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38. *Some Discussions on Aftershocks, Foreshocks and Earthquake Swarms—the Fracture of a Semi-infinite Body Caused by an Inner Stress Origin and Its Relation to the Earthquake Phenomena (Third Paper).*

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1. Introduction.

It has been widely believed among seismologists that earthquakes may be caused by fractures or fracture-like phenomena in the earth's crust and the upper mantle. However, earthquake phenomena have not been investigated from the standpoint of fracture physics. The present author wants to emphasize the above-mentioned standpoint and has been trying to show that a careful investigation of the brittle fracture of materials gives a clear understanding of earthquake phenomena[1)-3)]. The fracture model investigation of earthquake phenomena is made in the following way (Fig. 1).

(i) It is assumed that earthquakes are caused by brittle fracturing of the stressed earth's crust or the upper mantle. Under this assumption, a question of the mechanism of earthquake occurrence comes to that of fracture occurrence.

(ii) Experimental studies on fracture phenomena which seem to have close relations with seismological phenomena are carried out in laboratories.

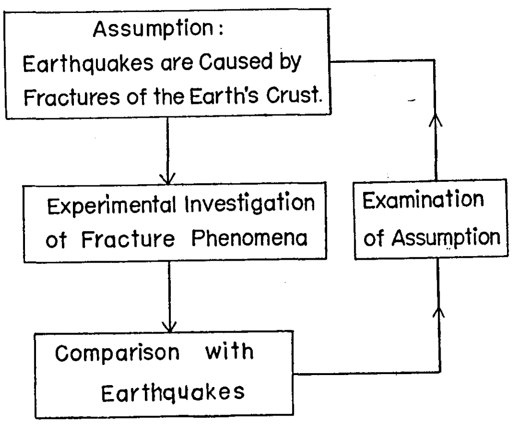


Fig. 1.

1) K. MOGI, *Bull. Earthq. Res. Inst.*, **40** (1962), 125-173.
2) K. MOGI, *Bull. Earthq. Res. Inst.*, **40** (1962), 831-853.
3) K. MOGI, *Bull. Volcanologique*, **26** (1963), 197-208.

(iii) The experimental results are compared with observed results of earthquakes. From this comparison, various seismological problems are clarified. Some new plans for seismic observations are suggested from the experimental results of fracturing.

(iv) The questions whether or not the above-mentioned primary assumption as to the nature of earthquake mechanism may be accepted, or whether or not the assumption should be modified, are examined. Then, the primary or the modified assumption is taken forward to the next step.

In previous papers[4], it has been experimentally clarified that the magnitude-frequency relation of elastic shocks accompanying fractures and the patterns of successive occurrence of elastic shocks are remarkably influenced by heterogeneous structures of materials. In preceding papers[5][6] of this series, the patterns of successive shock occurrence have been experimentally investigated on some model materials and their mechanism has been made clear. In this paper, this conclusion is applied to the related problems in seismology, that is, the occurrence of aftershocks, foreshocks and earthquake swarms. Then, it is shown that the distribution of the regions where these types of earthquake sequence frequently appear is closely related to the mechanical structures of the earth's crust and mantle, in and near Japan.

Systematic investigations on the patterns of earthquake sequence do not seem to have been carried out, except for aftershock sequences[7]-[9].

2. The mechanism of various patterns of earthquake sequences.

According to the experimental investigations[10], the frequency curves of the elastic shocks accompanying fractures of a semi-infinite body containing an inner origin of increasing stress, are schematically represented in Fig. 2. The types of shock sequences have a close relation with structural states of materials and space distributions of applied stresses, as shown in the same figure. On the other hand, earthquakes are also classified into the above-mentioned three types, as seen in a later section. Typical examples of these types in earthquakes are represented

4) K. MOGI, *loc. cit.*, 1)-3).
5) K. MOGI, *Bull. Earthq. Res. Inst.*, **40** (1962), 815-829.
6) K. MOGI, *Bull. Earthq. Res. Inst.*, **41** (1963), 595-614.
7) F. ŌMORI, *Rep. Imp. Earthq. Invest. Comm.*, **2** (1894), 103-139; **30** (1900), 4-29.
8) H. BENIOFF, *Bull. Seis. Soc. Amer.*, **41** (1951), 31-62.
9) T. UTSU, *Geophys. Magazine*, **30** (1961), 521-605.
10) K. MOGI, *loc. cit.*, 6).

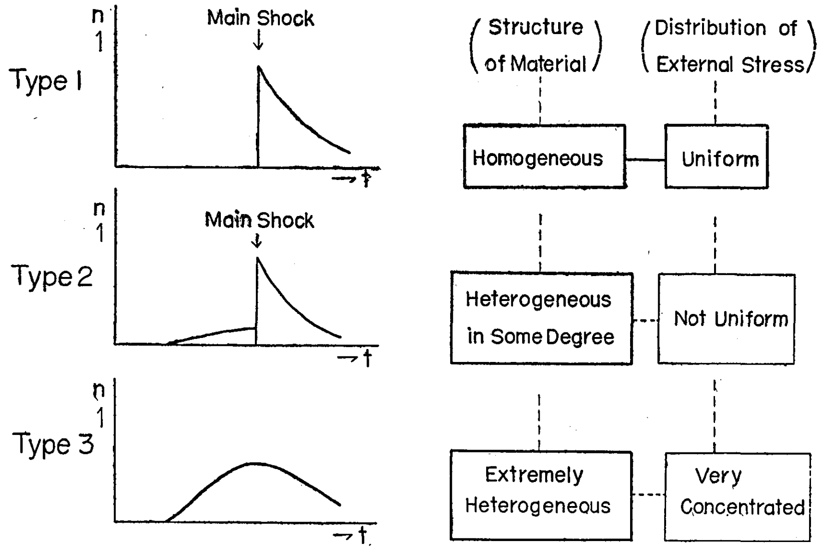


Fig. 2. Three types of the successive occurrence of the elastic shocks accompanying fractures and their relations to the structures of materials and the applied stresses.

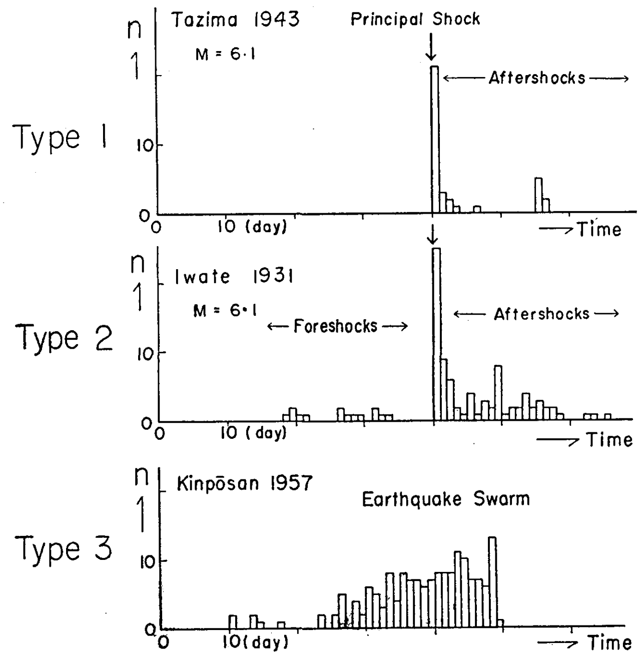


Fig. 3. Examples of the three types of earthquake sequence.

in Fig. 3. The relation of the pattern of successive shock occurrence to the structural state and the space distribution of stress may be applicable to earthquake sequences. Therefore, if an applied stress is assumed to increase gradually, the following results may be deduced.

(1) The first type pattern appears only at regions of homogeneous structure, caused by a uniformly applied stress.

(2) The third type pattern appears at remarkably fractured regions or it also may be caused by the concentrated application of stress (for example, by an intrusive stress by viscous magma).

(3) The second type pattern is an intermediate one between the first type and the third type. This pattern appears at regions of moderately heterogeneous structure or it may be caused by a stress which is not uniform.

Since these types of earthquake sequences are thought in many cases to be caused by structural states of the crust, the distribution of the regions where these type of earthquake sequences frequently appear is expected to give information about the mechanical structure of the Japanese islands, and the mutual relations among these three types are found in their space distribution. In the following sections, these problems are investigated.

3. Procedure of the investigation.

Most of the earthquakes listed in the "Catalogue of Major Earthquakes which occurred in and near Japan (1926–1956)" by the Japan Meteorological Agency are tested with respect to the following points.

(A) Whether or not an earthquake was followed by aftershocks. If it was followed by some aftershocks, their number was counted.

(B) Whether or not the seismicity at the epicentral region increased before the earthquake (namely, test of the presence of foreshocks).

These points are tested with data in the Geophysical Review and the Seismological Bulletin of the Japan Meteorological Agency. According to T. Utsu[11], as seismograph stations are located at intervals of about 80 km in Japan, the earthquakes in the land area of Japan are all observed by at least one station if their magnitude exceeds about 3. Therefore, in the present paper, aftershocks and foreshocks whose magnitudes are larger than 3 are investigated, although smaller aftershocks and foreshocks are expected to occur more frequently. The lower limit of registered earthquakes may not give an essential effect to the

11) T. UTSU, *loc. cit.*, 9).

following discussion, since the magnitude-frequency law of earthquake occurrence seems to be satisfied[12) 13)]. However, for earthquakes in the sea area, the lower limit of registration increases clearly. This is considered in the following procedure of investigation.

The above-mentioned tests were carried out for about 1500 earthquakes selected from the "Catalogue of Major Earthquakes" according to the following standard.

(a) An earthquake whose epicenter, depth h, and magnitude M are known.

(b) $M \geq 4$ for earthquakes in land area.
$M \geq 4.5$ for earthquakes in sea area.

(c) An earthquake which is not a foreshock or aftershock of another larger earthquake, or member of earthquake swarms.

However, earthquake sequences of a swarm type were independently investigated with data in the Geophysical Review and the Seismological Bulletin of the Japan Meteorological Agency. Earthquakes during the years 1957–1961 were similarly tested with recent data available in the Seismological Bulletin.

4. Aftershocks.

After a large earthquake, remarkable aftershocks frequently occur and their number and magnitude decrease gradually. The nature of such remarkable aftershocks has been studied statistically and physically by many seismologists[14–20)], and many valuable results have been obtained. However, some earthquakes are followed by many aftershocks, while other earthquakes of the same magnitude are not. Recently, the percentage of earthquakes followed by aftershocks has been obtained by T. Asada[21)] for earthquakes in the Kwanto district and by Utsu[22)] for earthquakes in and near Japan, and they discussed its relation to the

12) M. Ishimoto and K. Iida, *Bull. Earthq. Res. Inst.*, **17** (1939), 433-478.
13) B. Gutenberg and C.F. Richter, *Seismicity of the Earth*, (1954).
14) F. Ōmori, *loc. cit.*, 7).
15) O. Enya, *Rep. Imp. Earthq. Invest. Comm.*, **35** (1901), 35-56.
16) S. Kusakabe, *Publ. Earthq. Invest. Comm.*, **17** (1904), 1-48.
17) T. Matuzawa, *Zisin (Journ. Seis. Soc. Japan)*, [ii], **11** (1936), 15-24.
18) T. Matuzawa, *Bull. Earthq. Res. Inst.*, **32** (1954), 341-347.
19) H. Benioff, *loc. cit.*, 8).
20) T. Utsu, *loc. cit.*, 9).
21) T. Asada, *Zisin (Journ. Seis. Soc. Japan)*, [ii], **8** (1955), 1-7.
22) T. Utsu, *Zisin (Journ. Seis. Soc. Japan)*, [ii], **10** (1957), 35-45.

magnitude. However, the probability of aftershock occurrence varies remarkably in various regions. From a consideration of the mechanism of aftershock phenomena, the spatial distribution of this probability may be attributed to the difference of the crustal structure in various regions.

Here, the probability that an earthquake is followed by aftershocks is obtained for various regions in and near Japan and its spatial distribution is discussed. Furthermore, its relation to the magnitude of the principal shock and to the focal depth is statistically investigated.

(A) *The spatial distribution of the probability that an earthquake is followed by aftershocks.*

Figure 4 shows the distribution of epicenters of the earthquakes which were followed by at least a single aftershock (closed circles) and of the earthquakes which were not followed at all by aftershocks (open circles). Figures 4(a) and (b) are for shallower earthquakes ($0 \leq h < 30$ km) and deeper earthquakes ($30 \leq h \leq 60$ km), respectively. Question often arises whether or not a small earthquake after a larger one was an aftershock. Here, the aftershock is distinguished from other normal earthquakes according to the following standard.

(i) The epicenter of the aftershock locates nearly at the place of the principal shock or within an estimated aftershock region[23] of the principal shock.

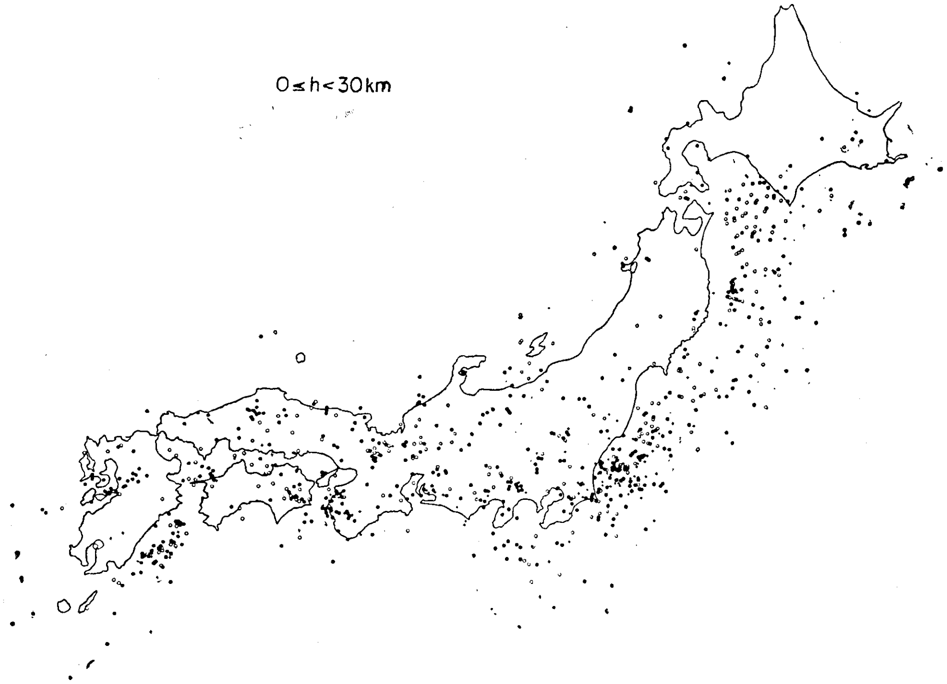
(ii) The aftershock follows immediately after the principal shock or takes place during an estimated aftershock duration.

