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Aftershocks and Earthquake Statistics (I)

—— Some Parameters Which Characterize an Aftershock Sequence and Their Interrelations ——

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Abstract

In order to provide basic data for developing a suitable model of aftershock occurrence and for giving proper interpretations of earthquake statistics in general, several parameters which characterize an aftershock sequence have been evaluated for many sequences which occurred in and near Japan from 1926 through 1968 and their interrelations have been investigated. The parameters or quantities treated here are as follows.

1) M_0: Magnitude of the main shock.
2) M_1: Magnitude of the largest aftershock.
3) M_2: Magnitude of the second largest aftershock.
4) D_1: Difference between M_0 and M_1.
5) D_2: Difference between M_1 and M_2.
6) $D_1/\tilde{D}_1$: Ratio of D_1 to $\tilde{D}_1$. $\tilde{D}_1$ is the standard value of D_1 given as a function of M_0: $\tilde{D}_1=5.0-0.5\,M_0$ $(M_0\geq 6)$.
7) T_1: Time interval between the main shock and the largest aftershock.
8) p: Index in the modified Omori formula: $n(t)=K/(t+c)^p$
9) c: Constant in the same formula.
10) A: Area of the aftershock region.
11) $A/\bar{A}$: Ratio of A to $\bar{A}$. $\bar{A}$ is the standard value of A given as a function of M_0: $\log\bar{A}=M_0-3.7$, where $\bar{A}$ is measured in km^2.
12) b: Coefficient in Gutenberg-Richter's formula: $\log n(M)=a-bM$.

The values of some parameters for 66 Japanese sequences investigated in detail fall in the following ranges.

D_1: 0.0–2.9, T_1: 1 min.–483 days, p: 1.0–1.8, c: 0.01 day or less – 1.5 days,
$A/\bar{A}$: 0.17–29, b: 0.4–1.8.

The correlations between parameters are not remarkable except between A and M_0, and A and M_1. Slight indication of correlation is observed between the following pairs.

Positive correlation: c and M_0, T_1 and M_0, p and c, b and D_1, p and b.
Negative correlation: D_1 and M_0. c and D_1, D_1 and $A/\bar{A}$, p and T_1.

It should be remarked that the sequences investigated are those accompanied by rather remarkable aftershock activities (some of them may be called as swarms), therefore some of the above results may reflect such a biased selection of data. Some preliminary discussions are made about the relations between these parameters.

1. Introduction

The statistical properties of the occurrence of aftershocks have long been one of the main objects of seismological studies in connection with the processes of earthquake generation. Distributions of aftershocks in time, space, and magnitude are usually included in a general survey of a destructive earthquake. The author published a paper[1] in 1961 which dealt with many Japanese aftershock sequences during the period from 1926 to 1959. Several statistical laws of aftershock occurrence were examined or newly introduced there, such as those relating to the decrease in frequency of aftershocks with time, the difference in magnitude between a main shock and the largest aftershock, the magnitude frequency relation of aftershocks, the dimension of the spatial spread of aftershocks, etc. After the publication of the above paper, aftershock studies have made remarkable advances. The important achievements in this field include various types of statistical studies using recent high-quality data on natural aftershocks and microaftershocks recorded at permanent and temporary stations and the experimental data on microfracturing of rock specimens and other materials obtained in laboratories. However, owing to the nature of the phenomena, the results show considerable scatter, and more data must be collected and analyzed to have a better understanding of the processes of aftershock occurrence.

In the present paper the statistical laws of aftershock occurrence are examined again using data on aftershock sequences of shallow earthquakes in and near Japan with magnitude 5.5 and greater during ten years from 1959 through 1968 together with the data used in the previous paper with some additions and modifications. The data are supplied mainly from the Seismological Bulletin of the Japan Meteorological Agency and partly from other publications. Some unpublished data are also adopted. Improvements of the instrumentation and the data processing during recent years have much increased the quality and quantity of the data.

Distributions of aftershocks in time, space, and magnitude in each sequence are characterized by several parameters. Although values for some parameters are not very accurately determined, it seems certain that they vary from sequence to sequence. There are possibilities that some parameters are to some extent correlated with each other and with parameters for the main shock. The values of these parameters are determined during the course of the present study and the relations among them are investigated.

Some aftershock sequences and swarms occurring in some particular regions have fairly complex patterns of time distribution. This can be interpreted as results of multiple occurrence of rather simple aftershock sequences. Large scale swarms in non-volcanic regions may be regarded as groups of aftershock sequences triggered by several large shocks of approximately equal magnitudes. Some features of such complex sequences will be discussed in the second part of this paper.

Several stochastic models have been proposed to represent at least part of the observed characteristics of the occurrence of aftershocks. A disucssion of these and other possible models for aftershocks will be made in a later part referring to the results of the present investigation.

The importance of aftershocks in earthquake statistics has been pointed out by some investigators. For example, it has been remarked that misleading conclusions are sometimes drawn about the time distribution of earthquakes without proper consideration to the aftershocks included in the data. A small number of large earthquakes are accompanied by a large number of aftershocks, therefore the existence of such large earthquakes and fluctuation in their occurrence produce a large effect on the time distribution of earthquakes when all earthquakes are treated on the equal basis. The existence of aftershocks also affects the interpretation of the distributions of earthquakes in space and magnitude. The statistical properties of aftershock occurrence may be a factor to be considered in a general study of earthquake occurrence.

The term "aftershock" or "foreshock" is widely used without giving its exact definition. A broad definition may be as follows. "It is often observed that a number of earthquakes occur in a group within a limited interval of time and space. The largest earthquake in such a series is called the main shock, and smaller ones occurring before and after the main shock are called foreshocks and aftershocks respectively." Usually aftershocks are easily identified, especially in regions where the background seismic activity is low. However a question sometimes arises whether a particular shock should be regarded as an aftershock (or foreshock) of another larger earthquake, or an independent shock. Although such ambiguous shocks do not seriously influence the results and conclusions of many studies, some definite criterion is required to distinguish the aftershocks and foreshocks from other types of earthquakes in order to make a detailed discussion of the problem.

Some authors set up some tentative rules to classify earthquakes into aftershocks, foreshocks, etc. Yamakawa[2)-4)] proposed a method to distinguish an abnormal seismic activity, such as an aftershock sequence, a swarm, etc., from the background seismic activity in the region concerned, though this method does not give a rule to decide whether an earthquake belongs to an aftershock sequence or not. After all, it is concluded that a definition of aftershocks uniformly applicable to all kinds of aftershock problems is difficult to establish, and a suitable working definition must be formulated according to the character of the problem and the data employed. It is important to use the same criterion throughout the same problem.

2. Difference in magnitude between a main shock and the largest aftershock and related problems

In 1957 the author5) plotted D_1 $(=M_0-M_1)$ against M_0 (M_0: magnitude of the main shock, M_1: magnitude of the largest aftershock) for 90 Japanese shallow earthquakes having M_0 equal to and larger than 6, and stated that for $M_0 \geq 6.5$ D_1 is distributed from 0 to 3 with a median $\tilde{D}_1$ of 1.4. The value of 1.4 approximately agrees with the value of 1.2 reported by Båth.6)-7)

For a group of earthquakes for which the magnitude distribution follows Gutenberg-Richter's law

$$\log n\,(M) = a - b\,M\,, \tag{1}$$

the distribution of the magnitude difference D between the largest and the second largest earthquakes is represented by1)

$$q\,(D) = b \ln 10\; 10^{-bD}\,. \tag{2}$$

The value of $D_1=1.4$ or 1.2 is considerably larger than the median of D calculated from (2) with a value of b between 0.5 and 1.5, since

$$\tilde{D} = (\log 2)/b \fallingdotseq 0.3/b\,. \tag{3}$$

It has been observed that in many instances the magnitude distribution of aftershocks follows Gutenberg-Richter's law. If the main shock is included in the magnitude statistics of aftershocks, its magnitude M_0 is in most cases too large. This indicates that the main shock belongs to a different category from the aftershock sequence. It is not acceptable that the main shock is nothing but the largest event in a series of earthquakes.

Kurimoto8) tried to make an explanation of the author's result: $D_1 \fallingdotseq 1.4$. It seems impossible to provide an explanation of this result on a purely statistical basis.

In a paper of 1961 the author1) revised the diagram of D_1 vs M_0 using data on 223 Japanese shallow earthquakes with M_0 6 and more. The open circles in Figure 2 represent the same data. An important revision was the inclusion of the earthquakes whose D_1 could not be determined. Some of these earthquakes were followed by one or more aftershocks for which published seismometrical data were insufficient for determining their magnitudes. The other ones were followed by no observable aftershocks, as their magnitude were too small to be detected by routine seismic instruments. A misleading relation between M_0 and D_1 might have been obtained, if the earthquakes with unknown D_1 had been excluded in the investigation. The relation between the median of D_1 and M_0 was given by the equation

$$\tilde{D}_1 = 4.7 - 0.45\, M_0 . \tag{4}$$

A similar study was published in 1967 by Papazachos et al.[9] for earthquakes in the region of Greece with $M_0 \geq 5\ ^3/_4$ in the years 1926–1964. Their relation, when expressed in the same form as equation (4), is

$$D_1 = -1.07 + 0.29\, M_0 . \tag{5}$$

If this equation is extended to lower magnitude, it gives a strange result, $D_1 = 0$ at $M_0 = 3.7$. Equations (4) and (5) give the equal value of D_1 ($=1.2$) at $M_0 = 7.8$.

Table 1 lists all shallow earthquakes (depth $h \leq 60$ km) occurring within the area shown in Figure 1 during ten years from 1959 through 1968. The marks "a" and "f" in the column D_1 denote that the earthquake in question is classified as an aftershock and a foreshock of another earthquake in the table respectively. D_2 denotes the difference in magnitude between the largest and the second largest aftershocks. T_1 is the time interval between a main shock and the largest aftershock.

The definition of foreshocks and aftershocks used here is as follows. First, it should be confirmed that any earthquake listed in Table 1 is not classified as an aftershock of an earthquake before 1959.

The earthquakes in Table 1 are picked up in descending order of magnitude (for equal magnitude events, in order of the time of occurrence), and for each earthquake its foreshocks and aftershocks are selected out by the method described below, if it has not been classified as a foreshock or an aftershock of another earthquake already examined.

(1) The case of earthquakes whose aftershock areas are determined.

The aftershock area will be discussed in Chapter 4, (p. 159), in which ellipses A, B, and C are defined. All earthquakes whose epicenters fall within the ellipse B during the one month's intervals immidiately before and after

Table 1. List of shallow earthquakes with $M \geq 5.5$ which occurred in the area shown in Figure 1. This list includes all earthquakes with $h \leq 60$ km, and also those with $h > 60$ km each of which is regarded as a foreshock, or a main shock, or an aftershock of a listed earthquake with $h \leq 60$ km. Marks "f" and "a" in the column D_1 denote that the earthquake is a foreshock and an aftershock of another earthquake listed, respectively. For mark C see the text.

No.	Origin Time (GMT) d h m	Epicenter °N	°E	h km	M_0	$D_1 = M_0 - M_1$	$D_2 = M_1 - M_2$	T_1 d h m	Mark
1	1959 Jan. 22 05 10	37.6	142.4	30	6.8	1.1	0.4	04 36	
2	07 33	43.5	144.2	10	5.7	f			
3	09 46	37.5	142.7	30	5.7	a			
4	30 20 38	43.4	144.4	20	6.2	0.1	1.1	01 38	
5	22 16	43.5	144.4	0	6.1	a			
6	Feb. 5 10 05	36.3	141.7	30	5.6				
7	Mar. 20 15 44	37.2	143.5	30	5.6				
8	24 15 18	34.1	142.0	30	5.5				
9	Apr. 15 00 15	41.1	143.2	40	6.1	1.4	1.3	01 03	
10	June 2 00 47	31.4	132.1	20	5.8				
11	July 7 14 40	39.7	143.7	30	5.5				
12	Sept. 8 10 03	36.4	140.7	50	5.6				
13	23 22 23	34.7	138.4	10	5.8	0.9	0.2	04 23	
14	Oct. 19 02 46	43.5	148.0	60	5.5				
15	26 07 35	37.6	143.2	20	6.7	1.5	0.8	1 14 41	
16	Nov. 8 03 54	43.8	140.6	10	6.2	2.3	0.2	04 23	
17	Dec. 22 17 20	37.7	142.0	40	5.7				
18	1960 Jan. 31 05 08	32.9	135.0	20	6.1				
19	Feb. 4 16 50	38.6	143.2	20	6.1	0.4	1.1	04 07	C
20	20 57	38.8	143.1	20	5.7	a			
21	Mar. 20 13 36	39.8	143.3	10	5.7	f			
22	17 07	39.8	143.5	20	7.5	0.8	0.5	2 07 16	
23	21 00 34	39.7	143.4	20	6.2	a			
24	06 51	39.8	143.8	20	5.6	a			
25	09 18	39.6	143.6	20	5.9	a			
26	22 10 22	39.3	143.5	20	5.6	a			
27	23 00 23	39.3	143.8	20	6.7	a			
28	01 07	39.5	143.4	20	6.1	a			
29	01 51	39.5	143.5	20	5.6	a			
30	02 09	39.5	143.5	20	5.6	a			
31	08 46	39.7	143.5	20	5.9	a			
32	10 28	39.0	143.8	20	5.7	a			
33	11 50	39.1	143.8	20	5.8	a			
34	16 01	39.2	143.8	10	5.7	a			
35	21 34	39.2	143.8	20	5.6	a			
36	22 22	39.2	143.5	20	6.2	a			
37	24 09 58	39.6	143.8	20	5.6	a			
38	31 03 02	39.5	144.0	30	5.5	a			
39	06 13	39.5	143.8	40	5.6	a			
40	Apr. 15 10 06	41.5	144.8	40	5.5	0.5		57	
41	June 3 16 18	41.5	142.0	60	5.7	1.8	0.4	55	
42	15 15 36	40.1	142.5	40	6.0	0.8	0.3	1 22 17	
43	July 8 12 51	30.3	130.7	60	6.1				
44	13 20 27	34.3	139.1	0	5.5	1.1	0.2	17 09	
45	29 17 31	40.2	142.6	30	6.7	0.5	1.1	14 13 40	
46	Aug. 12 13 12	36.4	141.5	40	5.9	2.2		13 11	
47	13 07 11	40.3	142.5	40	6.2	a			
48	Sept. 6 15 24	41.9	142.7	60	5.5	1.0	1.0	03	
49	26 11 36	32.5	132.0	20	5.6	f			
50	Oct. 28 22 29	34.6	141.7	40	6.1	1.5	0.2	19	

Table 1. Continued.

