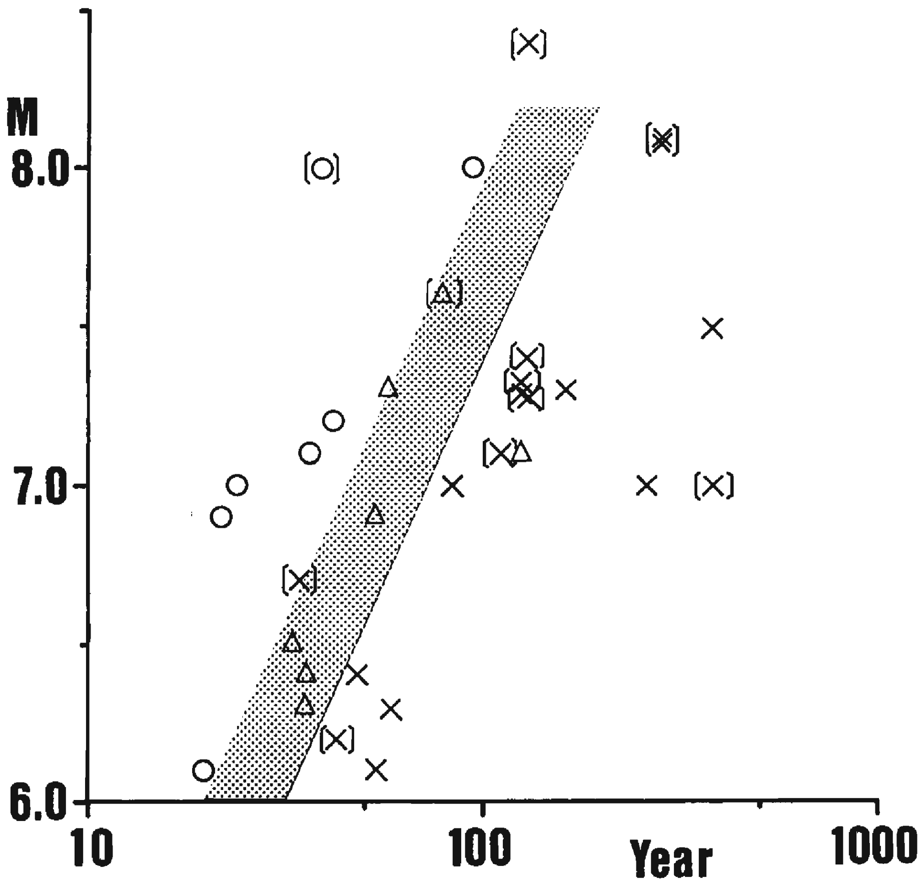

Fig. 15. The vertical axis denotes magnitudes and the horizontal one denotes lapse intervals from those occurrences. The results whether aftershocks are active or not are illustrated by symbols of ○, △ and ×. The meanings of the symbols are: ○—the possibility of aftershocks is fair; △—the possibility can not be ignored; ×—aftershock activity has already ended.

Omori's formula for the main shock sequence, the Gutenberg-Richter's *b*-value about the present activity in the aftershock area and the detectability of the microearthquake networks, the number of aftershocks expected in the area at present can be calculated. By comparing the calculated number with that of the observed ones, the judgment can be done whether present activity is an aftershock sequence or not. Nevertheless, it is reasonable to consider that any *b*-value is not always constant but changes with time. Furthermore, a *p*-value may also depend on the detectability of the observing station or on the epicentral distance from the station[21]. Consequently, it is unreliable to estimate present seismic activity by taking into account both the *b*-value of Gutenberg-Richter's relation and the *p*-value of the modified Omori's formula.

On the other hand, there is another reasonable idea for estimating the aftershock duration time and thus determine the end of an aftershock activity. This is when the decreasing rate of earthquake frequencies deviates from the attenuation curve obtained for aftershocks just after the main shock.

5. Conclusions

The results of the present paper are as follows;

a) Concerning a big earthquake of *M*8 class, according to the usual detectability of microearthquake networks of universities, aftershock activity is regarded to be finished after one hundred to two hundred years.

b) In the case of *M*7 class earthquakes, aftershock activity may finish after about one hundred years.

c) In the case of *M*6 class earthquakes, aftershock activity will finish after about thirty years.

d) Concerning an earthquake of *M*7 class or less, the aftershock activity does not continue longer than dozens of years when the J.M.A. catalogue is used.

The method explained in this paper is to estimate the aftershock duration roughly by using many examples of aftershock sequences, and not adopting Gutenberg-Richter's relation nor the modified Omori's formula. The aftershock activity may have regionality, which was not treated in this paper. The regionality of seismic activity is an important problem and should be investigated, especially for earthquake prediction.