(iii) The number of earthquakes expected in the normal seismic activity of the region is subtracted in the counting of the number of aftershocks.

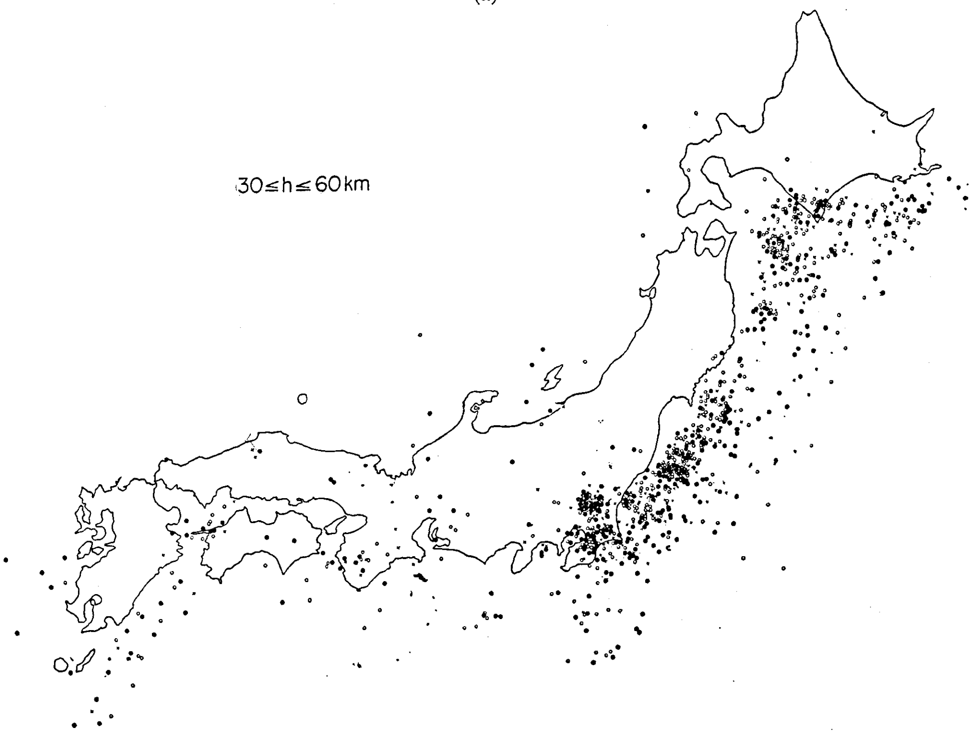
Therefore, in the calm state aftershocks are plainly distinguished from other normal earthquakes, but in active regions they frequently cannot be separated from the normal activity. The doubtful cases are indicated by (×) in Fig. 4. In sea area far off the Pacific coast of the north-east Japan, this test is sometimes impossible, because major earthquakes occur successively and the epicenters of small earthquakes in this region are not sufficiently clear.

In order to indicate the probability that an earthquake in a certain region is followed by aftershocks, the percentage $P(1)$ of the earthquakes followed by at least one aftershock to the total tested major earthquakes

23) T. UTSU, *loc. cit.*, 9).



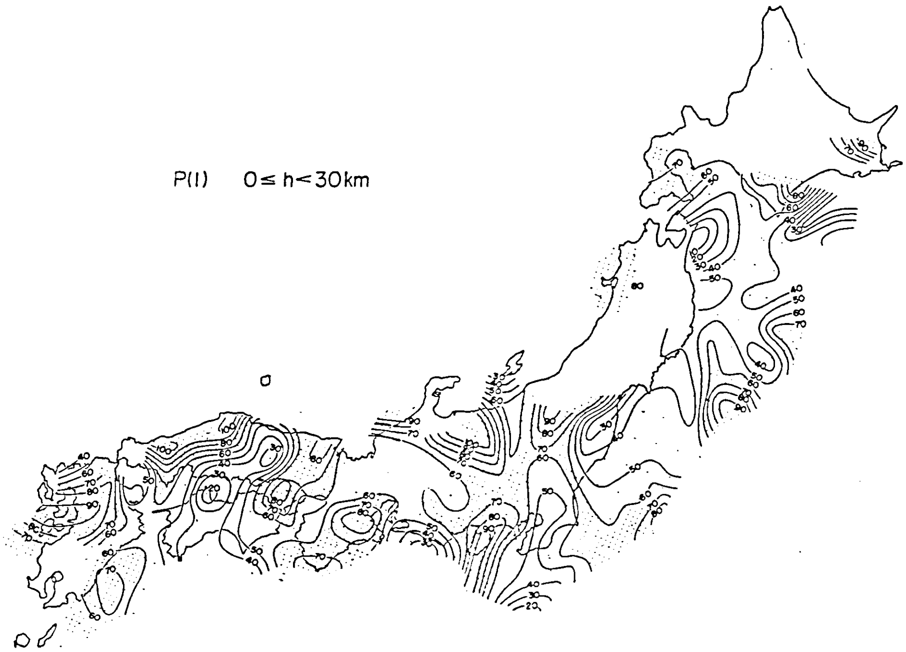
(a)



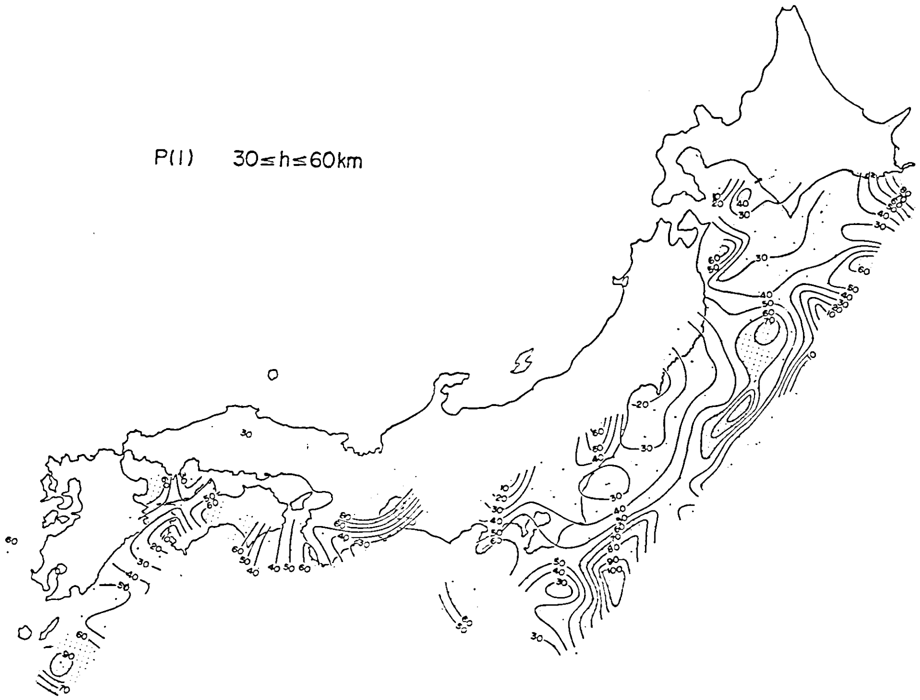
(b)

Fig. 4. The epicentral distribution of the earthquakes followed by at least one aftershock (closed circle) and of the earthquakes not accompanied by any aftershocks (open circle). (×: doubtful)

(a) Shallower earthquakes ($0 \leq h < 30$ km); (b) Deeper earthquakes ($30 \leq h \leq 60$ km).



(a)



(b)

Fig. 5. Distributions of the percentage $P(1)$ (%) of the earthquakes followed by at least one aftershock to total earthquakes occurred in a circular area of a diameter of 100 km. (a) $0 \leq h < 30$ km, (b) $30 \leq h \leq 60$ km.

in a circular area of a diameter of 100 km has been calculated from the above-mentioned epicentral distribution. Figures 5(a) and (b) show regional distribution of the probability $P(1)$ for the shallow earthquakes ($0 \leq h < 30$ km) and the deeper earthquakes ($30 \leq h \leq 60$ km), respectively. According to that, $P(1)$ is strikingly variable in various regions in and near Japan and the spatial distribution of $P(1)$ has clearly some relation to the geotectonic structures of the Japanese islands, as discussed in a later section.

Fig. 6. Distribution of epicenters of the earthquakes followed by at least 3 aftershocks (large closed circle) and other earthquakes (point). ($0 \leq h \leq 60$ km)

Figure 6 indicates the distribution of the epicenters of earthquakes which were followed by at least three aftershocks (large closed circles) and the other earthquakes (points) ($0 \leq h \leq 60$ km). The spatial distribution of the percentage $P(3)$ of the earthquakes followed by at least three aftershocks was also obtained as shown in Fig. 7. The results indicate more distinctly a general tendency than that of $P(1)$, but, since the number of earthquakes followed by at least three aftershocks is smaller, the local anomalies disappear. To confirm the distribution of the P value in a sea area, only large earthquakes whose magnitudes exceed 5.5 were investigated. The space distribution of $P(1)$ for the large earthquakes is represented in Fig. 8 and its special feature in a

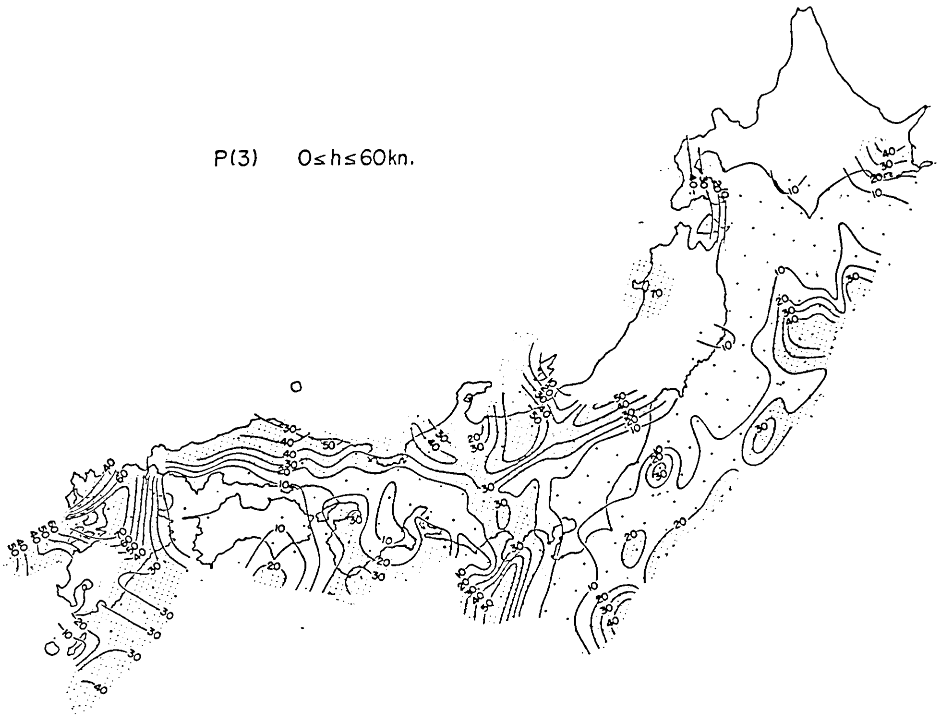


Fig. 7. Distribution of the percentage $P(3)(\%)$ of the earthquakes followed by at least 3 aftershocks to total earthquakes in a circular area of a diameter of 100 km. $(0 \leq h \leq 60\,\text{km})$

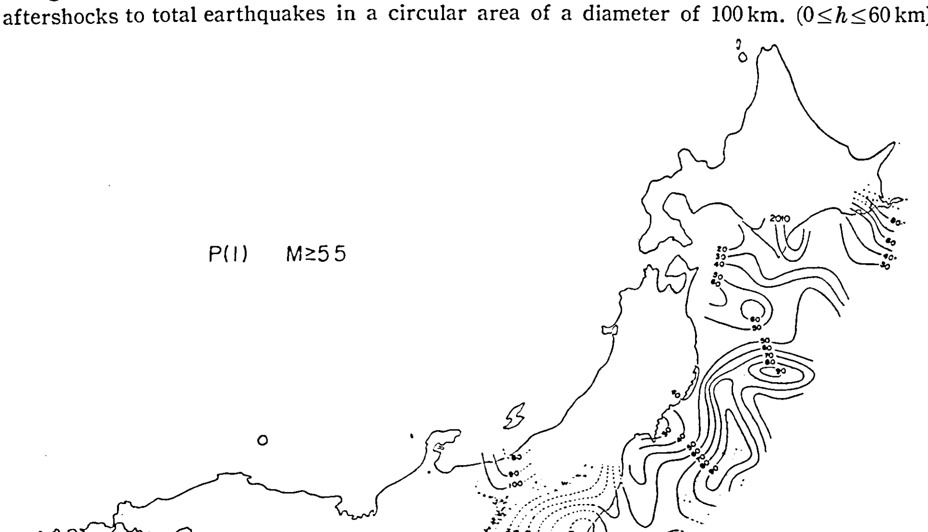


Fig. 8. Distribution of the probability $P(1)(\%)$ that an earthquake is followed by at least one aftershock. $(M \geq 5.5,\ 0 \leq h \leq 60\,\text{km})$

sea area is roughly similar to that of Fig. 5. According to the later discussion, the aftershocks seem to occur with high probability at some fractured regions. Therefore, the regions having high P values are deduced to be heterogeneous in structure.

(B) *Relation between the probability P of aftershock occurrence and the magnitude M.*

In the above-mentioned discussion, earthquakes whose magnitude exceeds a certain value have been discussed without any consideration of their magnitude. However, it is well known that a larger earthquake is more frequently followed by aftershocks. Here, the relation between the probability P that an earthquake is followed by aftershocks and the magnitude M is also investigated. However, as mentioned above, the P value varies strikingly between various regions in Japan. Therefore, the whole area in and near Japan was divided into three regions A, B and C, as shown in Fig. 9. This division which has been made also by C. Tsuboi[24] seems to be reasonable both on the geotectonic structures and on the spatial distribution of the P value.