No.	Origin Time (GMT)			Epicenter		h	M_0	$D_1=$	$D_2=$	T_1	Mark
			d h m	°N	°E	km		M_0-M_1	M_1-M_2	d h m	
51		Nov.	7 13 23	32.4	132.1	60	5.8				
52		Dec.	4 16 20	32.0	142.2	60	5.6				
53			26 01 04	34.2	136.2	60	6.0				
54	1961	Jan.	6 01 20	42.0	143.8	40	5.6	1.9		1 20 37	
55			16 07 20	36.0	142.3	40	6.8	0.2	0.1	08 21	
56			08 48	36.0	141.9	0	5.5	a			
57			09 19	36.0	141.9	20	6.4	a			
58			09 41	36.3	141.6	0	5.5	a			
59			12 12	36.2	142.0	20	6.5	a			
60			13 09	36.0	141.9	20	5.7	a			
61			14 04	36.1	142.5	40	6.1	a			
62			14 44	36.4	141.7	0	5.5	a			
63			15 41	36.2	142.1	40	6.6	a			
64			20 22 34	37.1	141.6	40	5.5	2.2		19 14	
*		Feb.	12 21 53	43.2	147.9	80	6.7	0.4	0.0	01 33	
65			23 26	42.9	147.2	20	6.3	a			
66			13 16 27	43.0	147.8	60	6.1	a			
67			15 10 45	43.3	147.9	60	6.3	a			
68			23 04 16	38.3	143.5	0	6.4				
69			26 18 10	31.6	131.9	40	7.0	1.7	0.1	01 33	
70		Mar.	15 22 16	32.0	130.7	0	5.5	0.5	0.5	2 08 06	
71			19 04 52	40.2	143.4	60	5.5				
72			24 22 57	35.7	141.3	0	6.1	2.8		01 42	
73		May	7 12 14	35.1	134.4	40	5.9	0.7	0.0	06	
74			16 21 45	30.5	132.0	60	5.8				
75			27 07 18	41.2	142.3	40	5.5	1.3	0.2	6 14 49	
76		June	19 02 46	39.1	143.7	40	5.6	f			
77			07 38	39.1	143.7	40	5.8	0.3	1.0	21	C
78			07 59	39.2	143.5	40	5.5	a			
79		July	17 16 20	35.8	141.6	0	5.8	1.6		09 23	
*		Aug.	11 15 51	42.9	145.6	80	7.2	0.3	0.8		
80			23 34	42.8	145.6	60	5.8	a			
81			19 05 33	36.0	136.8	0	7.0	1.8	0.2	02 34	
82			21 17 00	40.9	139.3	40	5.5				
83		Sept.	28 03 24	30.8	141.9	60	5.5	0.8		55	
84		Nov.	15 07 17	42.7	145.6	60	6.9	a			
85			25 20 20	36.2	141.7	20	5.8				
86			27 05 57	31.3	131.5	40	6.0				
87	1962	Jan.	4 04 35	33.6	135.2	40	6.4	2.1	0.2	04 54	
88			9 12 41	42.7	145.4	60	6.0	a			
*		Feb.	20 16 05	42.8	145.2	80	6.1	a			
89		Apr.	12 00 53	38.0	142.8	40	6.8	0.4	0.6	13 14 58	
90			05 16	37.8	142.9	40	5.8	a			
91			17 20 54	38.0	142.8	40	5.6	a			
92			23 05 58	42.2	143.9	60	7.0	1.7	0.3	09 20 40	
93			25 15 47	38.2	143.1	60	6.4	a			
94			30 02 26	38.7	141.1	0	6.5	1.7	0.1	4 21 15	
95		May	5 11 11	34.1	139.3	0	5.8	1.6	0.5	22 30	
96		July	17 17 20	42.6	145.2	60	5.9	1.7	0.2	09 23	
97			28 19 43	36.7	142.1	40	5.5	1.5		12 09 04	
98		Aug.	26 06 49	34.1	139.5	40	5.9	0.1	0.4	3 15 48	
99			27 16 20	38.2	142.8	40	5.8				
100			29 22 37	34.0	139.3	0	5.8	a			
101		Sept.	24 14 38	42.5	145.8	40	5.6	1.0		07	
102		Nov.	2 15 00	36.8	141.4	40	5.7				

Table 1. Continued.

No.	Origin Time (GMT) d h m	Epicenter °N	Epicenter °E	h km	M_0	$D_1=M_0-M_1$	$D_2=M_1-M_2$	T_1 d h m	Mark
103	Nov. 14 07 48	35.7	141.1	40	5.8	0.9	0.1	08	
104	Dec. 21 09 33	42.0	142.5	60	6.3	2.8	0.2	48	
105	27 18 18	39.7	142.2	40	5.9				
106	1963 Feb. 9 03 53	36.4	137.7	0	5.5	2.0	0.1	01 09	
107	Mar. 1 10 46	41.0	143.3	60	5.5				
108	26 21 34	35.8	135.8	0	6.9	1.6	0.1	9 15	
109	May 8 10 22	36.4	141.2	40	6.1	1.4	0.2	12 10 38	
110	June 3 07 36	34.1	138.8	40	5.9	2.1	0.4	01 29	
111	Aug. 15 06 11	37.7	142.0	40	6.6				
112	20 15 48	41.1	143.0	60	5.7				
113	Sept. 6 06 04	36.7	130.7	60	6.0	f			C
114	7 01 17	36.7	130.7	40	6.2				
115	Oct. 3 23 24	31.9	132.2	20	6.3	0.5	0.8	01 03	
116	4 00 27	31.6	132.2	40	5.8	a			
117	5 07 34	32.4	131.6	40	5.6				
118	1964 Jan. 10 04 51	41.7	142.9	40	6.1				
119	Feb. 5 11 30	36.4	141.1	40	6.0	2.0	0.0	1 18 59	
120	7 12 58	39.8	142.9	40	5.7	2.4		49	
121	29 15 20	34.7	142.2	60	5.5				
122	Apr. 16 01 04	36.9	143.1	0	6.0	0.8		20 14 07	
123	May 7 07 58	40.3	139.0	0	6.9	0.4	1.3	12 14	
124	20 12	40.5	139.1	0	6.5	a			
125	24 10 31	34.3	141.0	0	5.7	1.2		04 02	
126	30 14 30	36.2	141.2	40	6.2	0.8	1.6	8 09 19	
127	31 00 40	43.3	147.2	60	6.7	1.7	0.1	1 17 51	
128	June 16 04 01	38.4	139.2	40	7.5	1.4	0.0	16	
129	04 17	38.8	139.0	0	6.1	a			
130	06 53	38.6	139.2	0	6.1	a			
131	07 15	38.4	139.3	20	6.1	a			
132	19 10 05	38.8	139.5	0	5.5	a			
133	July 12 01 45	38.5	139.3	0	6.0	a			
134	Oct. 22 09 54	36.6	141.2	60	5.5				
135	Nov. 14 03 56	33.4	132.1	60	5.8				
136	27 13 47	38.0	138.3	40	5.8	1.8	0.3	02 05	
137	Dec. 8 17 49	34.6	139.3	0	5.8	0.3	0.2	16 23 12	
138	10 15 11	40.4	138.9	40	6.3	1.0	0.3	08 19	
139	25 17 01	34.7	139.3	0	5.5	a			
140	1965 Feb. 16 12 24	38.9	142.1	60	5.7	1.4	0.4	15 17 52	
141	Mar. 16 16 46	40.7	143.2	40	6.4	0.0	1.0	12 18 01	C
142	29 10 47	40.7	143.2	40	6.4	a			
143	Apr. 6 05 32	36.1	139.9	60	5.5	0.4	0.6	6 10 18	
144	19 23 42	34.9	138.3	20	6.1	2.9	0.2	10	
145	May 18 22 46	43.3	146.9	60	5.5	0.4	0.0	04 23	
146	June 13 07 06	41.6	143.8	20	6.0				
147	July 25 13 33	41.3	146.6	60	5.5				
148	Sept. 10 19 26	37.3	141.4	60	5.5				
149	17 12 59	36.3	141.5	20	5.5	f			
150	13 21	36.3	141.5	0	5.6	f			
151	14 22	36.2	141.5	40	5.5	f			
152	15 18	36.2	141.5	40	5.7	f			
153	16 21	36.3	141.5	40	6.8	0.5	1.4	4 05 47	
154	21 22 08	36.4	141.4	40	6.2	a			
155	25 14 37	39.5	143.7	60	5.6	0.0	0.1	16	C
156	14 42	39.5	143.7	40	5.5	a			
157	14 53	39.6	143.5	40	5.6	a			

Table 1. Continued.

No.	Origin Time (GMT) d h m	Epicenter °N °E	h km	M_0	$D_1=$ M_0-M_1	$D_2=$ M_1-M_2	T_1 d h m	Mark
158	Nov. 6 08 57	34.1 139.0	20	5.6	1.1	0.5	07 43	
159	12 17 52	30.6 140.6	0	6.5	0.9	0.2	14 09 13	
160	14 05 54	36.5 141.2	40	5.6	1.3	0.2	17 06 45	
161	27 03 05	30.4 140.3	60	5.6	a			
162	1966 Jan. 11 14 16	33.6 137.3	20	5.9	1.3	0.3	19	
163	Apr. 3 04 43	36.3 141.5	20	5.8				
164	21 15 45	35.5 142.3	40	5.8	0.3		01 52	C
165	17 37	35.5 142.2	40	5.5	a			
166	May 14 17 04	34.1 139.0	20	5.5				
167	Aug. 19 12 46	36.3 142.0	40	5.7				
168	Oct. 16 09 14	30.6 142.9	40	5.5				
169	Nov. 12 12 01	33.1 130.3	20	5.5				
170	12 50	41.6 144.4	40	5.9	1.2	0.1	10 15	
171	Dec. 27 01 22	37.1 141.2	40	5.5				
172	1967 Jan. 6 00 04	41.8 143.5	50	5.9				
173	17 11 59	38.3 142.1	30	6.3	1.5	1.0	27	
174	24 03 05	41.4 142.1	50	5.7				
175	Feb. 28 09 37	32.5 142.3	40	5.5				
176	Sept. 15 00 28	35.6 140.9	40	5.6	2.0		3 22 13	
177	Nov. 4 13 27	37.3 141.9	50	5.8				
178	14 30	43.5 144.3	20	6.5	0.8	1.3	15	
179	14 45	43.5 144.2	0	5.7	a			
180	19 12 07	36.4 141.2	50	6.0	1.3	0.7	17 18 39	
181	1968 Jan. 7 11 12	33.6 142.0	40	5.6				
182	29 10 19	43.2 147.0	30	6.9	1.1	0.1	6 00 42	
183	16 43	43.2 147.2	40	5.7	a			
184	30 03 02	42.9 147.6	50	5.6	a			
185	Feb. 4 11 01	42.7 147.1	10	5.8	a			
186	20 23 51	32.0 130.7	0	5.7	f			
187	21 01 45	32.0 130.7	0	6.1	0.4	0.1	32 14 13	
188	22 10 19	32.0 130.8	0	5.6	a			
189	Mar. 24 15 58	32.0 130.7	0	5.7	a			
190	Apr. 01 00 42	32.3 132.5	30	7.5	1.2	1.6	06 31	
191	07 13	32.3 132.4	0	6.3	a			
192	21 08 34	38.6 143.5	60	5.8	0.3	0.7	10 00 10	
193	May 1 08 44	38.6 143.5	60	5.5	a			
194	9 14 22	34.0 136.9	0	5.6	1.1	0.8	41	
195	16 00 48	40.7 143.6	0	7.9	0.4	0.3	09 51	
*	01 05	40.9 144.5	80	6.2	a			
196	01 51	41.4 143.6	10	5.5	a			
197	06 36	41.0 143.3	40	5.9	a			
198	08 58	41.4 142.6	10	5.8	a			
199	10 39	41.4 142.9	40	7.5	a			
200	12 09	41.0 143.3	50	5.5	a			
201	16 13	39.8 143.9	50	6.1	a			
202	16 21	39.9 144.0	10	5.6	a			
203	18 43	40.8 142.3	40	5.9	a			
204	19 16	41.3 142.6	30	5.9	a			
205	20 22	41.4 142.7	0	5.9	a			
206	23 04	39.8 143.5	30	6.7	a			
207	17 10 42	39.6 143.8	60	5.7	a			
208	13 02	41.4 143.0	40	5.7	a			
209	16 02	40.6 144.3	50	5.6	a			
210	18 17	39.7 143.5	20	5.7	a			
211	22 36	40.6 144.2	50	5.5	a			

Table 1. Continued.