The author would like to thank Mr. Yuzo Ishikawa of the Seismological Observatory, J.M.A. and our colleagues of the Tottori and the Hokuriku Observatories of Disas. Prev. Res. Inst. of Kyoto University for permitting us to quote their observed data and computer programs. The author thanks Dr. Yasuhiro Umeda of the Abuyama Seismological Observatory, Faculty of Science of Kyoto University, Prof. Yoshimichi Kishimoto and Mr. Fumiaki Takeuchi of the Microearthquake Research Section of Disas. Prev. Res. Inst. of Kyoto University for their encouragement and critical reading of the text. The author also thanks the members of the Microearthquake Research Section of Disas. Prev. Res. Inst. of Kyoto University for their valuable discussion.

References

1) Utsu, T. (Editor): Zishin no Jiten, Asakura Shoten, 1987, pp. 152–153 (in Japanese).
2) Utsu, T.: Magnitude of Earthquakes and Occurrence of their Aftershocks, Jour. Seis. Soc. Japan, Vol. 10, No. 1, 1957, pp. 35–45 (in Japanese).
3) Yamakawa, N., M. Homae and E. Kobayashi: Aftershock Activity and Normal Seismic Activity, Jour. Seis. Soc. Japan, Vol. 18, 1965, pp. 68–81 (in Japanese).
4) Utsu, T.: Aftershock and Earthquake Statistics (I)—Some Parameters Which Characterize an Aftershock Sequence and Their Interrelations—, Jour. Fac. Sci. Hokkaido Univ., Ser. 7, Vol. 3, No. 3, 1969, pp. 129–195.
5) Nishida, R.: Variation of the Parameter "m" in the Ishimoto-Iida's Relation on the Matsushiro Earthquake Swarm, Jour. Seis. Soc. Japan, Vol. 23, 1970, pp. 142–151 (in Japanese).
6) Imoto, M.: Time-Space Variations of the Magnitude-Frequency Relation in the Tokai Area,

Jour. Seis. Soc. Japan, Vol. 40, 1987, pp. 19–26 (in Japanese).
7) Ishikawa, Y., K. Matsumura, H. Yokoyama and H. Matsumoto: SEIS-PC—its outline—, Geol. Data Proc., Vol. 10, 1985, pp. 19–34 (in Japanese).
8) Hamada, N.: Re-Examination of Seismicity Associated with Destructive Inland Earthquakes of Japan and Its Seismological Significance, Papers in Meteorology and Geophysics, Vol. 38, No. 2, 1987, pp. 77–156 (in Japanese).
9) The Hokuriku Microearthquake Observatory: Personal communications.
10) Fukui city: "Fukui Resshinshi", 1978 (in Japanese).
11) Ogata, Y.: Estimation of the Parameters in the Modified Omori Formula for Aftershock Frequencies by the Maximum Likelihood Procedure, Jour. Phys. Earth, Vol. 31, No. 2, 1983, pp. 115–124.
12) Utsu, T.: Some Problems of the Frequency Distribution of Earthquakes in Respect to Magnitude (II), Geophysical Bull. Hokkaido University, Vol. 18, 1967, pp. 53–69.
13) Aki, K.: Maximum Likelihood Estimate of b in the Formula $\log N = a - bM$ and its Confidence Limits, Bull. Earthq. Res. Inst. University of Tokyo, Vol. 43, 1965, pp. 237–239.
14) Nishida, R.: The Mechanism of Occurrences of the Main Shock and Aftershocks of the 1983 Tottori Earthquake and their Relation to the Tectonic Stress Field, Jour. Fac. Gen. Edu. Tottori University, Vol. 22, 1988, pp. 77–116.
15) School of Science, Nagoya University: The Western Nagano Pref. Earthquake, 1984, Report of the Coordinating Committee for Earthquake Prediction, vol. 33, 1985, pp. 123–134 (in Japanese).
16) The Tottori Microearthquake Observatory: Personal communications.
17) Utsu, T.: Yoshin no Jikanteki Bunpu, Spec. Issue, Jour. Seis. Soc. Japan, Vol. 20, No. 4, 1967, pp. 141–142 (in Japanese).
18) Usami, T.: Materials for Comprehensive List of Destructive Earthquakes in Japan, Tokyo University Press, 1987 (in Japanese).
19) Earthquake Research Institute: Earthquake Prediction Data Center (Pamphlet), 1986 (in Japanese).
20) Earthquake Research Institute: Jishinn wo saguru (Pamphlet), 1986 (in Japanese).
21) Otsuka, M. and O. Tanaka: Curve Fitting of Omori's Formula to Aftershock Activity (I)—Effects of the Observing Conditions—, Jour. Seis. Soc. Japan, Vol. 40, 1987, pp. 51–55 (in Japanese).