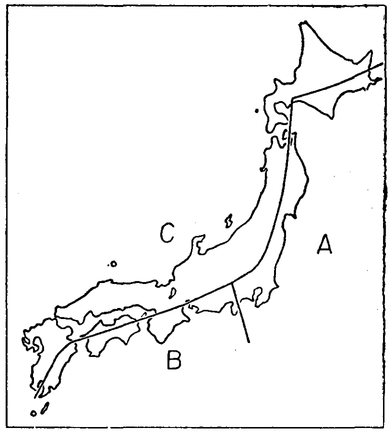


Fig. 9.

Figures 10(a), (b) and (c) show the P–M relations for $P(1)$, $P(3)$ and $P(20)$, respectively. $P(20)$ is the probability that an earthquake is followed by more than twenty aftershocks. Thus, it is confirmed for each region that the probability P increases remarkably with the magnitude M. However, the P–M relation varies considerably in different regions. The increase of probability with the magnitude M is not so steep in C-region as in the other regions. This also depends on the remarkable local variations of the P value in C-region. Then, the $P(20)$ value increases abruptly at the magnitude $5\sim6$, and the difference in localities is not remarkable. Therefore, $P(20)$ may be influenced more by the magnitude than by the places of epicenter. Furthermore, it is seen from the figures that the P value in deeper earthquakes ($26 \leq h \leq 60$ km) is lower than that in shallower earthquakes ($0 \leq h \leq 25$ km).

24) C. TSUBOI, *Journ. Phys. Earth,* **1** (1952), 47–54.

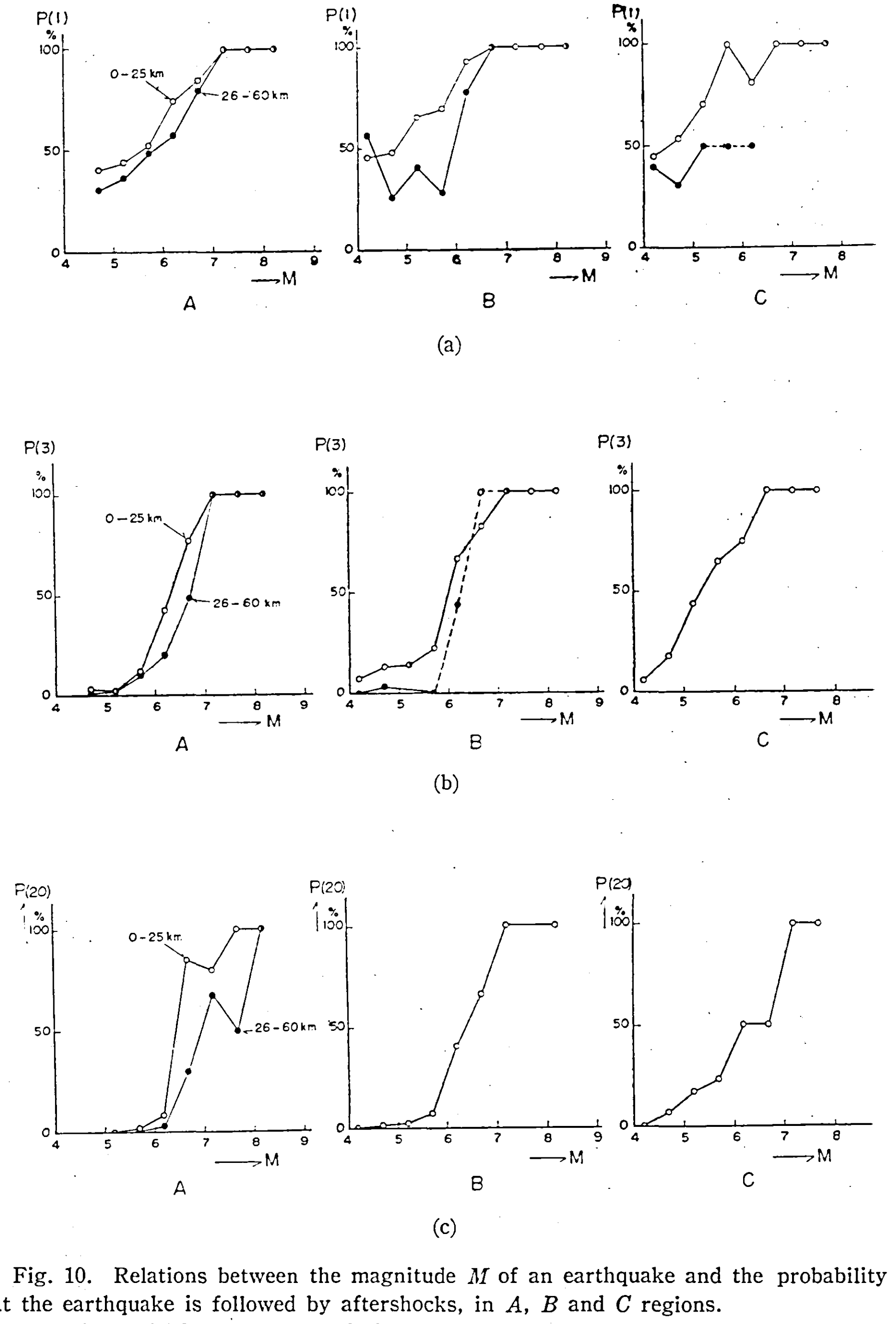


Fig. 10. Relations between the magnitude M of an earthquake and the probability P that the earthquake is followed by aftershocks, in A, B and C regions.
open circle: $0 \leq h \leq 25$ km; closed circle: $26 \leq h \leq 60$ km.
(a) $P(1)$-M relation, (b) $P(3)$-M relation, (c) $P(20)$-M relation.

Based on the above-mentioned *P–M* relations, rough relations between the magnitude *M* and the number of earthquakes *n* are obtained. The *P–n* relation in each region is represented in Fig. 11. From this figure, the probability that an earthquake of the magnitude *M* is followed by at least *n* aftershocks is obtained.

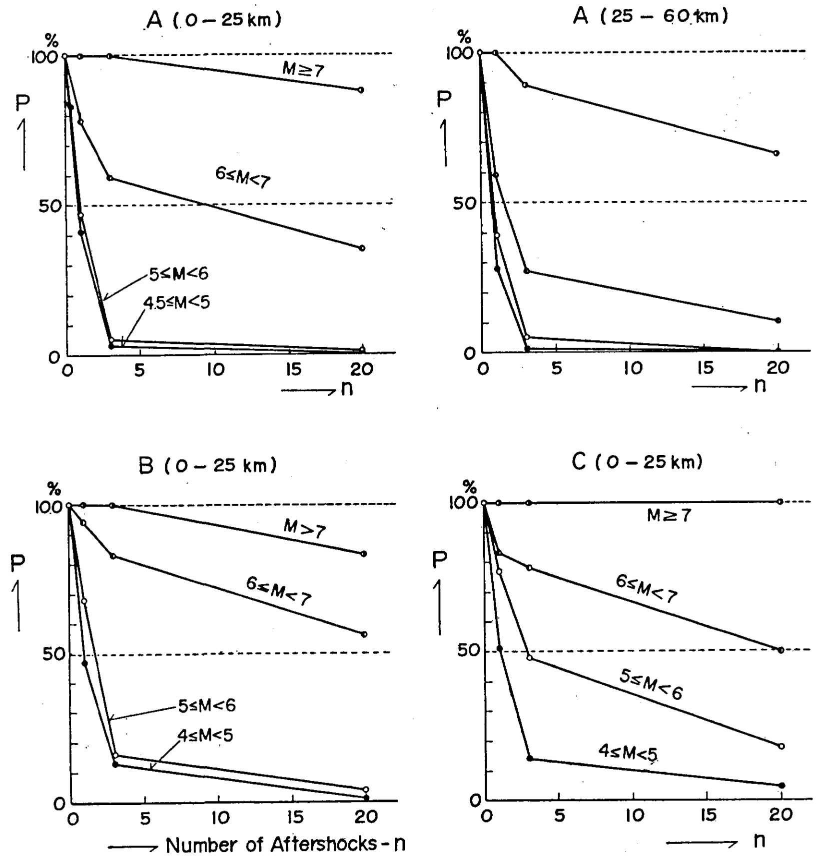


Fig. 11. Relations between the number of aftershocks *n* and the probability *P* that an earthquake is followed by at least *n* aftershocks, for various magnitude *M*.

(C) *Relation between the probability P of aftershock occurrence and the focal depth h.*

It has often been suggested that aftershocks seldom occur in deeper earthquakes. However, this problem has not been quantitatively investigated. Here, the *P–h* relation is discussed for the above-mentioned three regions. The results for $0 \leq h \leq 60$ km are shown in Figs. 12(a), (b)

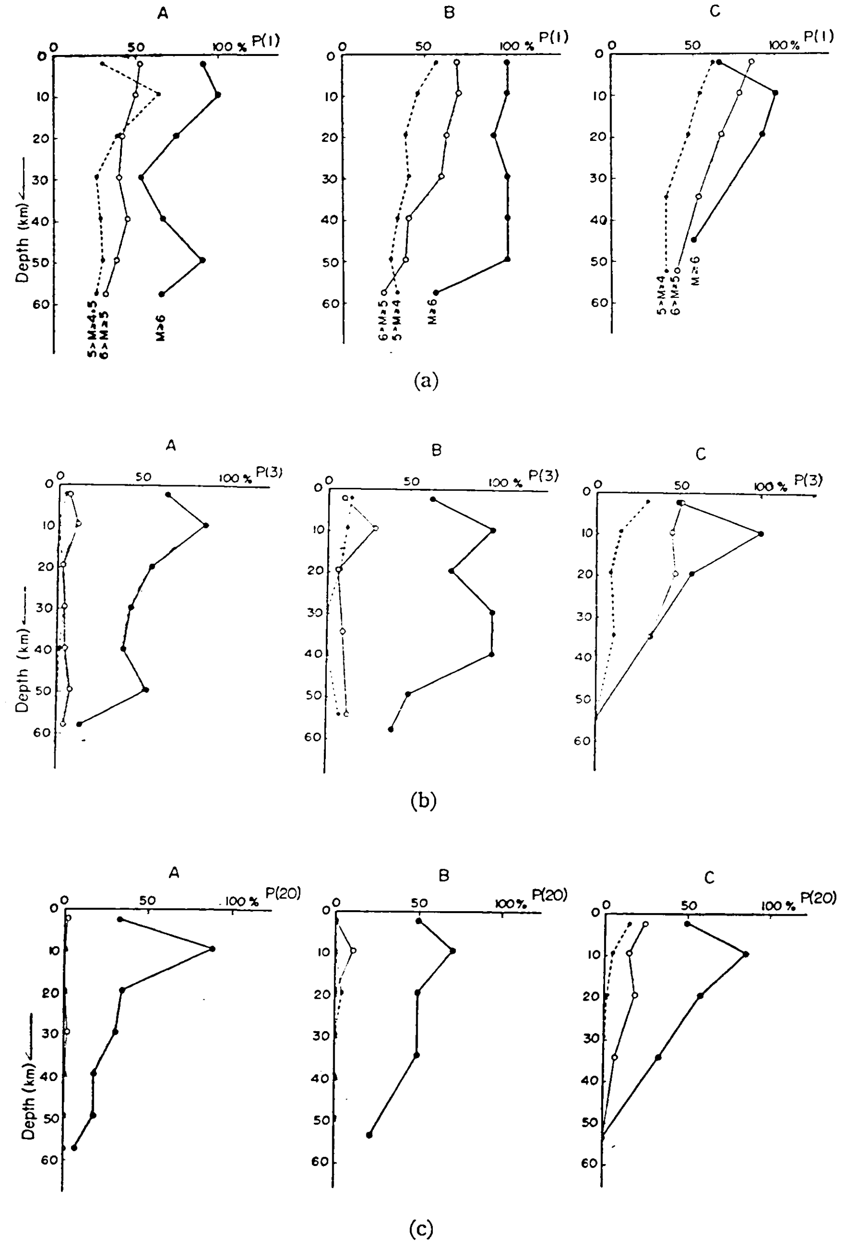


Fig. 12. Relations between the probability P of aftershock occurrence and the focal depth h, in A, B and C regions. large closed circle: $M \geq 6$; open circle: $6 > M \geq 5$; small closed circle: $5 > M \geq 4$ (4.5 in A-region).

(a) $P(1)$-h relation, (b) $P(3)$-h relation, (c) $P(20)$-h relation.

and (c). According to this result, the probability P generally decreases with the increasing depth h. However, the P-h relations are also different in different localities. That is, the P value in C-region always decreases monotonically, but $P(1)$ and $P(3)$ in A-region seem to have a maximum at about 50 km in depth. The P-h relation in B-region is

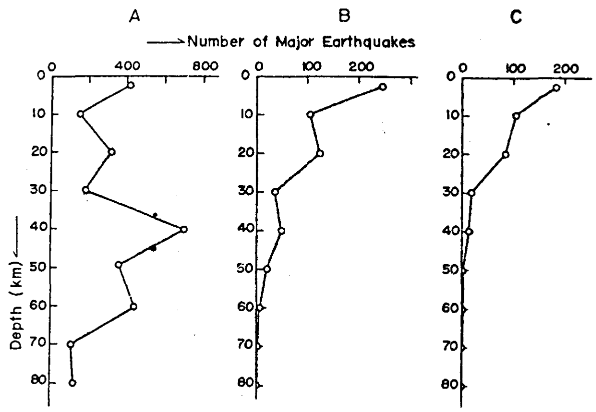


Fig. 13. Relation between the focal depth h and the number n of earthquakes which occurred at the depth h.

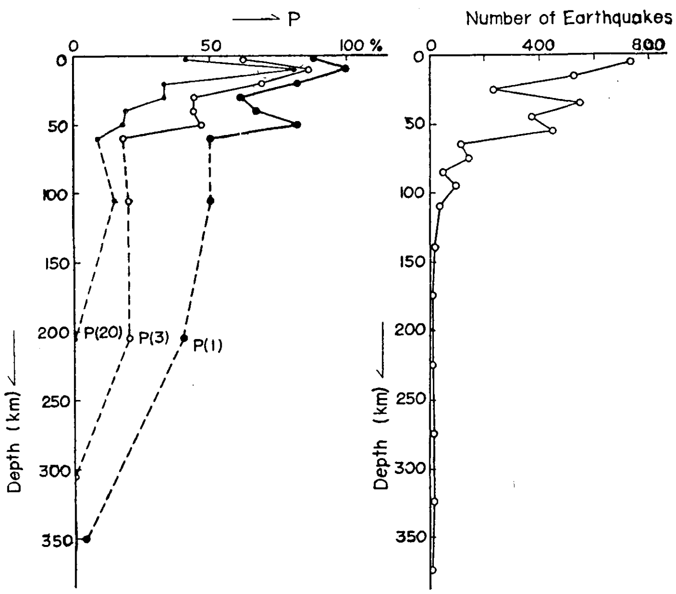


Fig. 14. Relation between P and h for earthquakes with various focal depths in and near Japan (left). (right: $n-h$ relation).

an intermediate type. It is interesting that the differences among the P–h relations of the three regions is analogous to that among the relations between the focal depth h and the number n of earthquakes occurring at the depth h (Fig. 13). Next, the deep and the intermediate earthquakes are investigated. In the above-mentioned "Catalogue of Major Earthquakes" by the Japan Meteorological Agency, the magnitude of earthquakes with a focal depth larger than 60 km is not determined and Gutenberg's magnitude M_G is described for some of those earthquakes. Although the available data are very few, the probability P for large depths was obtained. Thus, P–h relations in a wide range of focal depth ($0 \leq h < 400$ km) are summarized in Fig. 14. The result also shows that the probability P decreases remarkably with the increasing depth, as does also the number of earthquakes.