No.	Origin Time (GMT)		Epicenter		h	M_0	$D_1=$	$D_2=$	T_1	Mark
		d h m	°N	°E	km		M_0-M_1	M_1-M_2	d h m	
*	May	19 04 12	35.4	142.4	90	5.8	0.3		01 42	} C
212		05 53	35.5	142.5	40	5.5	a			
213		22 16	40.9	143.5	30	5.8	a			
214		20 06 54	40.4	144.0	40	5.6	a			
215		21 04 11	41.2	143.7	10	5.5	a			
216		22 10 51	41.4	143.0	50	5.9	a			
217		19 29	40.3	142.6	30	6.3	a			
218		24 04 06	40.8	143.5	40	6.2	a			
219		25 11 52	40.2	143.3	30	5.7	a			
220	June	1 10 31	40.2	142.5	30	5.7	a			
221		6 21 17	41.3	142.6	40	5.7	a			
222		8 05 30	43.1	147.1	40	5.7	a			
223		12 13 41	39.4	143.1	0	7.2	a			
224		14 17	39.3	142.9	20	5.5	a			
225		17 51	39.2	143.1	40	5.6	a			
226		21 57	39.3	143.1	40	6.1	a			
227		13 00 04	39.5	143.3	40	5.8	a			
228		02 05	39.4	143.2	30	5.8	a			
229		11 56	39.2	143.3	40	5.7	a			
230		21 10	39.4	143.1	40	5.8	a			
231		14 03 18	39.4	143.0	20	5.7	a			
232		11 52	39.3	143.1	30	5.5	a			
233		15 03 31	39.4	143.0	40	5.5	a			
234		17 11 52	40.9	143.4	10	6.4	a			
235		16 56	40.1	144.1	60	5.6	a			
236		18 57	38.6	144.2	40	6.0				
237		19 01 38	39.5	143.2	50	5.7	a			
*		22 01 12	40.3	143.9	70	5.9	a			
238		25 23 33	39.5	144.0	50	5.5	a			
239		26 10 23	41.9	142.8	40	5.7	a			
240	July	1 10 45	36.0	139.4	50	6.1	2.0	0.1	2 22 32	
241		5 11 28	38.4	142.2	50	6.4	1.8	0.3	21 20 55	
242		10 20 40	40.2	143.6	30	5.7	a			
243		12 00 44	39.6	143.5	40	6.4	a			
244		03 56	39.6	143.4	30	5.8	a			
245		23 23 00	40.3	143.7	30	5.7	a			
246	Aug.	5 16 17	33.3	132.4	40	6.6	1.3	0.4	12 04	
247		8 04 55	36.4	141.6	10	5.6	1.6		23 21	
248		16 10 39	38.6	143.9	0	5.9	a			
249		18 07 12	35.2	135.4	0	5.6	0.4	0.7	01	
250		25 09 07	40.1	143.6	30	5.8	a			
251		09 14	40.1	143.5	50	5.7	a			
252	Sept.	15 10 50	40.8	143.5	20	5.8	a			
253		23 05 03	40.3	143.9	10	5.7	a			
254		24 03 34	40.3	143.9	20	5.8	a			
255	Oct.	7 20 49	41.8	142.7	60	6.2	a			
256	Nov.	11 04 41	40.1	143.4	30	6.0	a			
257		13 18 41	40.2	142.8	30	6.0	a			
258		24 21 20	40.3	142.6	50	6.0	a			
259	Dec.	11 11 45	33.5	134.1	50	5.6	1.8		24 00 06	
260		16 21 22	39.8	143.9	40	5.5	a			
261		25 03 36	41.7	142.9	30	5.6	a			

the earthquake in question are designated as foreshocks and aftershocks respectively. If the number of epicenters (of all earthquakes located by JMA) falling within the ellipse A during adjacent one month's intervals before and after the intervals just tested is larger than half of the number of epicenters falling within the ellipse C, the shocks falling within the ellipse B are classified as foreshocks and aftershocks. The similar procedure is applied to the adjacent two months' intervals, four months' intervals, eight months' intervals, ... until the number of epicenters falling within the ellipse A becomes smaller than half of the number of epicenters falling within the ellipse C. (The intervals thus examined are represented by $2^n \leq t \leq 2^{n+1}$ and $-2^{n+1} \leq t \leq -2^n$ ($n=0, 1, 2, \ldots$), when t is measured in months from the origin time of the main shock.)

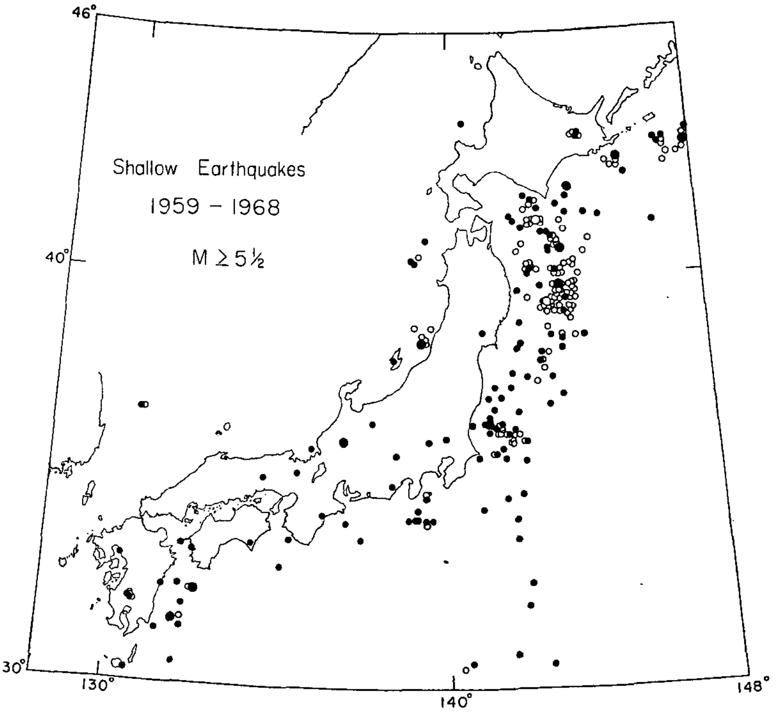


Fig. 1. Epicenters of shallow earthquakes with magnitude 5.5 and over during ten years from 1959 through 1968. Solid circles represent main shocks of earthquake sequences or isolated shocks. Open circles represent foreshocks or aftershocks of the other earthquakes. Large circles refer to earthquakes with magnitude 7 and over.

(2) The case of earthquakes whose aftershock areas are not determined. All earthquakes occurring within epicentral distance of r km from the earthquake of magnitude M_0 where $\log r = 0.5\,M_0 - 1.5$ and within one month's intervals immidately before and after the earthquake are designated as foreshocks and aftershocks respectively.

The epicenters of earthquakes listed in Table 1 are plotted in Figure 1. Solid and open circles indicate main shocks (including isolated shocks) and fore- and aftershocks respectively.

Solid circles in Figure 2 represent the data in Table 1. The earthquakes whose D_1 can not be determined are also plotted in the same figure. If D_1 for

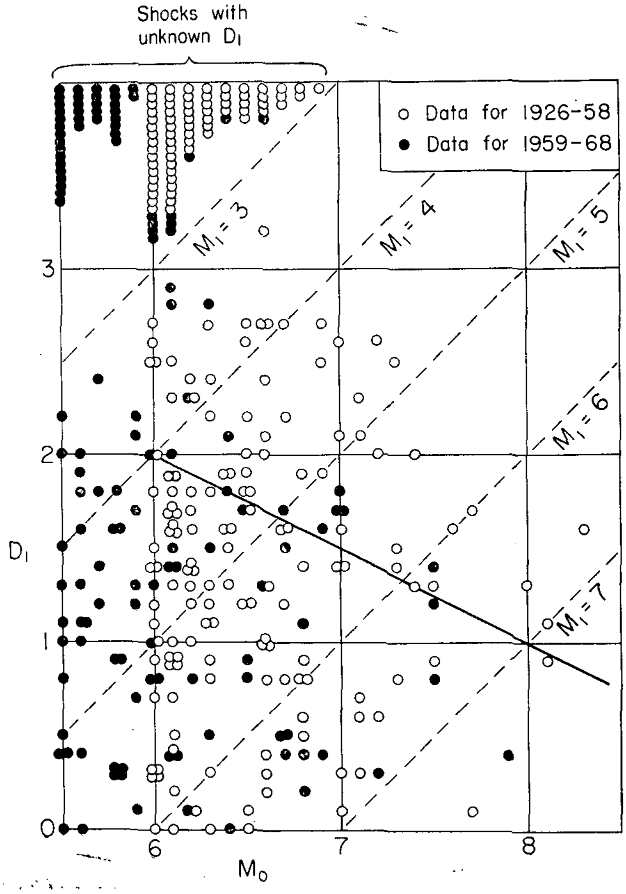


Fig. 2.

these earthquakes are known, the points for them will scatter somewhere above the line $M_1=4$. Considering such an effect and also the large scatter of the data, it seems unnecessary to revise equation (4). However if the relation between $\widetilde{D}_1$ and M_0 is expressed in a simpler form, it becomes

$$\widetilde{D}_1 = 5.0 - 0.5\,M_0 . \qquad (M_0 \geq 6) \qquad (6)$$

This equation is represented by a thick line in Figure 2. For $M_0 \leq 6$ this equation seems to give large $\widetilde{D}_1$ values, though sufficient data are not available in this magnitude range. Anyway it is a remarkable fact that the magnitude difference D_1 tends to increase with decreasing M_0 at least down to $M_0=6$. The scatter of D_1 also increases with decreasing M_0. Some examples indicating large scatter of D_1 are presented by Kárník.[10]

A look at Table 1 indicates that values of D_2 are in most cases smaller than D_1 and less scattered. The number of main shocks with M_0 6.2 and larger is 36, among which only three shocks have unknown D_1 and D_2 values. For the other 33 shocks the relation of D_1 and D_2 is shown in Figure 3. It is seen that D_2 is smaller than D_1 for 23 shocks. This suggests again the distinction between the main shock and its aftershocks.

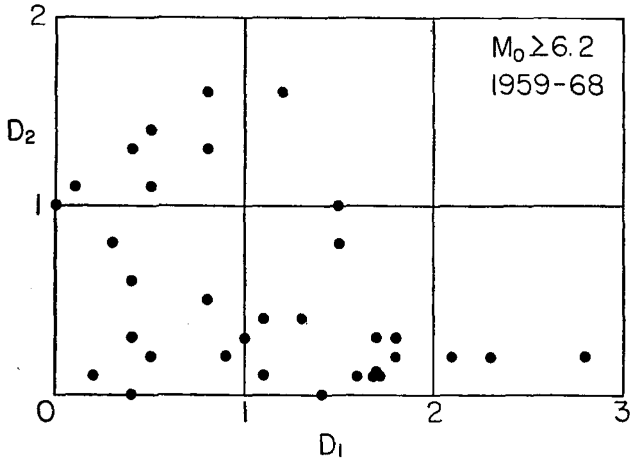


Fig. 3.