Furthermore, it is noteworthy that the P value shows a tendency to decrease again for the shallowest earthquakes ($h < 10$ km), and so it frequently has the maximum value at some shallow depth (~ 10 km).

In general, the accuracy of the focal depths is not satisfactory, especially in a sea area. Therefore, further discussions associated with the focal depths may be unsuitable at the present accuracy.

(D) *The mechanism of aftershock phenomena.*

In the previous paper[25], the mechanism of aftershock occurrence has been deduced on the basis of experimental results in the following way. A large part of the accumulated strain energy is liberated at the time of a principal earthquake and a fractured region takes place around the epicenter. If the residual part of the accumulated strain energy is not so small, many local fractures (or aftershocks) occur successively following the principal earthquake, because the residual stress concentrates highly at many weak points in the fractured region. Therefore, the aftershock occurrence is attributed to the generation of a fractured region around the origin. This mechanism of aftershock occurrence qualitatively explains the above mentioned results in aftershock phenomena.

(1) *P–M relation.* In large earthquakes, since the disturbance by a principal shock is greater, a larger fractured region is more probable and the residual strain energy after the main shock may be larger. Therefore, it is very natural that the probability P of aftershock occurrence increases with the magnitude of the main shock.

(2) *P–h relation.* The free surface of the earth's crust has an

25) K. MOGI, *loc. cit.*, 5).

important influence on the generation of the fractured region, because the stress distributes highly in the part between the free surface and the stress origin and produces a remarkably fractured region. In earthquakes with a deeper focus, the above-mentioned influence of the free surface is small and the increase of ductility by high pressure and high temperature also restrains the generation of the fractured region. Thus, the probability P of aftershock occurrence decreases with the increasing focal depth.

Furthermore, the fact that the P value of the shallowest earthquakes ($h<10$ km) is relatively small and the P value has a maximum value at some shallow depth (about 10 km) is analogous to the result of the previous model experiment. It may be explained as follows. In an extremely shallow case, the volume of the fractured region between the free surface and the source increases with the increasing depth of the source, at least to some depth.

(3) *Space distribution of the P value.* The variation in the P value of earthquakes with the same magnitude and the same focal depth will be attributed to the structural condition of the earth's crust or the upper mantle. It may be reasonably deduced that a fractured region is more likely to be caused by the great disturbance at the time of a main shock in a heterogeneous structure containing many weak points, than in a homogeneous structure. That is, the probability P of aftershock occurrence is higher in fractured regions than in other regions. This speculation is consistent with the experimental results and the present seismological data. Therefore, the distribution of the regions having high P values in Figs. 5 and 7 is thought to indicate the distribution of regions fractured in some degree. The relation between this distribution and the geological structure of the Japanese islands is discussed in a later section.

5. The first type of earthquake sequence.

In Section 2, it was related that various patterns of earthquake sequences are classified into three types. In this section, the first type of earthquake sequence is discussed. This type corresponds to the case of a large earthquake without any appreciable preceding small earthquakes, which is frequently followed by numerous aftershocks. A large proportion of great tectonic earthquakes belongs to this type. The epicentral positions of the principal earthquakes of this type followed by remarkable aftershocks are represented in Fig. 15 (a). Furthermore,

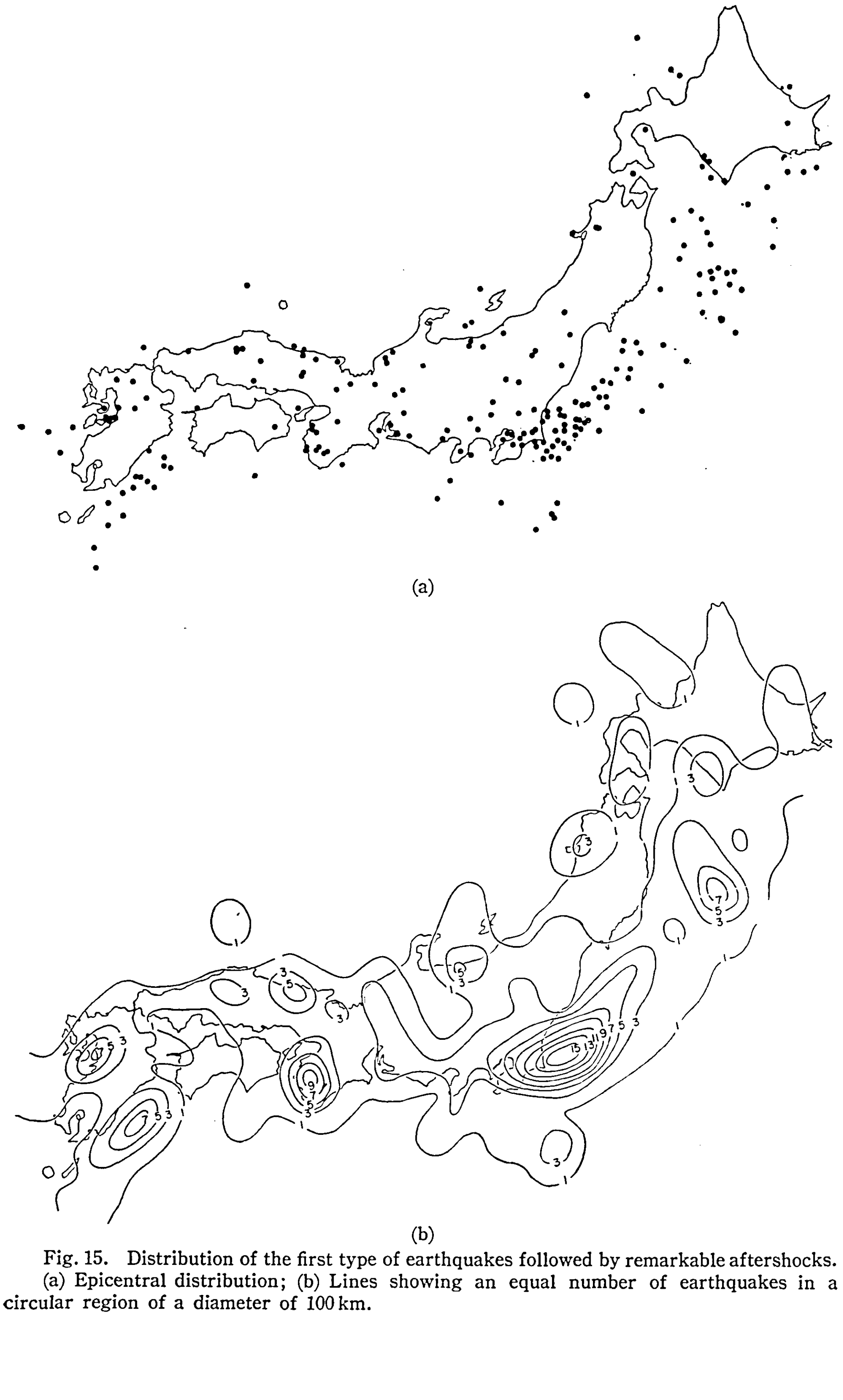


Fig. 15. Distribution of the first type of earthquakes followed by remarkable aftershocks. (a) Epicentral distribution; (b) Lines showing an equal number of earthquakes in a circular region of a diameter of 100 km.

all earthquakes that occur without any preceding earthquakes and do not belong to any series of earthquake swarms and to aftershocks of a larger earthquake should be classified broadly into the first type.

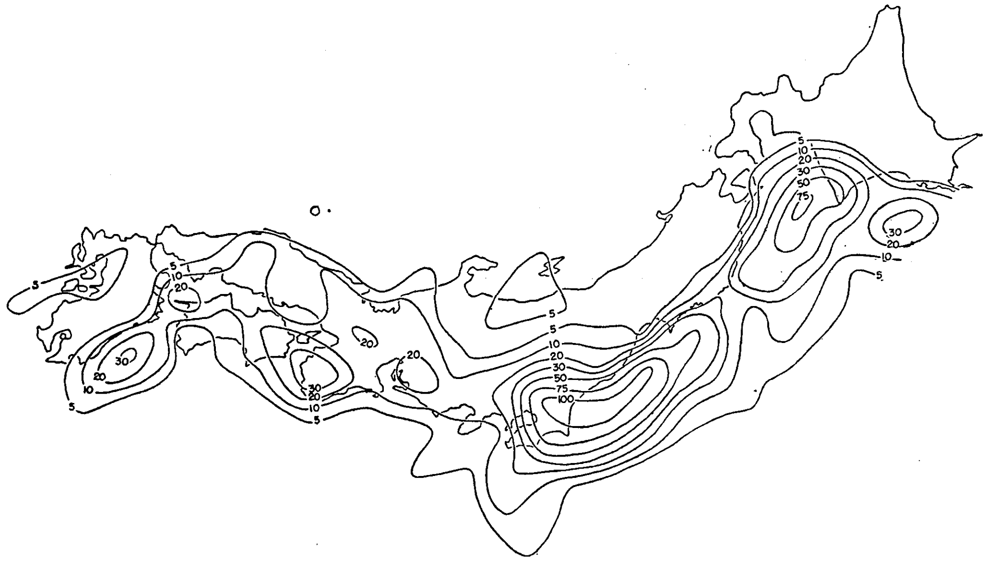


Fig. 16. Distribution of lines showing an equal number of the first type earthquakes in a circular region of a diameter of 100 km. ($0 \leq h \leq 60$ km)

Figure 16 is a distribution map of lines showing an equal number of the first type of earthquakes in a circular region of a diameter of 100 km. Since most major earthquakes belong to this type, this distribution is nearly identical to the spatial distribution of seismicity which has been obtained by S. Miyamura[26], I. Tamaki[27] and others.

According to the discussion in Section 2, earthquakes of this type occur only in regions of homogeneous structure, caused by uniformly applied stresses. Therefore, the regions where the first type pattern appears with very high probability as compared with the other types, may have a uniform structure.

Of course, the above-mentioned classification of earthquake sequences depends on the seismological data by the Japan Meteorological Agency. If the sensitivity of seismic observation is improved in future, the present classification may be more or less modified. However, because the transition from the first type to the third type is continuous, the

26) S. MIYAMURA, *Zisin (Journ. Seis. Soc. Japan)*, [ii], **15** (1962), 23-52.

27) I. TAMAKI, *Memoirs, Ōsaka Inst. Technology*, **7** (1961), 45-139.

essential results in the present discussion may remain.

6. The second type of earthquake sequence—foreshocks.

This type corresponds to cases where the seismicity in the epicentral region of a principal earthquake increases prior to the earthquake and where there are often numerous aftershocks. To call the earthquakes increasing prior to the principal earthquake "foreshocks" is convenient for discussion.

F. Ōmori[28] and A. Imamura[29][30] made some important investigations on foreshocks fifty years ago. They noted several earthquakes preceded by foreshocks from various data available in those days (Table 2) and suggested that such earthquakes were liable to occur in some limited regions. After the work of these pioneers, systematic investigations on the occurrence of foreshocks has been scarcely seen up to the present date, except for occasional reports on a few earthquakes which were preceded by remarkable foreshocks. However, it is desirable that this problem be systematically investigated on the basis of many seismological data accumulated in recent years.

Table 1. A list of the earthquakes preceded by foreshocks in and near Japan (1926–1961).

*): The occurrence of foreshocks may be uncertain in some measure.

	Region	Time	Epicenter Latitude	Epicenter Longitude	Depth	Magnitude
		d h	N°	E°	km	
1	North part of Hiroshima pref.	1926, Nov. 27, 18	35.0	132.8	40	4.6
2	North part of Gifu pref.	1927, Apr. 2, 8	36.1	137.0	0	4.6
3	North part of Hiroshima pref.	1927, May 8, 16	35.0	132.8	20	6.0
4	Off Niigata pref.	1927, July 29, 0	$37\frac{1}{4}$	$138\frac{1}{4}$	0—20	
5*	Central part of Wakayama pref.	1927, Dec. 2, 15	34.1	135.2	10	5.3
6*	Near Amakusa isl.	1927, Dec. 4, 12	32.6	129.9	0—10	5.4
7	North part of Hiroshima pref.	1928, Oct. 12, 21	34.9	132.8	10—20	4.5
8	West part of Ooita pref.	1928, Nov. 5, 13	33.2	130.9	0—10	4.9
9*	West part of Ooita pref.	1929, Jan. 2, 1	33.1	130.9	0	5.4

(to be continued)

28) F. ŌMORI, *Rep. Imp. Earthq. Invest. Comm.*, **68 A** (1910), 31-38.
29) A. IMAMURA, *Rep. Imp. Earthq. Invest. Comm.*, **77** (1913), 1-87.
30) A. IMAMURA, *Rep. Imp. Earthq. Invest. Comm.*, **82** (1915), 1-30.

Table 1.