Solov'ev and Solov'eva[11] have shown that the number k of afterhoscks with magnitude larger than M_0-2 has a negative exponential distribution, and the mean value of k decreases with increasing focal depth h (in km) of the main shock as

$$\bar{k} = 160/h\,. \tag{7}$$

The scarcity of aftershocks in deep earthquakes is occationally mentioned since Wadati's study.[12),13)] Besides equation (7), quantitative descriptions of the decrease in aftershock activity with increasing depth are found in Mogi's [14)] and Båth's[7)] papers. Although D_1 is a rough index of the aftershock activity of an earthquake, variation of D_1 with focal depth of the main shock in the range of 0 to 60 km is not clearly seen from Table 1. Slight tendency for D_1 to increase with depth may be seen in Table 2, which is compiled using data in Table 1, but a statistical test can not reject the hypothesis of independence of D_1 on h even at low significance levels.

Table 2. Number of shocks belonging to two ranges of h and three ranges of D_1. $\tilde{D}_1=5.0-0.5M_0$ for $M_0\geq 6$, and $\tilde{D}_1=2.0$ for $5.5\leq M_0\leq 6$.

D_1 h	$0\leq D_1<\tilde{D}_1/2$	$\tilde{D}_1/2\leq D_1<\tilde{D}_1$	$\tilde{D}_1\leq D_1$
0km$\leq h<$30km	11	11	6
30km$\leq h\leq$60km	19	23	14
Ratio	0.58	0.48	0.43

Some investigators (e.g., Vere-Jones and Davies,[15)] Isacks et al.,[16)] Utsu[17)]) reported that deep earthquakes have a tendency to cluster in space and time in a different manner from ordinary main shock — aftershock sequences. In some cases a few earthquakes with mangitudes not very much different from each other occur in a cluster. Such a type of clustering is also observed in shallow earthquakes. Two typical examples observed in recent years are two earthquakes in the southwestern part of the Japan Sea (Nos. 113 and 114 in Table 1, $M=6.0$ and 6.2) and three earthquakes off Sanriku (Nos. 155, 156, and 157, $M=5.6$, 5.5, and 5.6). In both cases no other earthquakes were observed near the epicenters of these earthquakes. If earthquakes with magnitude larger than about 4 had occurred, they would be detected at nearest seismic stations. Other cases of such clusters are indicated by a mark "C" in Table 1. The focal depths of these earthquakes are usually not very shallow, whereas ordinary aftershock sequences mostly occur at very shallow depths (on this point see Matsushima[18)]). Page[19)] stated that prominent aftershock sequences occur only in the crust. This is in general acceptable, but it is a too severe statement that typical aftershock sequences never occur in the mantle (see Lukk,[20)] Purcaru[21)], and some examples in Japan.).

The geographical variation of D_1 in and near Japan was studied by

Mogi.[22]. A similar map showing the distribution of D_1 in Table 1 is shown in Figure 4. Some regularities are seen from the figure, but the agreement with Mogi's results is neither very good nor very poor. The geographical distribution of D_1 in the world has been investigated only briefly.[22],[23] Utsu[23] suggested a probable correlation between average D_1 and coefficient b in equation (1) for earthquakes in various regions of the world. A correlation between D_1 and b in each aftershock sequence is also pointed out[23]. This relation will be discussed again in Chapter 6. D_1 is also correlated with $A/\bar{A}$, the ratio of aftershock area to its standard value as described in Chapter 4.

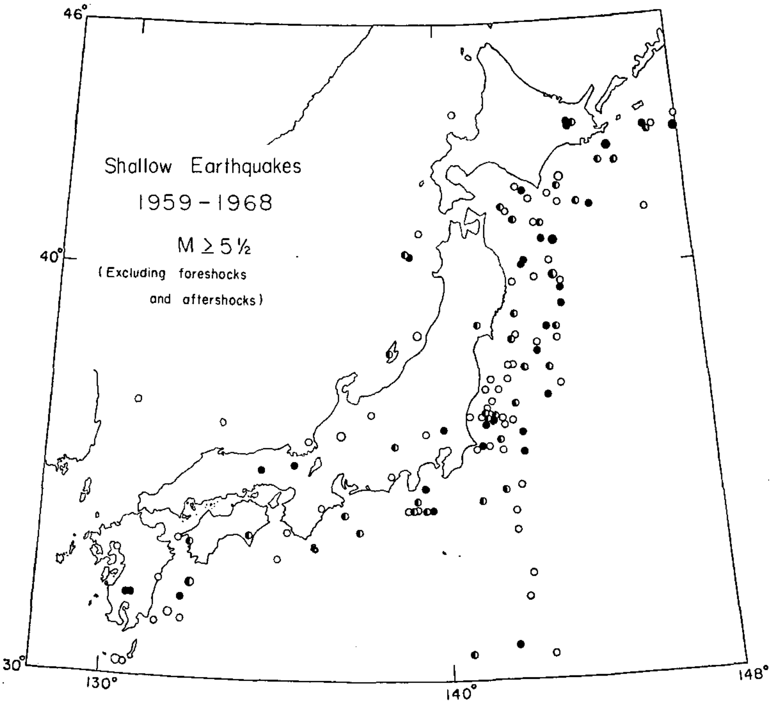


Fig. 4. Epicenters of main shocks of magnitude 5.5 and larger during 1959–1968 classified according to the ratio $D_1/\tilde{D}_1$. Filled cirles: $D_1/\tilde{D}_1 < 1/2$, half filled circles: $1/2 \leq D_1/\tilde{D}_1 < 1$, open circles: $1 \leq D_1/\tilde{D}_1$, where $\tilde{D}_1$ is the median of D_1 given as a function of M_0 by equation (6) for $M_0 \geq 6$ and $D_1 = 2$ for $M_0 < 6$.

3. Decrease in frequency of aftershocks with time

Omori[24)–27)] showed in 1894 that the frequency of aftershocks felt at Gifu per unit time interval (one day, one month, etc.) following the Nobi (Mino-Owari), central Japan, earthquake of October 28, 1891 was well represented by an equation of the form

$$n(t) = \frac{K}{t+c} \qquad (K,\ c\text{: constants}) \tag{8}$$

rather than an equation of the form

$$n(t) = K e^{-\lambda t}. \quad (K,\ \lambda\text{: constants}) \tag{9}$$

The aftershock data on this great inland earthquake ($M = 8\,{}^1/_4$) is still worth studying, since its aftershock activity can be traced for tens of years owing to a very large magnitude of the main shock and a comparatively low background seismic activity near the epicentral region.

Utsu[1)] compiled Omori's data[24)–27)] on Nobi aftershocks through 1899 and plotted them on a log-log scale, which is reproduced in Figure 5 as solid circles. Equation (8) is represented by a straight line with a slope of –1 for $t \gg c$ ($c \fallingdotseq 1/4$ day in this case), which fits the plotted data well for $t=1$ day to 3000 days.

The yearly frequency of earthquakes felt at Gifu after the Nobi earthquake is tabulated in Table 3. The average frequency of shocks per day after 1900 calculated from this table is plotted in Figure 5 as open circles. The data for the years marked with asterisks in Table 3 are excluded, because the large earthquakes listed in the same table which occured near the region of the Nobi earthquake considerably influenced the data. For the other years most of the felt shocks at Gifu occurred within 100 km from there. It is confirmed that the average yearly frequency of felt shocks for 1921–1967 (excluding the years with asterisks) whose epicenters lie beyond 100 km from Gifu is only 1.0. The aftershock area of the Nobi earthquake is not exactly known, but it probably covers a considerable part of the circle of radius of 100 km centered at Gifu. Open circles in Figure 5 lie near the extension of the line of slope –1 fitted to the data before 1900. If all data (open and solid circles) are fitted to a straight line, it has a slope of about –1.05. It is not an unreasonable idea that most of the near-by earthquakes felt at Gifu in recent years can be regarded as aftershocks of the Nobi earthquake. It is a remarkable fact that the aftershock activity continues for 80 years with a regularly decreasing rate of occurrence.

Table 3. Frequencies of earthquakes felt at Gifu after the Nobi earthquake of October 28, 1891.

Year	Freq.	Year	Freq.	Year	Freq.	Year	Freq.
1891	2181	1911	33	1931	11	1951	2
92	867	12	29	32	11	52	5
93	317	13	23	33	10	53	6
94	229	14	11	34	11	54	6
95	172	15	17	35	11	55	7
96	118	16	17	36	26	56	6
97	137	17	7	37	6	57	4
98	101	18	14	38	7	58	5
99	62	19	6	39	4	59	6
1900	77	20	10	40	10	60	5
01	64	21	8	41	4	61*	5
02	34	22	12	42	6	62	7
03	14	23*	26	43	8	63*	10
04	24	24	10	44*	13	64	4
05	54	25*	24	45*	74	65	3
06	39	26	14	46*	14	66	4
07	26	27*	33	47	10	67	0
08	22	28	10	48*	13	68	4
09*	90	29	4	49	10		
10	21	30	11	50	10		

* The years with asterisks include the following large earthquakes which considerably increase the frequencies of felt shocks at Gifu.

1909: Anegawa earthq. ($M=6.9$),
1923: Kwanto earthq. ($M=7.9$),
1925: Tajima earthq. ($M=7.0$),
1927: Tango earthq. ($M=7.5$),
1944: Tonankai earthq. ($M=8.0$),
1945: Mikawa earthq. ($M=7.1$),
1946: Nankaido earthq. ($M=8.1$),
1948: Fukui earthq. ($M=7.3$),
1961: Kita-Mino earthq. ($M=7.0$),
1963: Echizen-misaki earthq. ($M=6.9$).

A straight line with a slope of $-p$ on a logarithmic diagram like Figure 5 corresponds to the equation

$$n(t) = K t^{-p}. \tag{10}$$

This is a special form of the equation

$$n(t) = \frac{K}{(t+c)^p}. \tag{11}$$

Equation (11) was first adopted by Hirano[28] in 1924 to represent the frequency of aftershocks of the great Kwanto earthquake of 1923 observed at Kumagaya, though he used different p values (1.6 and 0.8) for two stages of the aftershock sequence. The original Omori formula (8) is also a special form of equation (11) which is now called the modified Omori formula.

The original Omori formula was applied successfully to many aftershock sequences[29)-39)]. However it is also reported that the frequency-time distribu-

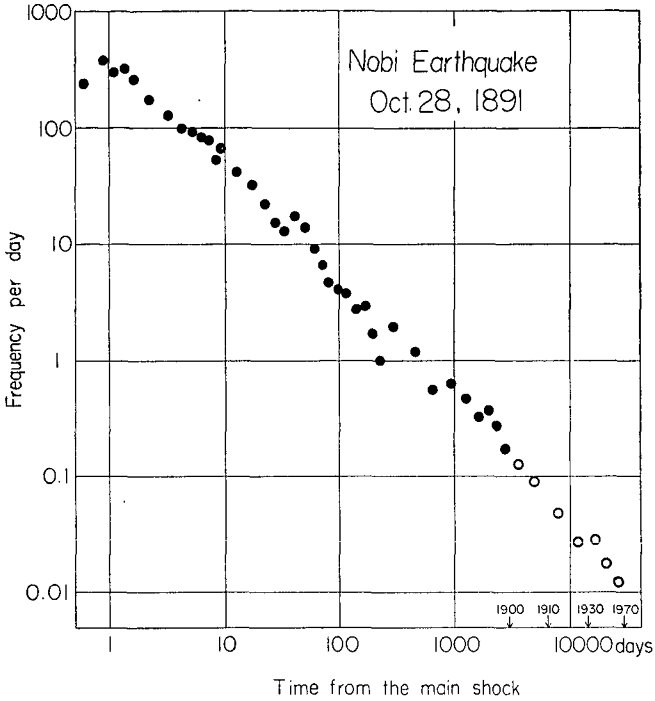


Fig. 5. Frequency of aftershocks of the Nobi earthquake of 1891 felt at Gifu plotted against the time from the main shock. Solid circles: data by Omori, open circles: data supplied from the Gifu Local Meteorological Observatory.

tions for some aftershock sequences could not well be represented by the Omori formula.40)–44) Some of these sequences contain remarkable secondary aftershock sequences or swarms.

For aftershock sequences following the original Omori formula, when the cumulative freuency $N(t)$, i.e., the number of aftershocks which occurred until time t, is plotted against log t, the curve tends to a straight line with a slope of K asymptotically with increasing t. However Utsu5) pointed out in 1957 that the cumulative frequency curves for many aftershock sequences do not tend to straight lines but gradually decrease their slopes with time, and the frequency vs time plots on log-log scales fit straight lines with slopes of about -1.4. This indicates that in many cases the modified Omori formula with p somewhat larger than unity is more suitable than the original one. Frequency vs time plots for more than 40 Japanese aftershock sequences published by Utsu1) and Mogi45) showed the fitness of the modified formula.

The values of p obtained in these studies fall in the range between 0.9 and 1.9 and values between 1.0 and 1.4 are most frequent. The value of p is considered to be an important parameter which characterize an aftershock sequence. Mogi[45),22)] noticed the regional variation of the p-value in Japan. No correlation was found between the p-value and the magnitude of the main shock M_0. The p-values for 27 aftershock sequences have been given commonly by Utsu[1)] and Mogi.[45)]. Although the source of data is mostly the same for both studies, the p-values for several sequences are somewhat different. This disagreement is mainly due to the fact that Utsu applied equation (11) to the data for the time interval from about 0.2 day to a few hundred to more than one thousand days while Mogi applied equation (10) to the data of 1 day to 100 days from the main shock. For some aftershock sequences (Off Sanriku: 1933, W off Hokkaido: 1940, Off Boso: 1953, Off Izu: 1956) the decrease in frequency becomes more rapid after several tens to hundreds of days from the main shock, thus p-values determined by Utsu are larger than those by Mogi. (The p-value of the Oga sequence of 1939 by Utsu is in error. This should be corrected to $p=1.5$.) Utsu[5)] mentioned in 1957 that the frequency of aftershocks seems to decrease according to an exponential law (9) after about 100 days from the main shock. However examinations of many sequences indicate that this may not be a general law.

In some sequences the frequency of aftershocks is well represented by the modified Omori formula for more than ten years as illustrated in Figure 5. These sequences occur in regions where usual seismic activity is relatively low. Another good example of such sequences is the Tottori sequence started on September 10, 1943.[46)] Asano[47)] reported that the seismic activity in Kwanto district was decreasing rather irregularly for more than ten years after the great Kwanto earthquake of 1923. The modified Omori formula is not applicable to this activity probably due to the contamination of various types of activities not directly related to the great Kwanto earthquake.

Frequency vs time plots for ten aftershock sequences in Japan after 1959 are shown in Figures 6–15. Here the earthquakes listed in the Seismological Bulletin of JMA are counted among the aftershocks based on the following principle. For these sequences it is very remarkable that the seismic activity suddenly increased to a very high level at the time of the main shock. All shocks which belong to this increased activity are regarded as aftershocks. Actually if the same name of the epicenter location appears three times or more in the list of earthquakes of the JMA seismological bulletin for the

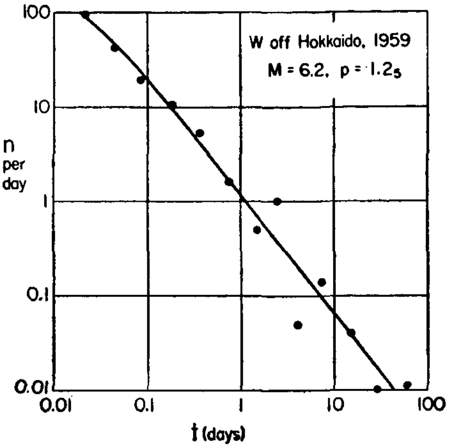


Fig. 6.

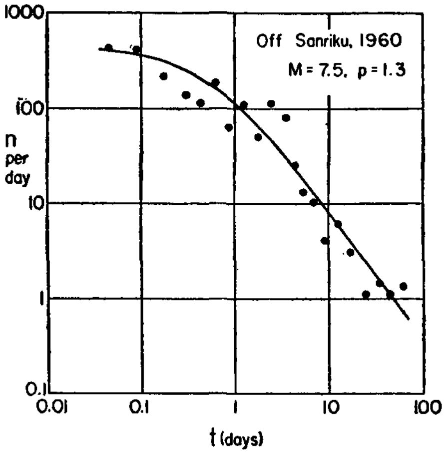


Fig. 7.

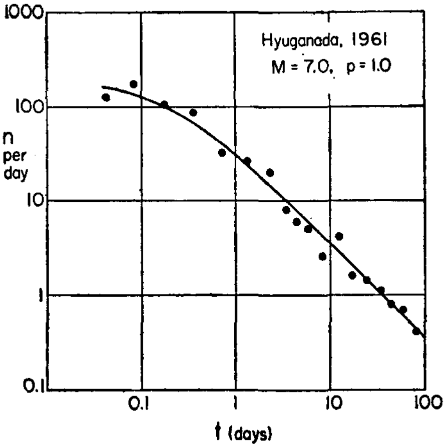


Fig. 8.

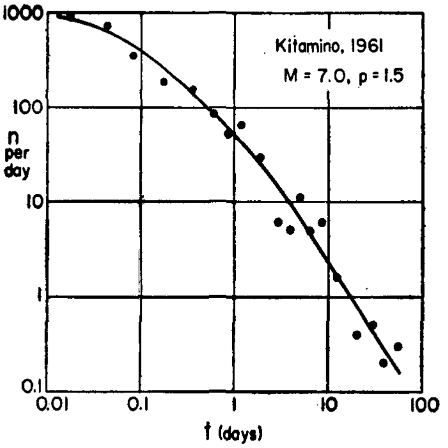


Fig. 9.

first 24 hours after the main shock, the shocks bearing that name (or other geographically equivalent names — for example, "Off Miyazaki Pref." ~ "Hyuganada") in the list are regarded as aftershocks throughout the whole period of investigation, unless the name indicates that the epicenter is certainly located at a place more than r km from the epicenter of the main shock where $\log r = 0.5M_0 - 1.5$.

The curves in Figures 6–15 represent equation (11) with parameters p, c, and K whose values are chosen to obtain the best fit to the plotted points in

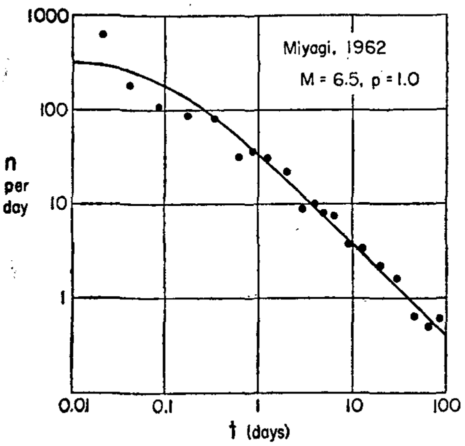


Fig. 10.

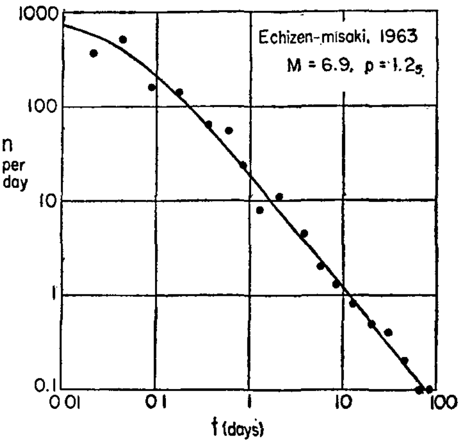


Fig. 11.

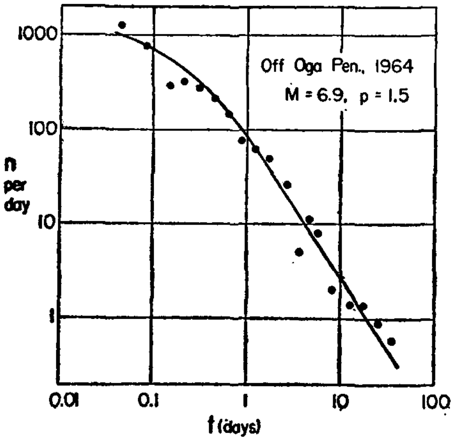


Fig. 12.

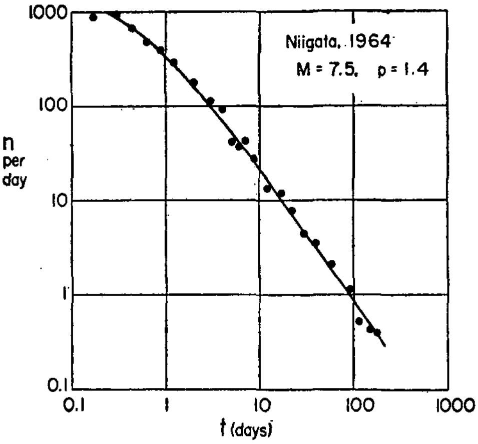


Fig. 13.

each case. Values of p and c for each sequence are listed in Table 4, together with those obtained in the previous study[1] for earthquakes of $M_0 \geq 6$ before 1959. For earthquakes No. 60 and No. 61 values of p and c have been obtained by Hirota.[48]-[49] For earthquakes No. 42 and No. 56 p and c values are estimated from papers by Yamakawa[4] and Tsumura[50] respectively. These values are also included in the table. For the Oga earthquake (No. 53) Research Group for Aftershocks (Tôhoku University)[51] gives $p = 1.34$, and for the Niigata earthquake (No. 54) Japan Meteorological Agency[52] gives

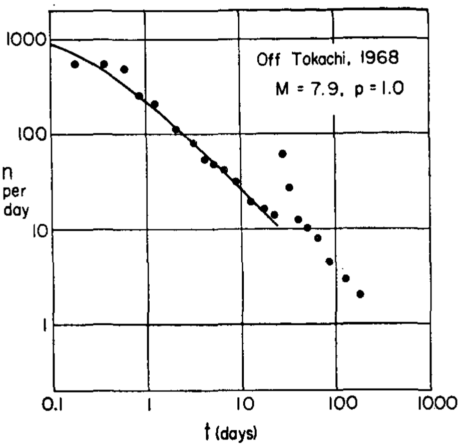


Fig. 14.

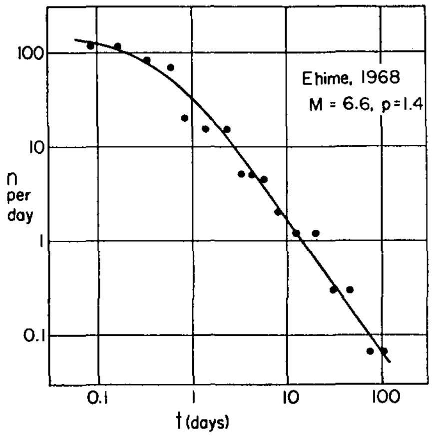


Fig. 15.

$p=1.6\sim1.7$, Parties for Aftershock Observation (Earthquake Research Institute)[53] $p=1.6$, Yamakawa[54] $p=1.3$, and Mogi[22] $p=1.55$. Mogi[22] also obtained $p=1.45$ for the Kita-Mino earthquake (No. 44), $p=1.0$ for the Miyagi earthquake (No. 49), and $p=1.42$ for the Echizen-misaki earthquake (No. 52). Ohtake et al.[55] obtained fairly small p values for aftershocks accompanying three large earthquakes in the Matsushiro swarm of 1966.

Equation (10) or (11) has been been applied to many aftershock sequences outside of Japan. Table 5 lists the values of p reported by various investigators[56]-[66] for sequences during the last twenty years.

The values of p for sequences listed in Table 4 and 5 are plotted against the magnitude M_0 of the main shock as shown in Figure 16 in which circles and crosses refer to earthquakes in and outside the Japanese region respectively. It is seen that values of p for most sequences fall in the range between 1.0 and 1.5, and no relation is found between p and M_0. In the same figure the values of c are plotted against M_0. The values of c are determined only very roughly, but they are smaller than 2 days. There is no obvious relationship between c and M_0, but it is recognized that for greater earthquakes ($M_0>7.5$) c is not very small ($c>0.2$ day).

In Figure 16 p and c values are plotted against D_1. These parameters are not clearly related with D_1, but for aftershock sequences with small D_1 ($D_1<0.8$) c is not very small ($c>0.2$ day). In Figure 17 the relation between p and c are shown using three different marks according to the value of D_1.

A tendency is found for c to increase with decreasing D_1 at each level of p. For sequences with large p ($p>1.4$), c is not very small ($c>0.1$ day).

Hitherto it has been assumed that p and c are constants for each sequence independent of the lower limit of magnitude M_s chosen for counting the frequency of aftershocks, thus p and c can be regarded as quantities characterizing the sequence. The validity of this assumption has been confirmed by Utsu[57] in the case of three Alaskan sequences of 1957 and 1958. If p or c depends on M_s, the magnitude-frequency relation of aftershock occurrence must change with time, but this fact has not been recognized generally (cf. Chapter 5). However, for some sequences the occurrence of aftershocks in the early stages is more or less complicated and there is a possibility that c changes with M_s as pointed out by Yamakawa.[54]

Some seismologists are of the opinion that the number of aftershocks cannot be counted completely in the beginning of a sequence when smaller shocks are often obscured by larger ones due to overlapping, thus too large value of c is obtained. The value of c might be zero if all aftershocks should be counted. The values of c treated here may to some extent be subject to such an effect, but careful examinations of some sequences have shown that the c-values are certainly larger than zero.