(continued)

	Region	Time	Epicenter		Depth	Magnitude
			Latitude	Longitude		
10	Central part of Kumamoto pref.	1929, Feb. 9, 21	32.9	130.8	0	4.9
11	West part of Kumamoto pref.	1929, Oct. 25, 3	32.6	130.5	0	4.8
12	Kita Izu (East part of Shizuoka pref.)	1930, Nov. 26, 4	35.1	139.0	0—5	7.0
13	North part of Hiroshima pref.	1930, Dec. 20, 23	35.0	132.9	20	6.0
14	East part of Yamanashi pref.	1931, June 11, 15	35.4	138.9	0—5	6.0
15	Hyūganada	1931, Nov. 2, 19	32.2	132.1	20	6.6
16	Central part of Iwate pref.	1931, Nov. 4, 1	39.5	141.7	0—10	6.1
17	North part of Hiroshima pref.	1931, Nov. 15, 10	34.9	132.8	10	4.3
18*	Off Chiba pref.	1932, Oct. 5, 23	35.2	141.3	40	5.0
19*	North part of Kumamoto pref.	1933, Mar. 25, 21	33.0	130.9	0	5.0
20	Off Noto-peninsula	1933, Sept. 21, 12	37.1	137.0	15	6.0
21	South part of Niigata pref.	1934, Nov. 8, 12	37.2	138.1	0	5.7
22	West part of Ooita pref.	1935, Mar. 7, 19	33.1	131.1	20	4.8
23*	Central part of Kyoto pref.	1936, Feb. 5, 16	35.1	135.75	0—10	4.5
24*	Off Ibaragi pref.	1936, July 15, 10	36.3	141.7	40	5.7
25	East part of Yamanashi pref.	1936, Nov. 19, 22	35.5	139.1	10—20	5.4
26	Off Niishima, Izu	1936, Dec. 27, 9	34.5	139.2	0—20	6.3
27	Hyūganada	1937, Jan. 6, 6	31.5	132.5	0—20	6.5
28	Central part of Kumamoto pref.	1937, Jan. 27, 16	32.8	130.8	0—10	5.0
29*	Hyūganada	1937, June 24, 5	31.4	131.6	35	6.4
30	South part of Nagasaki pref.	1937, July 9, 13	32.8	130.0	0	5.0
31	South part of Nagano pref.	1937, Nov. 23, 2	35.6	138.2	0—10	5.4
32	Central part of Yamanashi pref.	1940, Mar. 1, 16	35.6	138.5	10	5.0
33	North part of Nagano pref.	1941, Mar. 7, 12	36.7	138.4	5	5.0
34	Near Nagano	1941, July 15, 23	36.7	138.3	5—20	6.2
35	Hyūganada	1941, Nov. 19, 1	32.6	132.1	0—20	7.4
36	Near Okinawa	1943, Jan. 7, 12	26.3	126.4	40	6.0
37	Off Hachinoe	1943, June 13, 14	41.1	142.7	20	7.1
38	North part of Nagano pref.	1943, Oct. 13, 14	36.8	138.2	0	6.1
39	Hyūganada	1943, Nov. 18, 16	32.7	131.9	0	5.1
40	Off Ooshima, Izu	1944, Dec. 8, 5	34.4	139.5	30	5.7
41	Mikawa (Aichi pref.)	1945, Jan. 13, 3	34.7	137.0	0	7.1
42*	Hyūganada	1946, May 1, 19	32.0	132.0	0	5.4
43*	West part of Nagano pref.	1946, Nov. 12, 5	36.4	137.7	0—30	5.4
44*	Off Kii-peninsula	1946, Dec. 21, 4	33.0	135.6	30	8.1

(to be continued)

Table 1.

(continued)

	Region	Time	Epicenter Latitude	Epicenter Longitude	Depth	Magnitude
45*	Kinpōsan (Kumamoto pref.)	1946, Dec. 22, 3	32.7	130.6	0	5.1
46*	Central part of Kyoto pref.	1949, Aug. 10, 1	35.3	135.6	20	5.1
47*	Hyūganada	1949, Nov. 6, 13	32.0	132.0	40	4.7
48	Off Noto-peninsula	1952, Mar. 7, 16	36.45	136.20	20	6.8
49	Near Ooshima, Izu	1952, May 31, 14	34.1	139.2	20	4.9
50*	Off Fukui pref.	1953, May 31, 13	36.7	136.0	20	5.4
51	North part of Hiroshima pref.	1953, June 8, 22	35.0	132.8	10	5.4
52	West part of Oshima-peninsula	1953, July 14, 21	42.2	139.9	20	5.4
53*	Central part of Shimane pref.	1954, May 16, 21	35.2	132.8	40	5.8
54*	Hyūganada	1954, May 27, 15	31.7	131.7	20	5.4
55	Near Amami-ooshima	1954, June 19, 10	$29\frac{1}{4}$	$131\frac{1}{4}$	0—10	6.1
56	East part of Yamanashi pref.	1955, Mar. 2, 7	35.5	138.9	20	4.5
57	West part of Tottori pref.	1955, June 23, 22	35.2	133.4	20	5.1
58	South part of Tokushima pref.	1955, July 27, 10	33.75	134.3	0—10	6.0
59	Off Izu-peninsula	1956, Mar. 10, 18	$33\frac{3}{4}$	$138\frac{3}{4}$	40	5.2
60	West part of Oshima-peninsula	1957, May 30, 7	42.4	139.7	0	5.0
61	Near Niishima, Izu	1957, Nov. 11, 4	34.3	139.35	0	6.3
62*	Teshikaga (Hokkaido)	1959, Jan. 31, 5	43.35	144.4	20	6.2
63*	Off Iwate pref.	1960, Mar. 21, 2	39.8	143.5	20	7.5
64	Gifu-Fukui border	1961, Aug. 19, 14	36.01	136.46	0	7.0

Table 2. The earthquakes preceded by foreshocks, described by Ōmori[31] and Imamura[32].

Region	Time	Epicenter		Magnitude
		Latitude	Longitude	
	d h	N °	E °	
Nara pref.—Mie pref.	1854, July 9, 0			
Hamada (Shimane pref.)	1872, Mar. 14, 17			
Nemuro-Kushiro	1894, Mar. 22, 19	44.	145.	7.5
Akita pref.	1896, Aug. 31, 17	39.	141.	6.9
Ooshima, Izu	1905, June 7, 14	34.8	139.5	7.0
Off Hachizyō-zima	1908, May 13, 5	33.7	138.5	7.7
Akita pref.	1914, Mar. 15, 4	39.4	140.1	6.4

31) F. ŌMORI, *loc. cit.*, 28).
32) A. IMAMURA, *loc. cit.*, 29), 30).

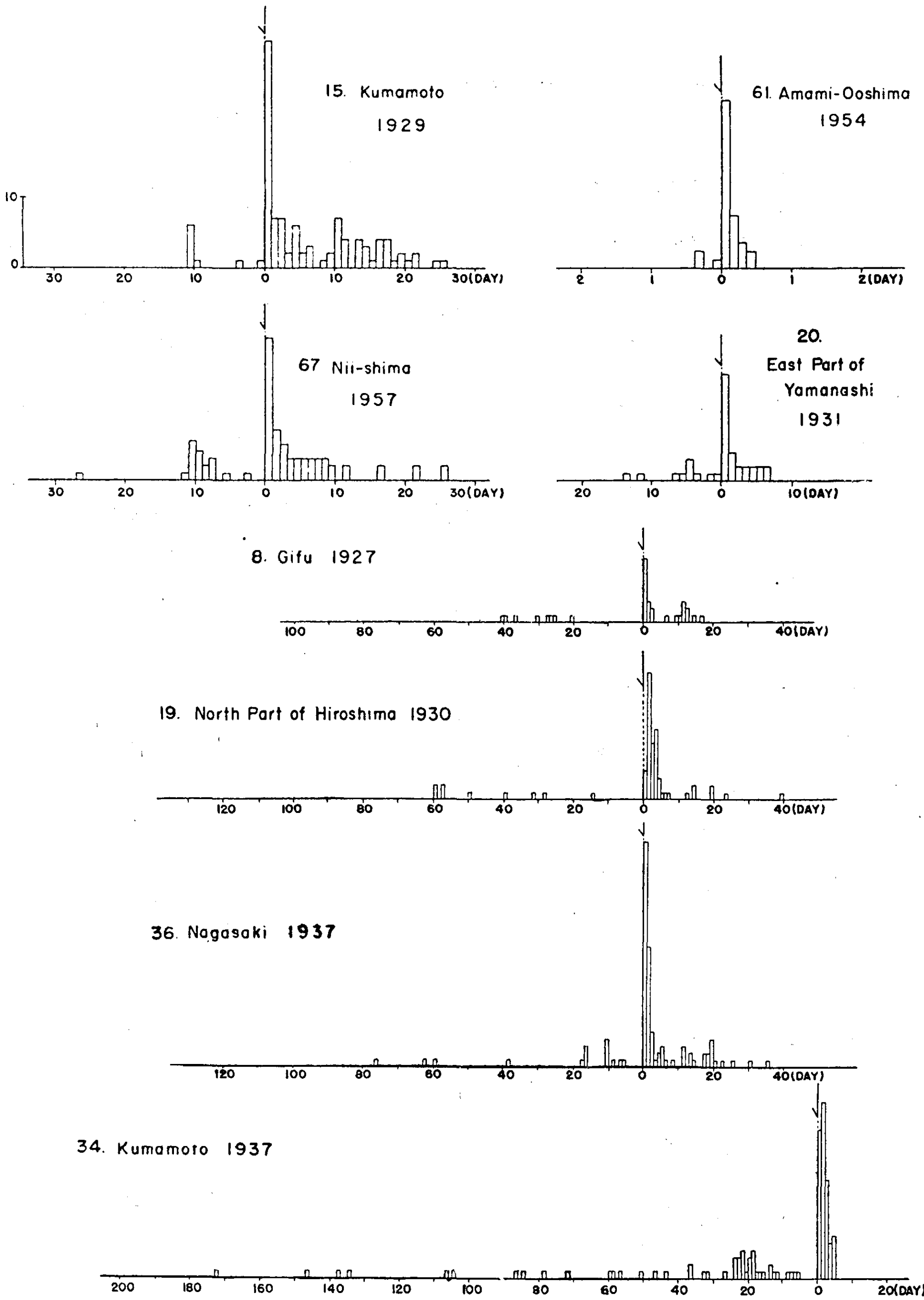


Fig. 17 (a)

Fig. 17. Examples of the earthquakes preceded by foreshocks (the second type).
Arrow: principal earthquake

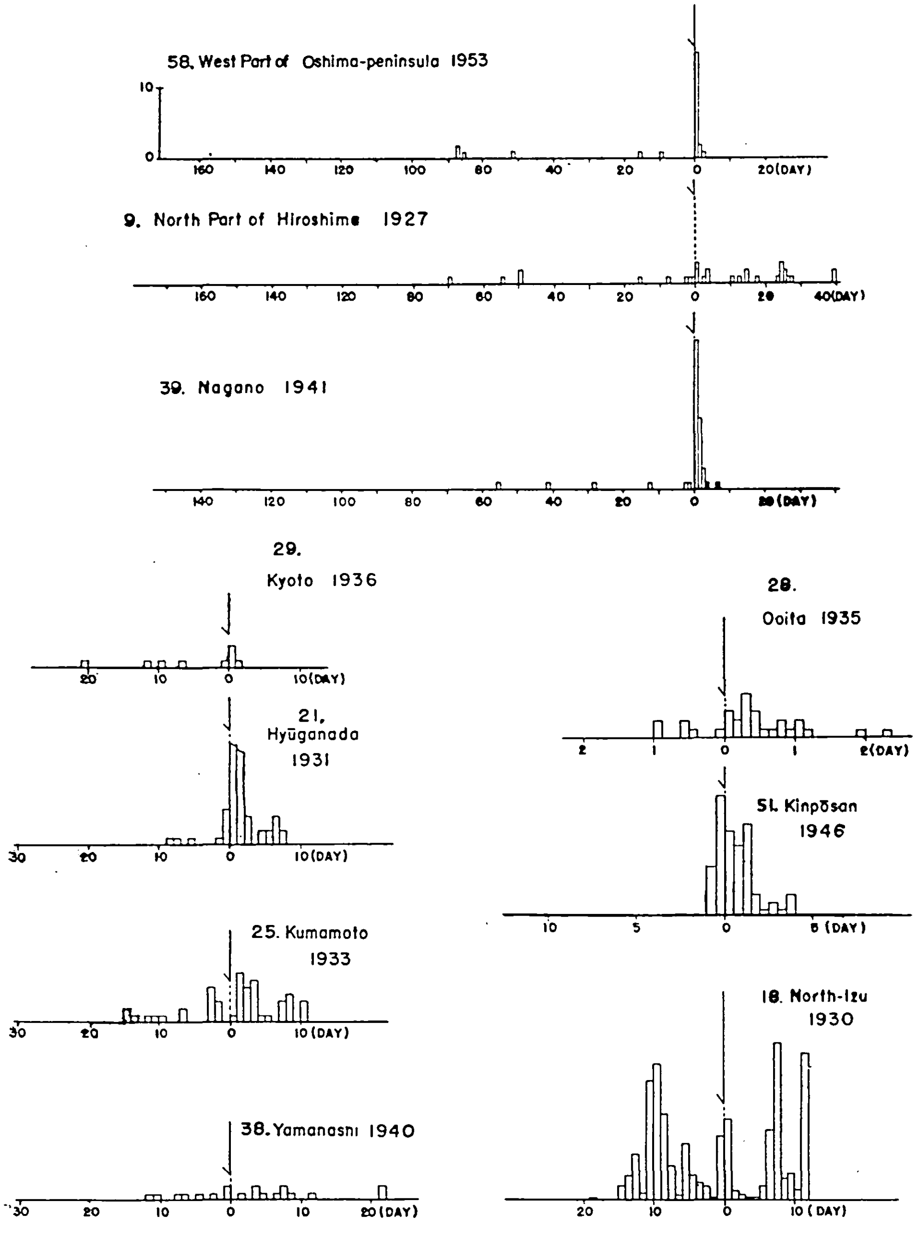
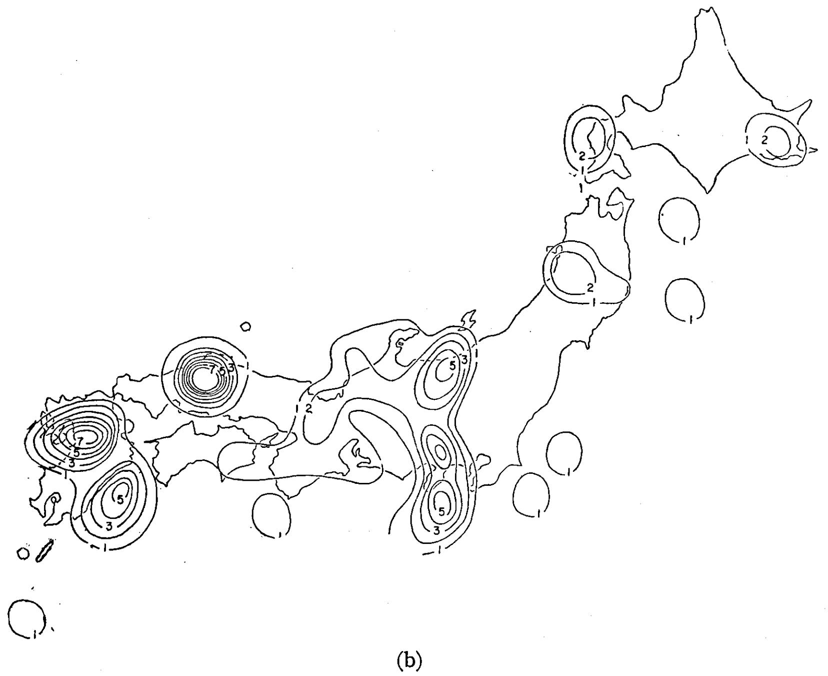

58. West Part of Oshima-peninsula 1953
10
0
160 140 120 100 80 40 20 0 20(DAY)
9. North Part of Hiroshima 1927
160 140 120 80 60 40 20 0 40(DAY)
39. Nagano 1941
140 120 100 80 60 40 20 0 (DAY)
29.
Kyoto 1936
20 10 0 10(DAY)
21.
Hyūganada
1931
30 20 10 0 10(DAY)
25. Kumamoto
1933
30 20 10 0 10(DAY)
38. Yamanashi 1940
30 20 10 0 10 20(DAY)
28.
Ooita 1935
2 1 0 1 2(DAY)
51. Kinpōsan
1946
10 5 0 5 (DAY)
18. North-Izu
1930
20 10 0 10 (DAY)

Fig. 17 (b)

(a)



(b)

Fig. 18. (a) Epicentral distribution of earthquakes preceded by foreshocks. open circle: uncertain case. (b) Distribution map of lines showing an equal number of earthquakes in a circular region of a diameter of 100 km.