The time interval T_1 between a main shock and the largest aftershock shown in Table 1 is plotted in Figure 18 (left) against the magnitude of the main shock as solid circles. The data before 1959[1] are also plotted in the same figure as open cricles. Although the scatter of T_1 is very wide, there seems to be a tendency for T_1 to increase with M_0. The median of T_1 (in days) is approximately represented by

$$\log \tilde{T}_1 = 0.5\, M_0 - 3.5 \tag{12}$$

for $M_0 \geq 6$. Most of the observed T_1 fall in the range between $0.01\tilde{T}_1$ and $100\tilde{T}_1$. The frequency distribution of T_1 is shown in Figure 19. From 0.01 day to 10 days the distribution is well represented by a straight line of slope -1.0. The distribution of T_1 is thus in approximate agreement with, but not in complete agreement with the time distribution of aftershocks. The largest aftershocks are approximately but not exactly regarded as random samples from a distribution same as the decay law of aftershock frequencies. No apparent relationships are found between T_1 and D_1, and T_1 and c, but T_1 has a tendency to decrease with increasing p as shown in Figure 18 (right).

Table 4. Values of M_0, D_1, p, c, A, and $A/\bar{A}$ for 66 aftershock sequences in and near
swarm". Values of A with asterisks are based on

No.	Date (GMT)			Name of earthquake	Epicenter		h	M_0	D_1
					°N	°E	km		
1	1927	Mar.	7	Tango	35.6	135.1	10	7.5	1.3
2	1928	May	27	Off Sanriku	40.0	143.2	10	7.0	0.1
3	1930	Nov.	25	Kita-Izu	35.1	139.0	0	7.0	1.6
4	1931	Feb.	16	Hidaka, Hokkaido	42.3	142.6	40	6.8	1.9
5		Mar.	9	Off Aomori Pref.	41.5	142.5	0	7.6	1.6
6		Sept.	21	Saitama	36.1	139.2	10	7.0	1.4
7		Nov.	2	Hyuganada	32.2	132.1	20	6.6	(0.3)
8	1932	Nov.	26	Hidaka, Hokkaido	42.4	142.4	40	6.8	1.3
9	1933	Jan.	7	Off Sanriku	40.0	144.5	20	6.8	(0.4)
10		Mar.	2	Off Sanriku	39.1	144.7	10	8.3	1.6
11	1935	Oct.	12	Off Sanriku	40.0	143.6	40	7.2	0.1
12	1936	Feb.	11	Kawachi-Yamato	34.5	135.7	20	6.4	1.6
13	1937	Jan.	5	Hyuganada	31.5	132.5	10	6.5	1.2
14	1938	May	23	Off Ibaraki Pref.	36.7	141.4	10	7.1	1.2
15		Nov.	5	Off Fukushima Pref.	37.1	141.6	20	7.7	0.1
16	1939	May	1	Oga Peninsula	40.0	139.8	0	7.0	0.3
17	1940	Aug.	2	W off Hokkaido	44.1	139.5	10	7.0	2.2
18	1941	July	15	Nagano	36.7	138.3	10	6.2	2.4
19	1943	Apr.	11	Kashimanada	36.3	141.3	0	6.6	0.2
20		June	13	Off Aomori Pref.	41.1	142.7	20	7.1	0.3
21		Sept.	10	Tottori	35.5	134.2	10	7.4	1.3
22	1944	Dec.	7	Tonankai	33.7	136.2	20	8.0	1.3
23	1945	Jan.	12	Mikawa	34.7	137.0	0	7.1	0.7
24		Feb.	10	Off Aomori Pref.	40.9	142.1	30	7.3	0.8
25	1946	Dec.	20	Nankaido	33.0	135.6	30	8.1	0.9
26	1947	Nov.	4	W off Hokkaido	43.8	141.0	20	7.0	1.4
27	1948	May	12	Off Fukushima Pref.	37.8	142.3	40	6.6	0.3
28		June	15	Hidaka River	33.8	135.5	20	7.0	2.1
29		June	28	Fukui	36.1	136.2	20	7.3	1.5
30	1949	Dec.	25	Imaichi	36.7	139.7	10	6.7	0.8
31	1952	Mar.	4	Off Tokachi	42.2	143.9	45	8.1	1.1
32		Mar.	7	Off Daishoji	36.5	136.2	20	6.8	1.5
33		Oct.	27	Off Sanriku	39.4	143.4	50	6.6	(0.1)
34	1953	Nov.	25	Off Boso	34.3	141.8	60	7.5	0.9
35	1956	Aug.	12	Off Izu Peninsula	33.8	138.8	50	6.5	1.8
36		Dec.	21	S off Miyakejima	33.8	139.6	20	6.0	0.0
37	1957	Nov.	10	S off Niijima	34.3	139.4	0	6.3	(1.0)
38	1958	Nov.	6	Off Etorofu Is.	44.3	148.5	80	8.2	0.9
39	1959	Jan.	30	Teshikaga	43.4	144.4	20	6.2	0.1
40		Nov.	8	W off Hokkaido	43.8	140.6	10	6.2	2.0
41	1960	Mar.	20	Off Sanriku	39.8	143.5	20	7.5	0.8
42	1961	Jan.	12	Off Ibaraki Pref.	36.0	142.3	40	6.8	0.2
43		Feb.	16	E off Hokkaido	43.2	147.9	80	6.7	0.4
44		Feb.	26	Hyuganada	31.6	131.9	40	7.0	1.7
45		May	7	Hyogo Pref.	35.1	131.4	40	5.9	0.7
46		Aug.	11	Off Nemuro	42.9	145.6	80	7.2	0.3
47		Aug.	19	Kita-Mino	36.0	136.8	0	7.0	1.8
48	1962	Apr.	12	Off Miyagi Pref.	38.0	142.8	40	6.8	0.4
49		Apr.	30	Miyagi Pref.	38.7	141.1	0	6.5	1.7
50		Aug.	26	Miyakejima	34.1	139.5	40	5.9	0.1

Japan during 1926–1968. Mark "s" in the column headed by p indicates "earthquake temporary observations near the aftershock region.

p	c days	A $10^2\mathrm{km}^2$	b	$A/\bar{A}$	Reference
1.1	0.1	17*	0.8	0.27	1), 39), 45), 69) –73), 83), 155)
s		100	0.5	5.0	1), 83), 154), 157)
s		7.8		0.40	1), 74), 76), 84), 85), 155)
1.0	0.01		0.9	1.0	1), 45), 83)
		80			155), 157)
1.3	0.3	4.0	0.7	0.20	1), 45), 83), 86), 155)
		21	0.8	2.6	1), 83), 87), 155), 157)
1.4	0.35	14	0.8	1.1	1)
s		100	1.0	8.0	1), 83),
1.4	1.0	180	1.1	0.45	1), 45), 78), 83), 88), 89), 155), 157)
s		34	0.5	1.1	83), 155), 157)
1.3	0.01	2.3	0.9	0.46	1), 83), 90), 91), 155)
1.3	0.4		1.2		1), 3), 4)
1.1	0.03	17	0.8	0.68	1), 83), 155), 157)
1.2	1.5	110	0.65	1.1	1), 45), 83), 93), 155), 157)
1.6	1.0	3.6*	0.6	0.18	1), ,45), 83), 94), 95), 155), 157)
1.8	0.2		1.5		1), 45)
1.1	0.01				1), 45)
s		12	0.5	1.5	83), 155)
		62	0.4?	2.4	83,, 155), 157)
1.2	0.01	19	1.0	0.38	1), 45), 46), 83), 96), 97), 155)
1.1	0.4	210	0.7	1.0	1), 45), 83), 98), 155), 157)
1.3	1.0	14	0.7	0.56	1), 45), 83), 99), 155), 157)
		130	0.4?	3.3	83), 157)
1.0	0.3	360	0.7	1.4	1), 4), 45), 83), 155), 157)
1.2	0.1	42	1.0	2.1	1), 83)
		12	0.6	1.5	83), 155)
		10		0.5	83), 155)
1.3	0.3	6.9*		0.17	1), 45), 83), 100) -102), 155)
1.2	0.2	4.8	0.9	0.48	1), 45), 83), 103), 104), 155)
1.1	0.25	280	0.8	1.1	1), 45), 83), 105), 155), 157)
1.4	0.7	4.5	0.8	0.36	1), 45)83), 155)
s		43	0.55	5.4	155)
1.5	1.5	86	0.9	1.4	1), 45), 83), 106), 121), 155), 157)
1.8	0.8		1.4		1), 45)
s		5.5		2.7	
s		17	0.85	4.2	1), 107)
1.3	0.6	500	1.1	1.6	1), 45), 128), 134)
1.2	0.5	1.3	1.2	0.41	1), 45), 48), 108), 155)
1.2	0.01		1.8		
1.3	0.5	93	0.85	1.5	1), 155)
1.3	0.3	84	0.8	6.7	4), 121)
		38	0.8	3.8	
1.0	0.25	25	0.75	1.3	109)
s		5.7		3.5	
		45		1.4	
1.5	0.15	9.7	1.0	0.48	22), 110) -112)
		75	0.8	6.0	
1.0	0.1	3.3	0.9	0.52	22)
s		46	1.0	29	113), 114)

Table 4. Continued.

No.	Date (GMT)	Name of earthquake	Epicenter °N	°E	h km	M_0	D_1
51	1963 Feb. 9	Nagano Pref.	36.4	137.7	0	5.5	2.0
52	Mar. 26	Off Echizen-misaki	35.6	135.8	0	6.9	1.6
53	1964 May 7	Off Oga Peninsula	40.3	139.0	0	6.9	0.4
54	June 16	Niigata	38.4	139.2	40	7.5	1.4
55	Dec. 8	Near Oshima	34.6	139.3	0	5.8	0.3
56	1965 Apr. 19	Shizuoka	34.9	138.3	20	6.1	2.9
57	Sept. 17	Kashimanada	36.3	141.5	40	6.7	0.5
58	Nov. 6	Near Kozushima	34.1	139.0	20	5.6	(0.4)
59	1966 Nov. 12	S off Hokkaido	41.6	144.4	40	5.9	1.2
60	1967 Nov. 4	Lake Kutcharo	43.5	144.3	20	6.5	0.8
61	1968 Jan. 29	Off Shikotan Is.	43.2	147.0	30	6.9	1.1
62	Feb. 21	Ebino	32.0	130.7	0	6.1	0.4
63	Apr. 1	Hyuganada	32.3	132.5	30	7.5	1.2
64	May 16	Off Tokachi	40.7	143.6	0	7.9	0.4
65	Aug. 5	Ehime Pref.	33.3	132.4	40	6.6	1.3
66	Aug. 18	Kyoto Pref.	35.2	135.4	0	5.6	0.4

Table 5. Values of M_0, D_1, p, A, and b for 30 aftershock

No.	Date (CMT)	Location	M_0
1	1948 Dec. 4	Desert Hot Springs, Calif.	6.5
2	1949 July 10	Khait, Tadzhik	7.6
3	1952 July 21	Kren County, California	7.7
4	Nov. 4	Kamchatka	8.3
5	1953 Aug. 12	Kephallenia, Greece	7.2
6	1954 Apr. 30	Shophades, Greece	7.0
7	1956 July 9	Amorgos, Greece	7.5
8	1957 Mar. 8	Magnesia, Greece	6.8
9	Mar. 9	Aleutian	8.3
10	1958 Mar. 22	San Francisco, California	5.3
11	Apr. 7	Central Alaska	7.3
12	July 10	Southeast Alaska	7.9
13	1959 Jan. 9	Owens Valley, California	3.3
14	1960 May 22	Chile	8.5
15	May 24	Fiordland, New Zealand	7.0
16	1962 May 10	Westport, New Zealand	5.9
17	July 27	Kaoiki, Hawaii	6.1
18	1963 July 26	Skopje, Yugoslavia	6.2
19	Sept. 14	Watsonville, California	5.4
20	Oct. 13	Southern Kurile Islands	8.1
21	1964 Mar 28	Alaska	8.5
22	Nov. 16	Corralitos, California	5.0
23	1965 Feb. 4	Rat Is., Aleutian Is.	8.0
24	Mar. 14	Dzhurm, Afganistan(h=200km)	7.5
25	Sept. 10	Antioch, California	4.9
26	1966 Feb. 5	Cremasta, Greece	5.9
27	June 28	Parkfield, California	5.5
28	Sept. 12	Truckee, California	5.8
29	Dec. 28	Off northern Chile	7.5
30	1967 June 21	Fairbanks, Alaska	6.0

p	c days	A $10^2\mathrm{km}^2$	b	$A/\bar{A}$	Reference
s		2.0*	1.2	4.8	115)
1.25	0.04	6.6	0.8	0.42	4), 22), 121)
1.5	0.2	19	0.7	1.2	51)
1.4	0.4	59	1.0	0.93	4), 22), 52)-54), 116)-118), 121)
s		19	0.8	15	
1.5			1.4		50)
s		8.8	0.5	0.86	
s		5.7		7.1	
s		2.1	0.6	1.3	
1.2	0.05		1.0		48)
1.3	0.2	58	0.75	3.7	49)
s		0.85	0.9	0.33	
		61	0.75	0.96	
1.0	0.5	450	0.9	2.8	119)
1.4	0.5	3.8	0.9	0.48	
		1.7	0.8	2.1	

sequences outside of Japan during the last twenty years.

D_1	p	A $10^2\mathrm{km}^2$	b	Reference
		4.1	1.00	122), 176)
1.1	1.3			56)
1.3	1.2	24	0.9	123)-124)
0.9	1.0	2500	1.5	45), 125)
0.7	1.26		0.85	9)
1.1	1.41		1.00	9)
0.7	2.50		0.92	9)
0.3	1.21		0.73	9)
1.0	1.05	3000	0.70	57), 126)
0.9		0.50	1.0	127)
0.6	1.05		0.93	57)
2.3	1.13		0.88	57)
0.1			0.36	176), 178)
1.0		3400	1.13	129)-130), 176)
1.4	1.12		1.05	58)
0.3	0.9			59)
2.6	0.9	0.57	0.98	60)
1.5		3.8		131)-132)
0.8		2.8	0.41	133)
1.4	1.1	500	1.2	61), 134)-136)
2.4	1.14	3000	0.88	62)
1.5		0.32	0.63	137)
1.0		1400	1.1	138)
1.8	1.4	55		20)
2.1		0.074	0.78	139)
	0.78		1.12	66)
0.5	0.9		0.63	63)-64)
1.7		0.33	1.40	65), 140)
		23		141)
0.7		1.9		142)

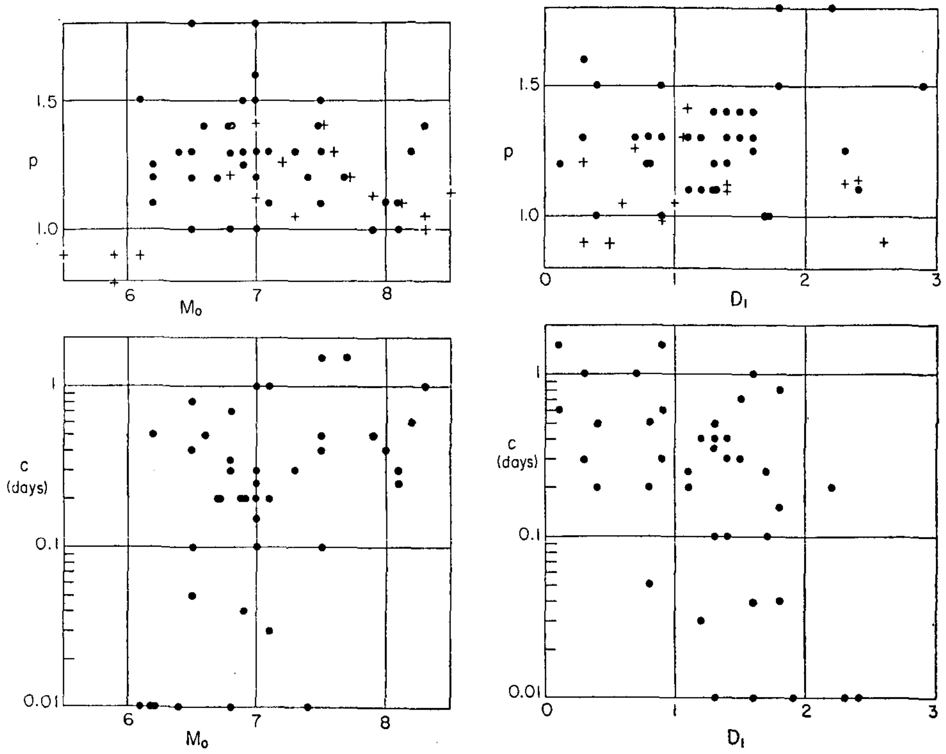


Fig. 16.

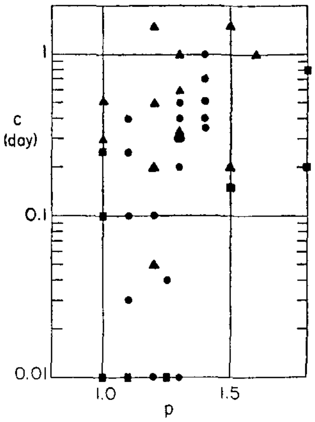


Fig. 17. c plotted against p. Triangles: $D_1/\widetilde{D}_1<1/2$, circles: $1/2\leq D_1/\widetilde{D}_1<1$, squares; $1<D_1/\widetilde{D}_1$.

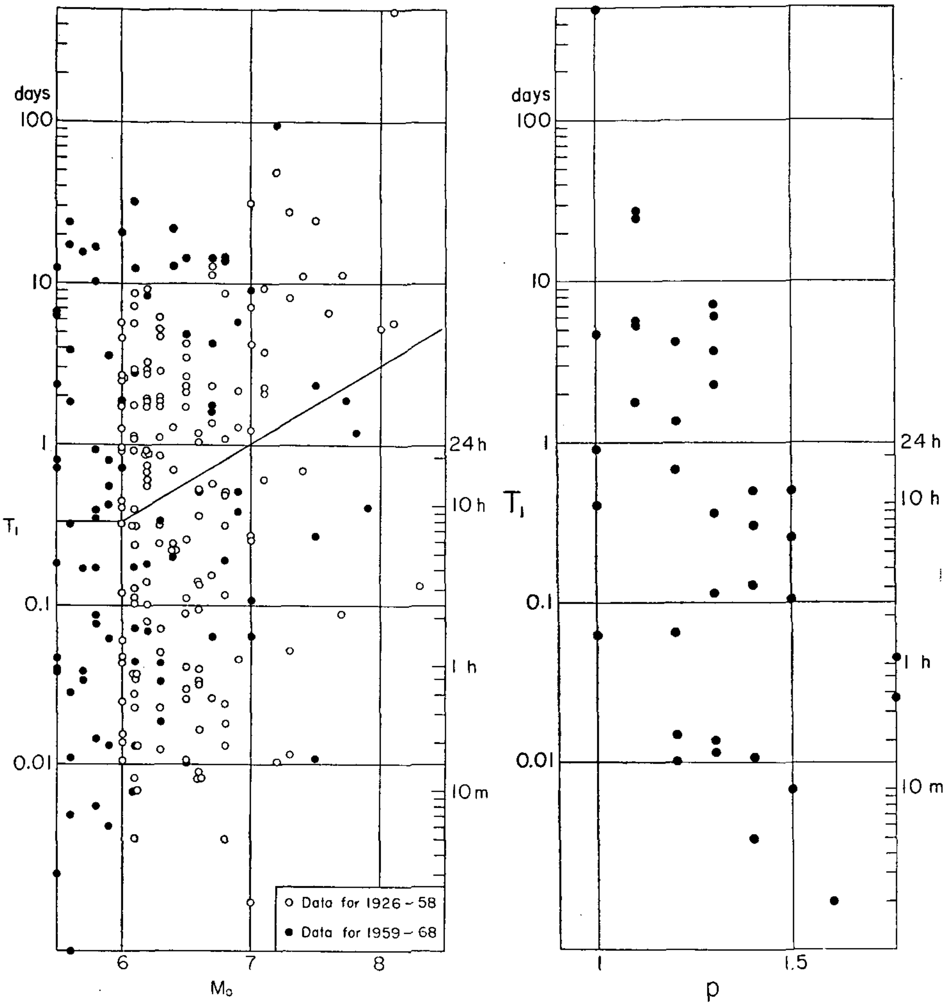


Fig. 18.

4. Space distribution of aftershock hypocenters

It had been known to seismologists in the last century that aftershocks do not always have the same focus as the main shock. Omori mentioned in his first paper[24] on aftershocks in 1894 that more aftershocks seemed to occur near the both ends of the fault ruptured at the time of the Nobi earthquake of 1891 from the geographical distribution of the frequency of felt aftershocks.

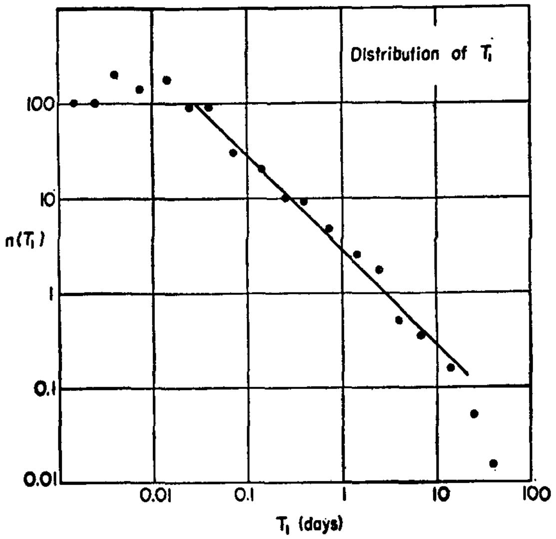


Fig. 19.

Distributions of aftershock epicenters determined instrumentally from routine or temporary seismic observations have been published since early years of this century67)-68). The Tagno earthquake may be the first thoroughly investigated series of aftershocks along this line.69)-73).

The idea that the region in which aftershocks of a large earthquake occur corresponds to the region where the strain accumulated before the earthquake is released by a sudden fracture or a fault displacement was expressed in 1930s. 74)-77) According to this idea aftershocks originate in the region where the crustal deformation took place as pointed out by Ishimoto,75) Kishinouye,76) Wilson,77) etc. The epicenter of the main shock which indicates the point where the fracture started is usually located near the border of the aftershock region rather than the center of the region (Matuzawa,78)-79) Wilson77)).

It was also suggested (e.g. Ishikawa,80) Wilson77)) that the size of the aftershock region depends on the size of the main shock. Seki and Homma81)-82) in 1949 obtained a relation between the aftershock area and the radius of perceptibility of the main shock from data on 21 Japanese earthquakes. In 1955 Utsu and Seki83) connected the aftershock area A (in km^2) with the magnitude of the main shock M_0 by the equation

$$\log A = 1.02\, M_0 - 4.01 \tag{13}$$

using data on 38 aftershock sequences in and near Japan. This equation was adopted by Tsuboi[84] to provide a systematic quantitative explanation of the relation between earthquake energy, source volume, and strength of the earth's crust.

Since the scatter of the plotted points in a log A vs M_0 diagram is considerably large, the above equation may be regarded as that giving a standard value of aftershock area at each magnitude M_0. This scatter is attributable to four causes. (1) Errors in M_0. (2) Errors in A resulting from errors in the location of epicenters of individual aftershocks. (3) Uncertainty in the identification of aftershocks. (4) Actual variations in A among sequences with equal M_0. For sequences with large A errors in the location of epicenters are less important than for those with small A. Errors in the location of epicenters are generally larger for sequences located offshore than for those inland. Most sequences with large M_0 and with small M_0 used in the study from which equation (13) has been obtained were offshore and inland ones respectively, therefore the above two effects may combine to yield a fairly accurate result. However it is very likely that the earthquakes located offshore have relatively large aftershock areas than the inland ones of equal magnitude, though errors in the location of epicenters may partly explain the difference.

Aftershock area of 57 earthquakes which occurred in and near Japan during 1926–1968 have been determined and given in Table 4. For some of the 30 earthquakes which occurred before 1955, the values of A are somewhat different from those published in 1955[83] due to differences in the method of estimating A and the source of data on epicenter location. The method used here is as follows.

(1) All known epicenters of earthquakes which occurred within at least 100 km from the epicenter of a main shock during the one month's intervals immidately before and after the main shock are plotted on a map. The limit of distance from the epicenter of the main shock should be extended according to the spread of the epicenters, so as not to find difficulties in defining the aftershock area under the following condition.

(2) Since the aftershock area is roughly represented by an ellipse, ellipses A, B, and C which are defined by the following conditions are drawn for each sequence, and the area of ellipse A is defined as the aftershock area.

i) Ellipses A, B, and C have the same center and the same directions of the major and minor axes.

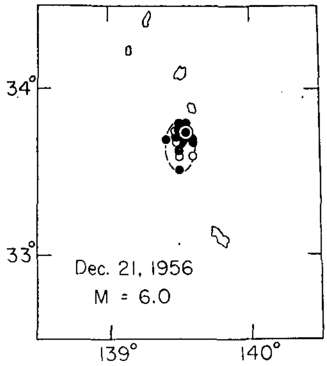
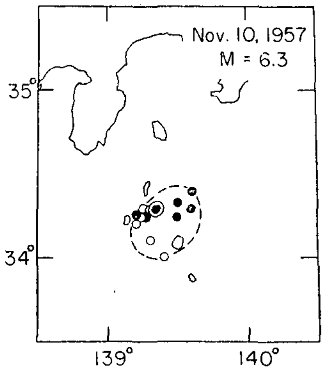


Fig. 20.