During the above-mentioned test of about 1500 major earthquakes, about 60 earthquakes preceded by foreshocks were found (Table 1). This corresponds to about 4% of the tested earthquakes. Figures 17 (a) and (b) show examples of the second type of earthquake sequences. The number n of earthquakes in the figures is that of the earthquakes in a specified time interval, which occurred at the same place as the principal earthquake or were registered at the seismograph station nearest to the epicenter of the principal earthquake. When the seismicity at the epicentral region of the principal earthquake increases after a long calm state or when the seismicity increases abruptly or remarkably as compared with the normal state, the foreshocks are clearly distinguished from other ordinary earthquakes. The earthquakes preceded by such foreshocks are plotted by large closed circles in Fig. 18 (a). However, when the increase of the seismicity before the principal earthquake is not so remarkable as compared with the normal seismicity of the region or when major earthquakes occur successively in this region, separation from the normal activity is more or less uncertain. Such uncertain cases are plotted by open circles in Fig. 18 (a). The smaller closed circles in the figure show the localities of the earthquakes described by Ōmori and Imamura. In Fig. 17, some patterns of these earthquake sequences are similar to the first type, except for the increase in the number of earthquakes before the main shock, and, on the other hand, some patterns are quite similar to the third type, except that they have one outstanding principal shock. Thus, the transition from one type to another type is continuous and the second type is an intermediate type.

(A) *Spatial distribution of the second type of earthquakes.*

The epicenters of the earthquakes preceded by foreshocks in Fig. 18 (a), distribute in groups at certain regions. To express this tendency explicitly, a distribution map of lines showing an equal number of earthquakes in a circular area of a diameter of 100 km is shown in Fig. 18 (b). Remarkable groups of the second type of earthquakes distribute at the following regions. (1) Izu-Nagano-Kyōto region, (2) Miyoshi-Hamada region (north part of Hiroshima prefecture), (3) Ōita-Kumamoto-Nagasaki region and (4) Hyūganada region. The spatial distribution is obviously different from that of the first type.

The spatial distribution of the percentage of the second type of earthquakes to the sum of the first and the second type of earthquakes

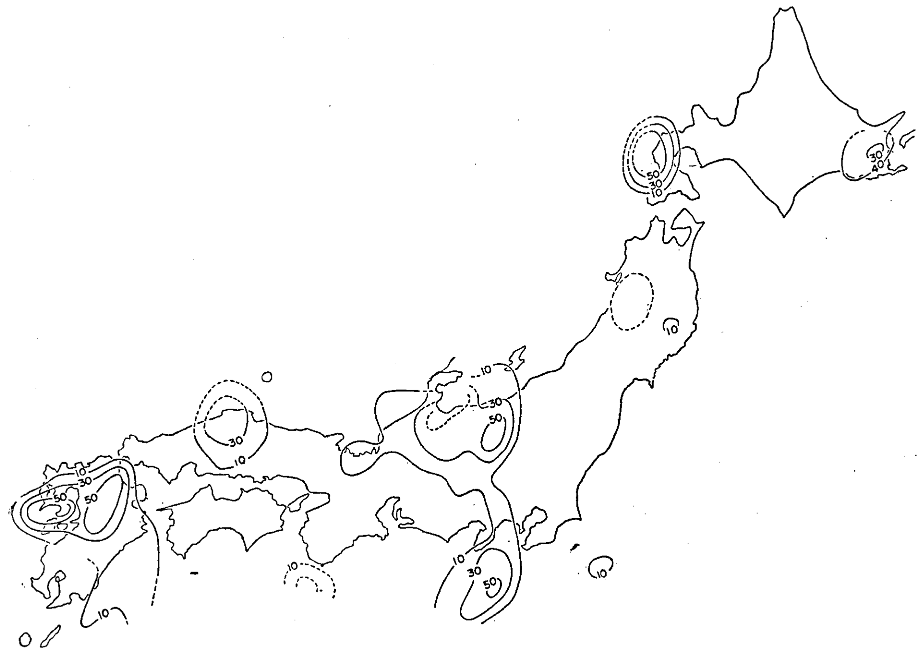


Fig. 19. Distribution of the percentage (%) of the second type of earthquakes to the sum of the first type and the second type.

Fig. 20. Distribution of the probability (%) that the earthquake followed by at least 3 aftershocks is preceded by foreshocks.

is shown in Fig. 19. This distribution of the probability of foreshock occurrence seems to be analogous to that of aftershock occurrence, as shown in Fig. 7. That is, the earthquakes preceded by foreshocks are liable to be followed by aftershocks, as seen also in Fig. 23. Furthermore, Fig. 20 shows the spatial distribution of the probability that earthquakes followed by at least three aftershocks are preceded by foreshocks. This indicates that foreshocks occur in more limited regions than aftershocks.

It is a very important fact that the occurrence of foreshocks is not accidental, and has a general tendency to be limited at certain regions. This regional distribution is attributed to the mechanical structure of the Japanese islands.

(B) *Relations of the magnitude M of the principal shock and its focal depth h to the foreshock occurrence.*

The histogram of the magnitude M of the earthquakes preceded by foreshocks is shown in Fig. 21. The relation between M and the

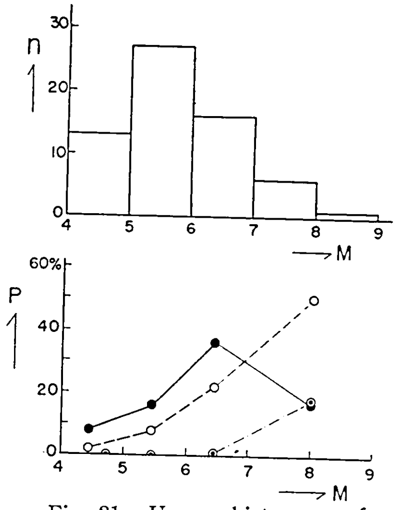


Fig. 21. Upper: histogram of the magnitude M of the principal earthquakes in the second type.

Lower: relation between M and the percentage P of the second type of earthquakes to the sum of the first type and the second type. double circle: A-region; open circle: B-region; closed circle: C-region.

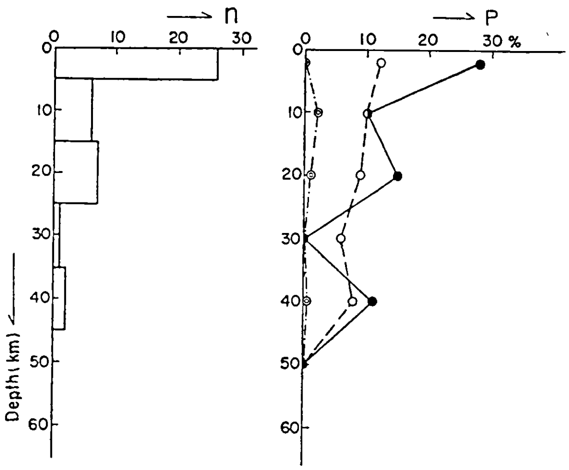


Fig. 22. Left: histogram of the focal depth h of the principal earthqakes of the second type.

Right: relation between h and the probability P of foreshock occurrence. double circle: A-region; open circle: B-region; closed circle: C-region.

percentage of these earthquakes to all tested earthquakes is also shown in the figure. This indicates that the probability of foreshock occurrence is not remarkably influenced by the magnitude M, but by the locality.

The histogram of the focal depth h of the earthquakes of this type and the relation between the probability of foreshock occurrence and h are shown in Fig. 22. Although the number of earthquakes is very few, the probability of foreshock occurrence decreases clearly with the increasing focal depth h.

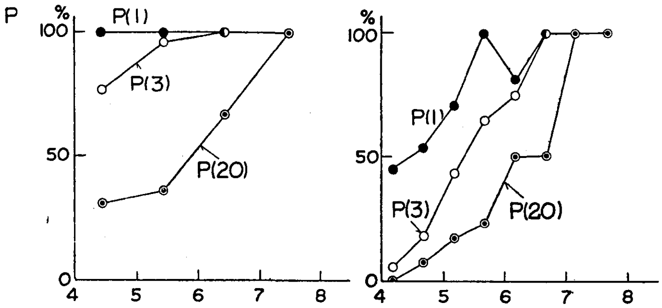


Fig. 23. Relation between M and the probability P of aftershock occurrence in the second type of earthquakes (left). (right: all earthquakes in C-region)

Then, the second type of earthquakes is frequently followed by remarkable aftershocks. To verify this relation, the P–M relation in the second type of earthquakes is shown in Fig. 23, with the mean P–M relation of all earthquakes. According to this result, the probability P of aftershock occurrence in the second type of earthquakes is clearly larger than the mean value.

(C) *The mechanism of foreshock occurrence.*

As mentioned in Section 2, the gradual increase of seismicity before the principal shock has a close relation with the heterogeneous structure of the region. That is, when an applied stress gradually increases, the stress concentrates highly at many irregular points in this heterogeneous crust and local fractures occur at such weak points even at a lower stress than the normal strength value of the crust. (This pattern of fracture occurrence is also caused by the application of an uneven stress to homogeneous materials.) Therefore, the above-mentioned regions where earthquakes are frequently preceded by foreshocks are deduced to be moderately fractured regions.

The time interval between the beginning of a foreshock sequence and the principal shock varies from a few hours to a few months. With certain assumptions, the rate of the stress increase before the principal earthquake is estimated from the process of the foreshock occurrence.

Lastly, the present author believes that the observation of foreshocks may give a clue for the prediction of major earthquakes at least in certain regions where the normal sequence of foreshocks is expected. Therefore, it is very important to discover where such behavior is to be expected and to clarify the process of foreshock occurrence.

7. The third type of earthquake sequence—earthquake swarms.

This type corresponds to cases where the number and the magnitude of earthquakes gradually increase with time, and then decreases after a certain period. There is no single predominant principal earthquake. This is called an earthquake swarm.

In this section, this type of earthquake sequence is investigated with data from the Geophysical Review and the Seismological Bulletin of the Japan Meteorological Agency. Although the larger part of volcanic earthquakes belongs to this type, earthquakes with direct relations to the surface activities of volcanoes[33] are excluded from the present discussion. Stationary series of numerous earthquakes, such as that of the Wakayama district, are also excluded from the discussion. The reason for this procedure is that only separate earthquake sequences are treated in this discussion.

Here, the swarm type of earthquakes has been selected by the following empirical measure. (i) Total number of earthquakes in a sequence exceeds 10. (ii) $n_m/\sqrt{t}>2$, where n_m is the maximum daily number of eathquakes and t is the duration of the earthquake sequence (in days). Examples of earthquake swarms are shown in Fig. 24. Their localities in and near Japan are shown in Fig. 25(a) and a distribution map of lines showing equal frequency of earthquake swarms in a circular area of a diameter of 100 km (1926–1961) is shown in Fig. 25(b). The swarms also distribute in groups in certain regions. The spatial distribution of the ratio of the frequency of earthquake swarms to the sum of the frequency of the first type and that of the second type is shown in Fig. 26. This indicates approximately the probability that seismic energy is radiated in the swarm type. This spatial distribution is

33) K. MOGI, *loc. cit.*, 3).

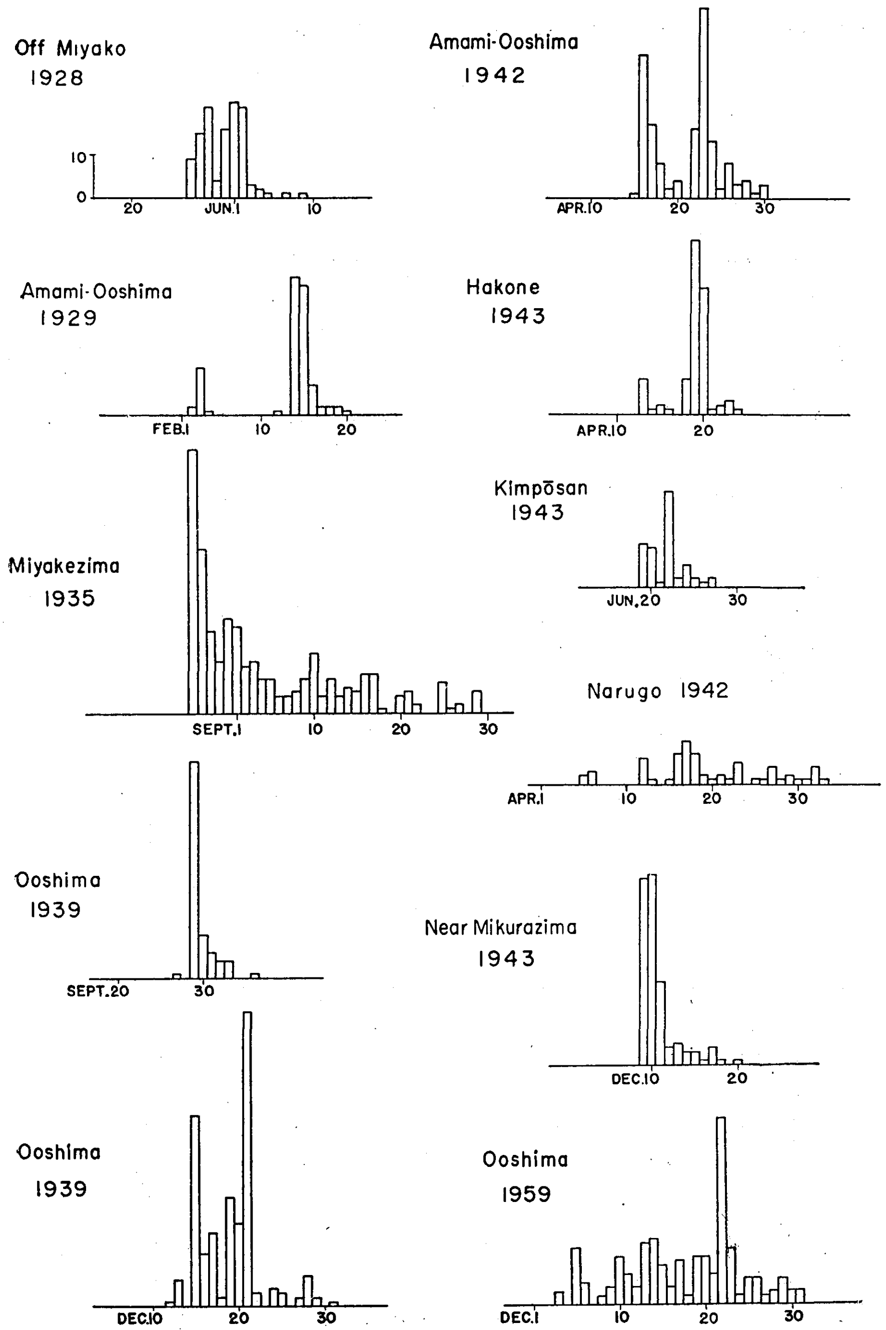


Fig. 24. Examples of earthquake swarm.

Table 3. A list of earthquake swarms in and near Japan (1926-1961).

	Region	Time	Number of earthquakes
1	Near Kure, Hiroshima pref.	1926, Jan. 7—25	33
2	Near Niigata	1926, Jan. 10—31	28
3	Beppu bay	1926, May, 1—21	13
4	Mito-Karenuma, Ibaragi pref.	1926, Nov. 12—Dec. 4	35
5	Near Ooita	1927, June 1—19	46
6	Near Gifu	1928, Apr. 23—24	10
7	Off Chōshi, Chiba pref.	1928, Dec. 21	33
8	Amami-ooshima	1929, Feb. 2—20	91
9	Off Chiba pref.	1929, Mar. 14—31	16
10	Off Mera, Chiba pref.	1929, Sept. 14—26	19
11	Unzendake, Nagasaki pref.	1929, Dec. 30—1930, Feb. 20	159
12	Near Ooita	1930, Apr. 13—29	14
13	Off Itō, Izu-peninsula	1930, Feb.—May	about 4000
14	Iida, Ooita pref.	1931, Apr. 28—30	48
15	Near Rokkō-san, Hyōgo pref.	1931, July 11—15	
16	Near Onikōbe, Miyagi pref.	1932, Mar. 11—13	(20)
17	Near Chōshi, Chiba pref.	1932, June 22—24	14
18	Near Mishima, Shizuoka pref.	1932, Aug. 10—11	16
19	Iwagasaki, Miyagi pref.	1933, Mar. 24—	>30
20	Miyakawa, Akita pref.	1933, Apr. 1—27	15
21	Funatsu, Yamanashi pref.	1933, May	41
22	Near Chichi-shima	1934, May 3—31	242
23	Iida, Nagano pref.	1934, Aug. 21—30	40
24	Amami-ooshima	1934, Sept. 6—27	107
25	Hakone-yama, Kanagawa pref.	1935, Jan. 7—31	20
26	Near Miyazaki	1935, July 3—21	25
27	Iida, Nagano pref.	1935, July 11—Aug. 4	51
28	Miyake-zima, Izu	1935, Aug. 27—Sept. 29	325
29	Unzendake, Nagasaki pref.	1935, Sept. 2—20	121
30	Off Amami-ooshima	1935, Nov. 2—12	36
31	Wakamatsu, Fukushima pref.	1936, Nov. 1—10	17
32	Hanawa, Akita pref.	1936, Nov. 5—25	13
33	Amami-ooshima	1937, Jan. 2—8	39
34	Near Chichi-shima	1937, Aug. 3—14	305
35	Ooshima, Izu	1938, June 18—19	(30)
36	Hakodate	1938, Apr. 6—7	11
37	Near Gifu	1938, Oct. 20	10

(to be continued)

Table 3.

(continued)

	Region	Time	Number of earthquakes
38	Amami-ooshima	1939, Apr. 13—30	54
39	Off Manazuru point, Kanagawa pref.	1939, June 19	12
40	Near Chichi-shima	1939, Aug. 25—26	17
41	Near Ooshima, Izu	1939, Sept. 29—Oct. 3	70
42	West side of Mt. Fuji	1939, Oct. 13	32
43	Ooshima, Izu	1939, Dec. 12—31	216
44	Teshikaga, Hokkaidō	1938, July	12
45	Ooshima, Izu	1940, Mar. 29—Apr. 8	50
46	Unzendake, Nagasaki pref.	1940, May 2	73
47	Hakone-yama, Kanagawa pref.	1940, July 1—14	25
48	Near Matsumoto, Nagano pref.	1941, Jan. 23—25	17
49	Off Miyako, Iwate pref.	1941, Mar. 12—20	30
50	NE side of Aso-san, Kumamoto pref.	1941, June 12—14	12
51	Ooshima, Izu	1941, Sept. 19—21	20
52	Ooshima, Izu	1941, Oct. 30	30
53	Near Hakone-yama	1941, Oct. 1	16
54	Yufuin, Ooita pref.	1941, Nov. 19—28	14
55	Amami-ooshima	1941, Dec. 6—24	48
56	Narugo, Miyagi pref.	1942, Apr. 5—May 3	64
57	Amami-ooshima	1942, Apr. 15—30	159
58	Ooshima, Izu	1942, Apr. 30	22
59	East coast of Chiba pref.	1942, May 18—23	19
60	Off Muroto point	1942, May 20—27	13
61	Off Muroto point	1942, July 8—10	17
62	Ooshima, Izu	1942, Aug. 25—31	27
63	Ooshima, Izu	1942, Nov. 4—30	308
64	Near Chōshi, Chiba pref.	1943, Jan. 11	16
65	Near Tomisaki, Chiba pref.	1943, Jan. 30	29
66	Off Ibaragi pref.	1943, Mar. 12—Apr. 26	240
67	Hakone-yama, Kanagawa pref.	1943, Apr. 13—36	96
68	Near Tomisaki, Chiba pref.	1943, Apr. 27	19
69	Near Morioka, Iwate pref.	1943, May 2—13	30
70	Onahama, Fukushima pref.	1943, June 1—12	19
71	Kinpōsan, Kumamoto pref.	1943, June 19—27	54
72	Near Morioka	1943, July 1—17	26
73	Onahama	1943, July 2—28	36
74	Tomisaki, Chiba pref.	1943, Nov. 26—30	30

(to be continued)

Table 3.

(continued)

	Region	Time	Number of earthquakes
75	Near Hakone-yama	1943, Dec. 1—16	106
76	Near Mikura-zima, Izu	1943, Dec. 9—21	129
77	Near Kagoshima	1943, Dec. 17—31	26
78	Kozu-shima, Izu	1943, Dec. 27—31	10
79	Ooshima, Izu	1943, Dec. 27—1944, Jan. 1	21
80	Hakone-yama	1944, Jan. 1—13	123
81	Hachizyō-zima	1944, Jan. 5—22	21
82	Ooshima, Izu	1944, Feb. 15—19	116
83	Ooshima, Izu	1944, Apr. 27—May 5	56
84	Tomisaki, Chiba pref.	1945, Aug. 24	13
85	Near Hakone-yama	1945, Aug. 29	25
86	Wazima, Noto-peninsula	1945, Oct. 29—30	13
87	Near Mito, Ibaragi pref.	1946, Jan. 2—15	24
88	Near Hakone-yama	1946, Sept. 9—20	27
89	Hyūganada	1946, Sept. 21—30	14
90	Near Hakone-yama	1946, Oct. 3—14	14
91	Kujūsan, Ooita pref.	1946, Dec. 21—30	53
92	Ooshima, Izu	1948, Dec. 15—24	266
93	Ooshima, Izu	1949, Apr. 12—19	45
94	Near Sendai, Miyagi pref.	1950, Jan. 14—28	16
95	Shirakawa, Gifu pref.	1950, Apr. 1—30	36
96	Iiyama, Nagano pref.	1950, June 22—30	13
97	Ooshima, Izu	1950, Aug. 1—13	134
98	Ooshima, Izu	1950, Sept. 7—20	52
99	Onikōbe, Miyagi pref.	1950, Sept. 14—17	27
100	Off Urakawa, Hokkaido	1951, Apr. 2—30	60
101	Unzendake	1951, Aug. 27	34
102	Near Yakushima, Kagoshima pref.	1951, Nov. 1—10	23
103	Near Kashiwara, Nara pref.	1951, Nov. 2—19	14
104	Ooshima, Izu	1952, Oct. 1—10	28
105	Off Erimo point, Hokkaidō	1951, Oct. 11	17
106	Off Iwate pref.	1952, Oct. 26—31	183
107	Hakone-yama	1952, Nov. 19—28	85
108	Ooshima, Izu	1952, Dec. 10—31	138
109	Near Towada, Aomori-Akita border	1952, Mar. 3—	20～30
110	Bandaisan, Fukushima pref.	1954, July 1—5	11
111	Near Tsuruga, Fukui pref.	1954, Aug. 12—14	13

(to be continued)

Table 3.

(continued)

	Region	Time	Number of earthquakes
112	Unzendake	1954, Oct. 21	22
113	North part of Chiba pref.	1954, Nov. 8—9	20
114	Nagano-Gifu border	1955, Feb. 4—9	28
115	Near Hiroshima	1955, Feb. 15	10
116	Off Iwate	1955, Apr. 30—May 12	34
117	Kōzushima, Izu	1955, July 22—23	13
118	Ooshima, Izu	1955, Sept. 5—23	90
119	Near Kumamoto	1956, Mar. 1—12	80
120	Ooshima, Izu	1956, Apr. 24—May 12	256
121	Unzendake-Kimpōsan	1956, Oct. 10—30	66
122	Off Miyake-zima, Izu	1956, Dec. 21—31	276
123	Ooshima, Izu	1957, Jan. 2—30	173
124	Kinpōsan, Kumamoto pref.	1957, Feb. 1—Nov. 13	161
125	Off Kinkasan, Miyagi pref.	1958, Apr. 8—17	29
126	West and North parts of Nagano pref.	1958, June 8—30	~200
127	ibid.	1958, Aug. 6—29	136
128	Ooshima, Izu	1959, June 7—26	49
129	Near Torishima	1959, July 5—31	75
130	Miyake-zima, Izu	1959, Aug. 3—15	23
131	Ooshima, Izu	1959, Dec. 3—31	221
132	Ooshima, Izu	1960, Apr. 3—30	118
133	Near Tottori	1961, Sept. 12—18	39

obviously different from that of the first type and seems to be nearly identical to that of the second type, and to that of the volcanic regions.

As mentioned in Section 2, this type occurs at remarkably fractured regions. That is, when the applied stress gradually increases, a high stress concentration appears around numerous cracks and faults, and so local fractures begin to occur already under a low stress. Thus, a single predominantly large fracture cannot occur. On the other hand, this pattern is also caused by the application of extremely concentrated stress. For example, in volcanic regions, this type may sometimes be caused by an intrusion of magma.

It is very natural that earthquake swarms frequently appear in volcanic regions because the structures of volcanic zones are remarkably heterogeneous and also a concentrated stress may be applied. A correlation with the spatial distribution of the second type of earthquakes

Fig. 25 (a)

(b)

Fig. 25. (a) Location of swarm type earthquakes. (b) Distribution map of lines showing an equal number of the earthquake swarms in a circular region of a diameter of 100 km.

Fig. 26. Distribution of the ratio (%) of the number of the earthquake swarms to the sum of the first type and the second type earthquakes.

is also explained from the above-mentioned mechanism of swarm occurrence.

8. Mechanical structures of the Japanese islands.

In the preceding sections, the patterns of the earthquake sequence have been classified into three types and the spatial distributions of these types in and near Japan have been obtained. The spatial distribution of the regions where foreshocks, aftershocks and earthquake swarms occur with high probability are summarized in Fig. 27. It is clearly seen that they distribute in certain regions with a similar general tendency.

According to the above-mentioned discussion, these spatial distributions of various earthquakes are attributed to the mechanical structures of the crust and the mantle and/or the spatial variation of external stresses. However, since the seismicity in and near Japan seems to distribute without any direct connection with the above-mentioned distributions of earthquakes of various types, it is reasonably supposed that the present spatial distributions of various earthquakes are not

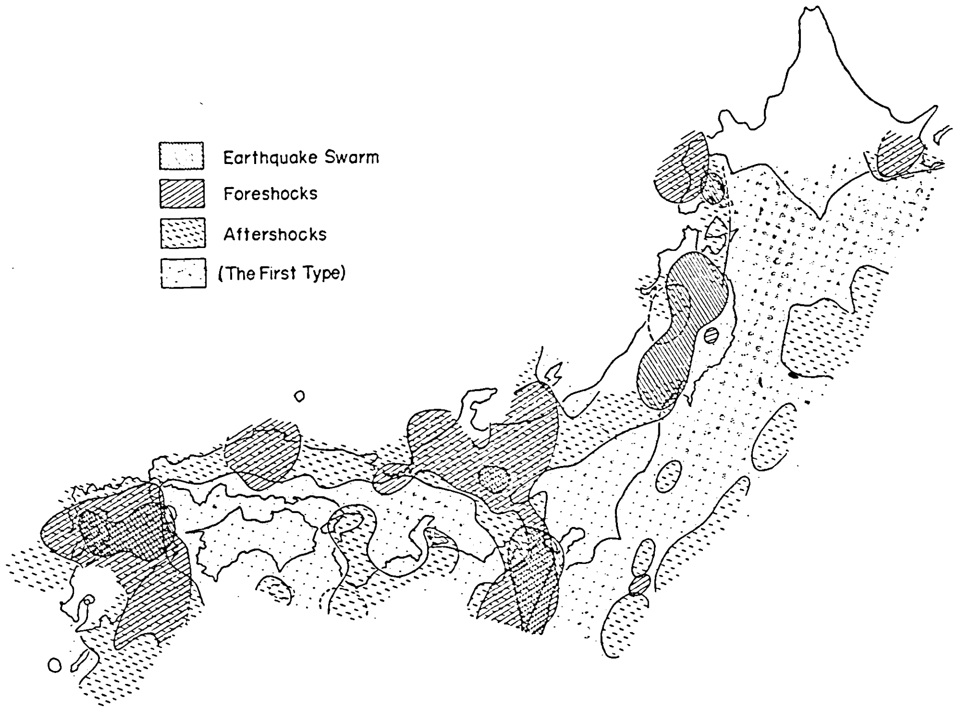


Fig. 27. Distributions of the regions where earthquake swarms, foreshocks and aftershocks occur with high probability.

caused by external stresses, but by the structural states in various regions, except for some cases of earthquake swarms. Therefore, it may be reasonably assumed that external stresses are nearly uniformly applied to various regions.

Under the uniformly applied stress, the pattern of earthquake sequence is dicidedly influenced by the degree of heterogeneity of the earth's crust or upper mantle. That is, the degree of heterogeneity (or the density of cracks or faults) in the regions where each type of earthquake sequences appears with high probability, may increase in the following order.

The first type $<$ (Aftershocks) $<$ The second type $<$ The third type.

Therefore, Fig. 27 indicates the distributions of regions fractured in various degrees. The regions where both the second type and the third type sequence frequently appear, that is, the Izu-Nagano region and the Ōita-Kumamoto-Nagasaki zone, are extremely fractured regions. The regions where the second type frequently occurs, that is, the Miyoshi-Hamada region, the Hyūganada region, etc., are moderately fractured regions. The regions where the probability of aftershock occurrence is large are fractured to some degree. The other regions where the first type of earthquakes without any aftershocks frequently occurs, are uniform in structure.

This mechanical structure of the Japanese islands seems to have close connections with their geotectonic structure. The Izu-Nagano region, which is one of the above-mentioned most fractured regions, corresponds to the Fossa Magna region, a very important tectonic break which crosses Honshū and separates Japan into a southwest and a northeast tectonic division. The other most fractured region, the Ōita-Kumamoto-Nagasaki zone, is also a very important fault region. These regions take the form of a graben filled with volcanic materials and in which some active volcanoes are found.

Next, the spatial distribution of the regions fractured in some

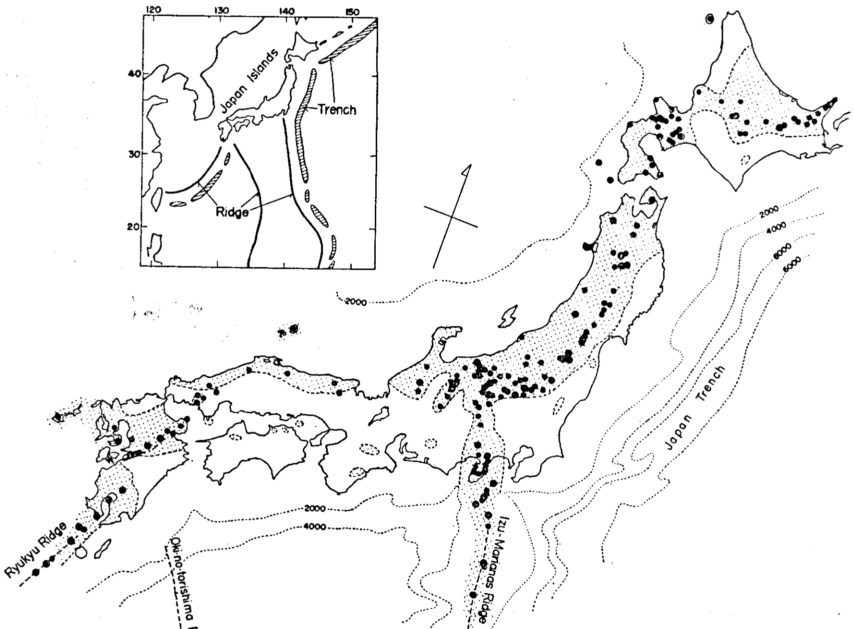


Fig. 28. Distributions of Quaternary volcanoes, trenches and oceanic ridges in and near Japan. closed circle: volcano; double circle: active volcano; dotted area: Neogene Tertiary and Quaternary vocanic region.

degree nearly agrees with the geographical distributions of Quaternary volcanoes and volcanic regions in Neogene Tertiary and Quaternary (Fig. 28). Since the volcanic zones are thought to be fractured zones of the earth's crust, this indicates that the fracturing structure of the earth's crust deduced from seismic data is consistent with the geological data of the earth's surface. However, although the Hyūganada region is one of the remarkably fractured regions, as mentioned above, only this region among them has not been thought to belong to a known volcanic zone. On the other hand, according to a submarine topographical map of the neighbourhood of the Japanese islands[34], a remarkable oceanic ridge, named the Okinotorishima ridge or the Kyūshū-Palau ridge, extends to Hyūganada from Palau. This ridge is the most remarkable one in this area after the Izu-Marianas ridge and the Ryūkyū ridge and seems to include recent submarine volcanoes[35]. Therefore, the special features of the Hyūganada region may also be attributed

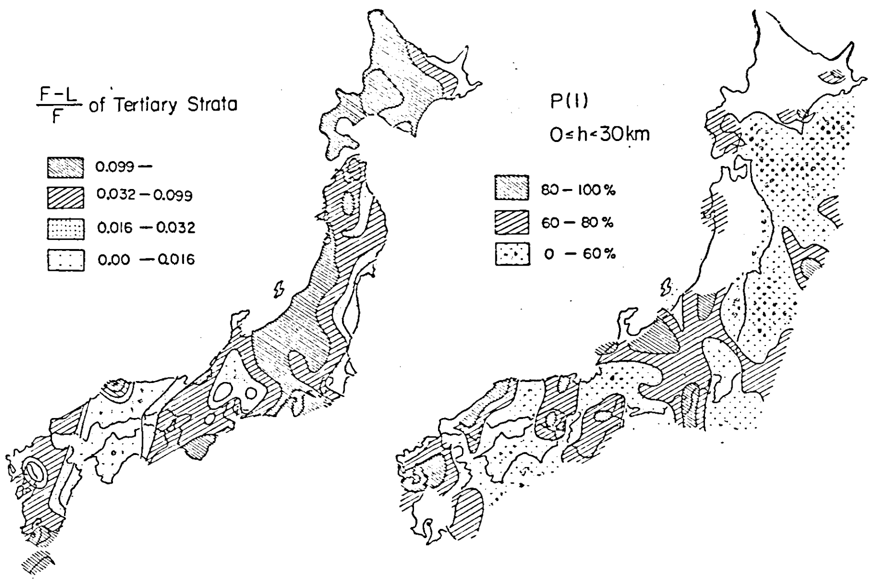


Fig. 29. Left: Distribution of Tertiary folded regions (after Otuka). F=measured length of strata along the folded structure, L=measured horizontal length of folded strata.
Right: Distribution of the regions where there was a high probability of the occurrence of aftershocks.

34) R. TAYAMA, *Hydrographic Bull.*, No. 32 (1952), 160-167.
35) *Catatalogue of Active Volconoes* (Japan).

to a heterogeneous structure related to the oceanic ridge or recent volcanic activity.

Furthermore, the above-mentioned spatial distribution of fractured regions seems to have some relation with other features of the geotectonic structure of the Japanese islands. The distribution map of Tertiary folded regions after Y. Otuka[36] is represented in Fig. 29 (left). The coefficient $(F-L)/F$ in this figure, where F is a measured length of strata along the folded structure and L is a measured horizontal length of folded strata, shows the intensity of folding, and thus the degree of mechanical disturbance in the earth's crust. The geographical distribution of Tertiary folded regions is nearly analogous to that of the fractured regions deduced from aftershock occurrence in the shallower earthquakes ($0 \leq h < 30$ km) and their similarity is very remarkable in

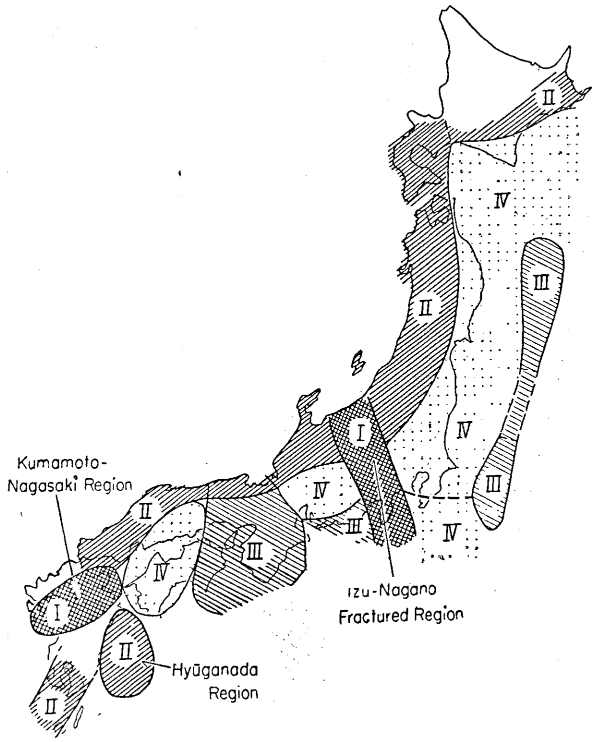


Fig. 30. Mechanical structure of the earth's crust in and near Japan deduced from earthquake occurrences. The number in each region indicates the degree of fracturing.

36) Y. OTUKA, *Bull. Earthq. Res. Inst.*, **15** (1937), 1041–1946.

southwest Japan (Fig. 29).

There is a fractured zone along the west side of the Japan trench. This zone is also supposed to be a fault zone on the basis of topographical features.

Moreover, it is remarked that the present spatial distribution of the fractured regions also has close relations with that of geophysical data. That is, it is very similar to the spatial distribution of regions where the frequency of aftershocks decreases at a high rate[37], and also analogous to that of regions of high heat flow[38]. On the other hand, the seismicity depends not only on the structural conditions, but also on the magnitude of external stresses. It should be noticed that the spatial distribution of fractured regions does not show any remarkable correlation with that of current seismicity.

The mechanical structure of the Japanese islands are summarized in Fig. 30. The number in each region indicates the degree of fracturing. According to previous work[39], these mechanical structures also may be independently obtained from the magnitude-frequency relations of earthquakes.

9. Summary.

In the preceding papers[40], the patterns of the successive occurrence of elastic shocks accompanying fractures under a simple stress state have been experimentally investigated and they have been classified into three types. The type of shock sequence is decidedly influenced by the mechanical structure of model materials. In this paper, this experimental conclusion has been applied to earthquakes in and near Japan (1926–1961). The main results are summarized as follows.

(1) The patterns of earthquake sequences are also classified into the three types which were obtained in the patterns of shock sequences, but the transition from one to another is continuous.

(2) About 60 earthquakes preceded by foreshocks (the second type) have been found. They distribute in groups at certain regions. In such regions where the normal sequence of foreshocks is expected, the seismic observations may give a clue for prediction of major earthquakes.

(3) The regions where a certain type of earthquake sequence

37) K. MOGI, *Bull. Earthq. Res. Inst.*, **40** (1962), 107–120.

38) S. UYEDA and K. HŌRAI, *Read at the meeting in Earthq. Res. Inst.*, (1961).

39) K. MOGI, *loc. cit.*, 2).

40) K. MOGI, *loc. cit.*, 5), 6).

frequently appears distribute following a general tendency. The various patterns of earthquake sequences are related to the various degrees of heterogeneity in structure. Thus, the spatial distribution of the regions fractured in various degrees are deduced from the data of the patterns of earthquake sequences.

(4) The probability P that an earthquake is followed by aftershocks increases with the magnitude and decreases with the focal depth. Furthermore, the P value varies remarkably in various regions. The spatial distribution of the regions having a high P value of aftershock occurrence is nearly identical to that of the second type and the third type. These regions are also the regions which are fractured to some degree.

(5) The spatial distribution of fractured regions deduced from the types of the pattern of earthquake sequences has close relations to various geotectonic structures of the Japanese islands, and to other geophysical data.

10. Acknowledgements.

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38. 余震，前震，群発地震の起こり方―半無限体の内部力源による破壊およびそれに関連した地震発生の二，三の問題（第3報）

地震研究所 茂 木 清 夫

前回までに，破壊に伴う Elastic shocks の代表的な発生型として三つの型があり，それが主として媒質の構造的不均一さによることを示した (Fig. 2). このことは自然地震の場合にも成り立つとの観点から，本論では日本附近に発生した主なる地震の起こり方を組織的に調査，分類して，その発生の機構および日本列島の地体構造との関係を考察した．その主なる結果を次に要約する．

(1) 日本附近に起こつた地震を上に述べた三つの型に分類して，各型の地理的分布を求めた．また，各地域について，それぞれの発生型のあらわれる確率を求めて，その地理的分布を求めた．これらの分布には，一定の規則性が認められ，日本列島の地体構造と密接な関係を示している．

(2) 前震を伴う地震は，調査された全部の地震の約4％に達し，特定の地域に起こり易い傾向があ

る．このような地域ではとくに小さい地震の観測から地震の発生を予測できる可能性が大きい．

(3) 余震の起こり易い地域もまた同様の一定の傾向をもつて分布している．余震は，本震が大きいほど，またその震源が浅いほど起こり易いが，同時に地域的差異も著しく，構造的に不均一な所で一層起こり易い傾向をもつている．

(4) 地震の発生型と地殻の構造的不均一度の関係としてモデル実験の結果を適用することによつて，日本附近の力学的構造状態が推定された．それによると，日本附近の地殻の破砕地域は，新第三紀以後の火山活動地域とよく一致する．特に，伊豆から長野に至る Fossa Magna 地域と大分から長崎に至る地域が最も破砕度の著しい地域である (Fig. 30)．中央構造線に沿つて明瞭な破砕帯が見られないのは，その活動の古いことによると思われる．

(5) 日向灘地域ではこれまで新しい火山活動があつたという地学的資料が知られていないが，この地域における地震の起こり方は，他の火山地域に類似の特徴を示している．しかも，噴火の記録のある沖ノ鳥島海嶺（または九州―パラオ海嶺）が北上して日向灘に達していることから，日向灘地域の地震学的異常は，このような地体構造に起因していると考えられる．