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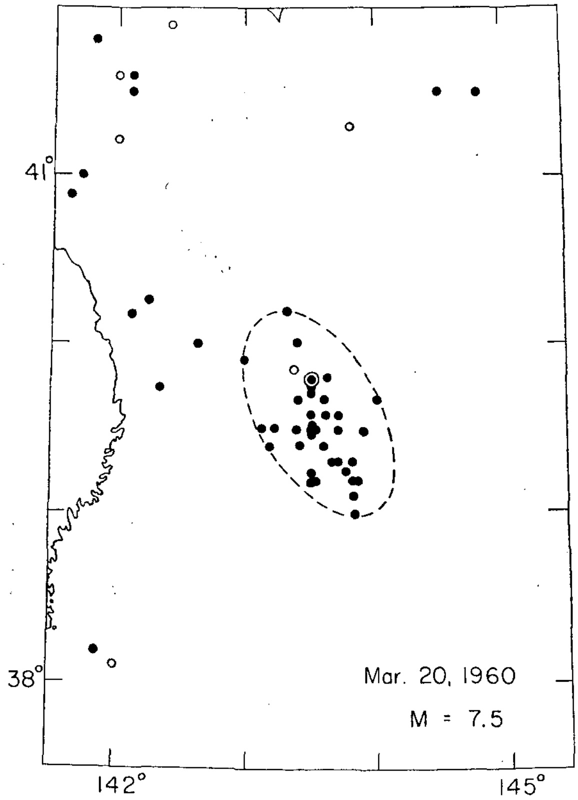

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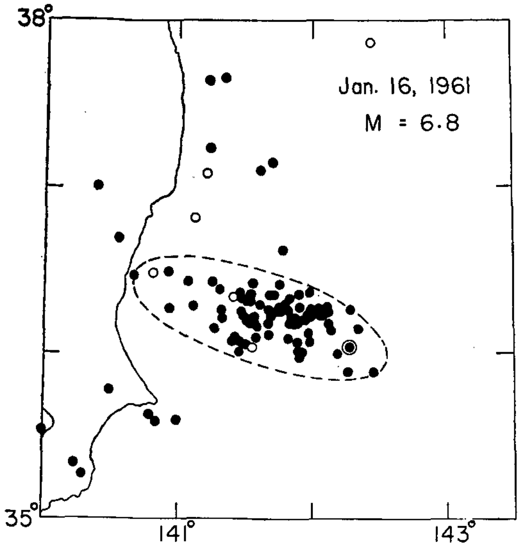

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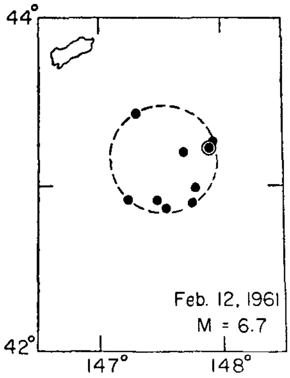

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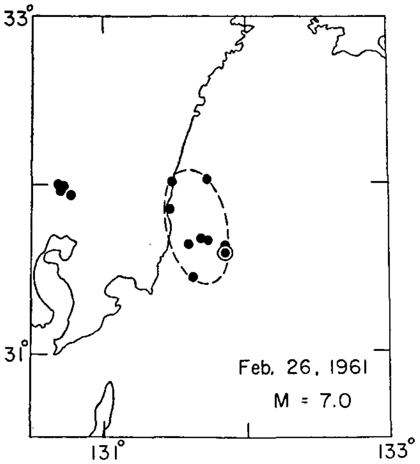

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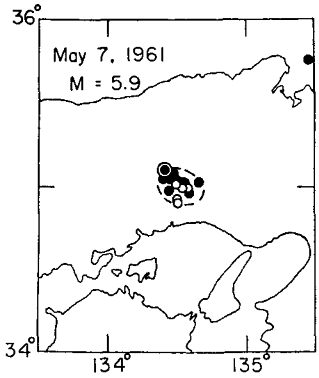


Fig. 26.

ii) The ratios of the lengths of both major and minor axes among the three ellipses are 1:1.2:2.

iii) Ellipse A contains 95% or more of the plotted epicenters falling within ellipse C.

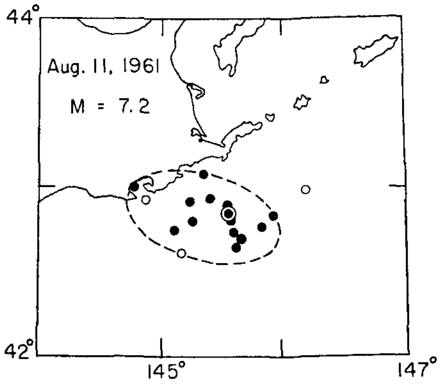
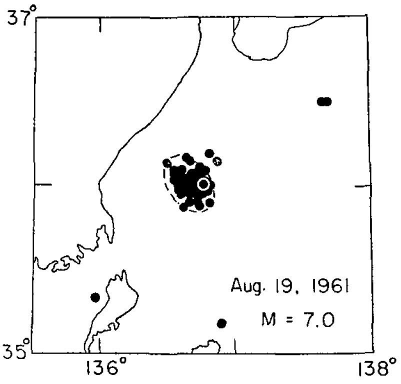


Fig. 27.



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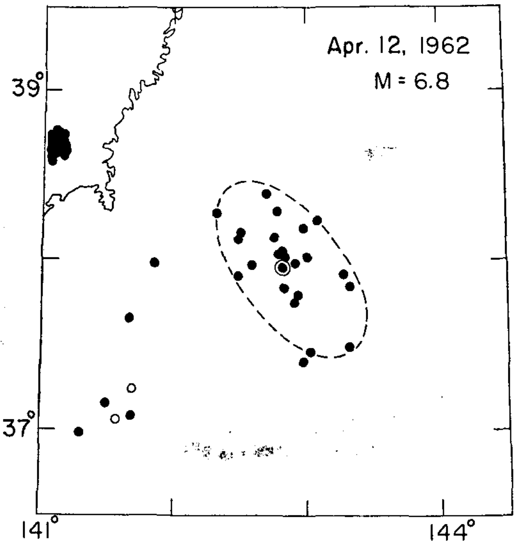

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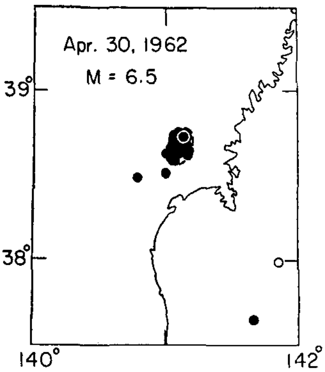
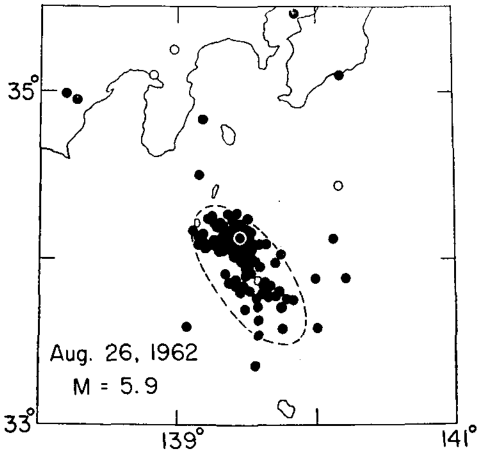


Fig. 30.

iv) Ellipse A should be the one having minimum area under the above conditions. (Very unreasonable cases, if any, are excluded.)

Aftershock and foreshock epicenters for 25 earthquakes after 1955 are shown in Figures 20–44 in which double circles refer to main shocks. Open circles are epicenters within one month before each main shock. Ellipse A for each sequence is indicated by a borken line. For other sequences such figures



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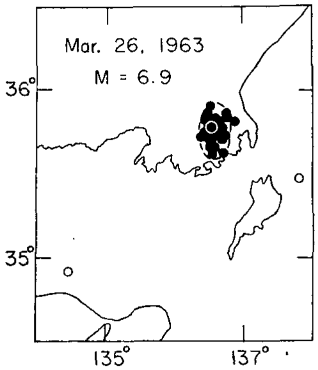

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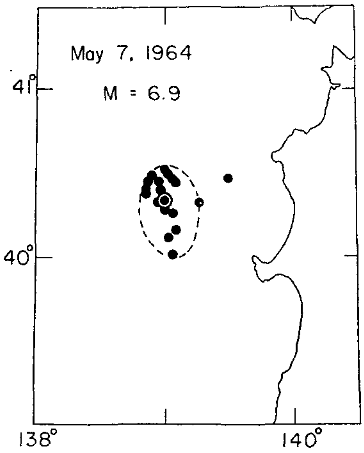


Fig. 33.

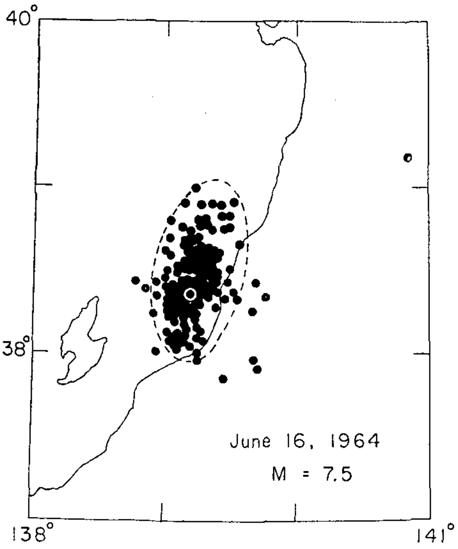


Fig. 34.

are not presented. For many sequences maps showing the distribution of aftershocks and foreshocks have been published by various investigators.85)-121) Some of them are based on the temporary seismic observations near the aftershock area. However most of the values for *A* listed in Table 4 are based

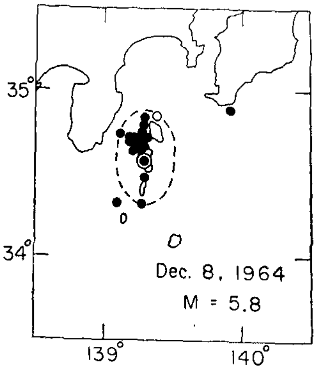
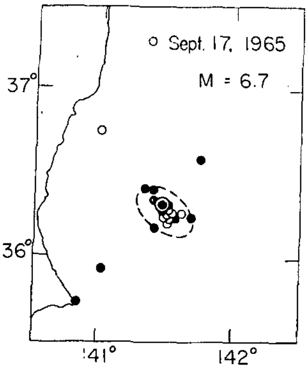


Fig. 35.



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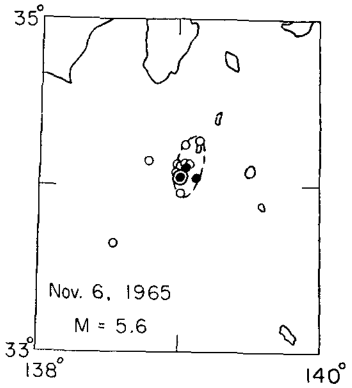

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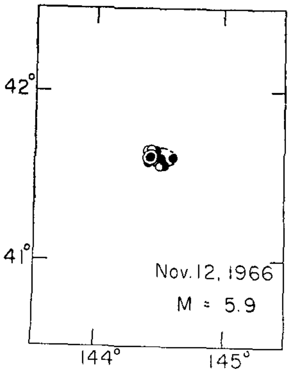

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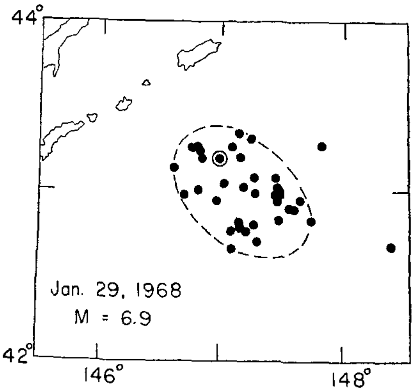


Fig. 39.

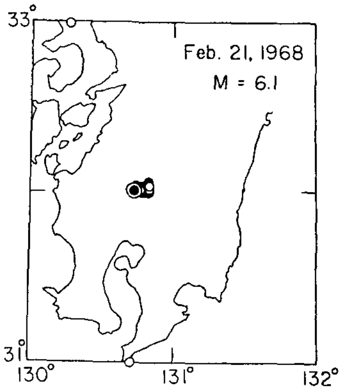


Fig. 40.

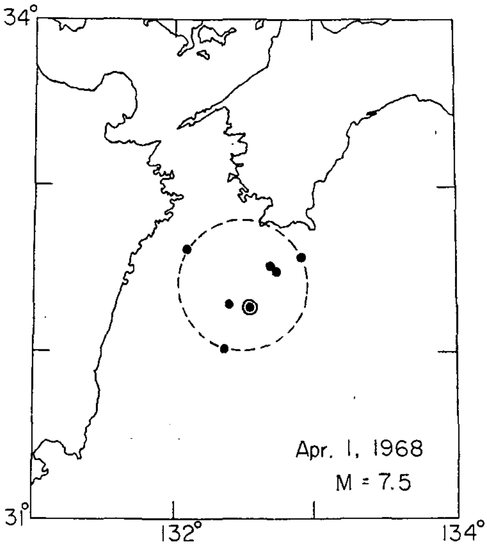


Fig. 41.

on the routine observations by the Japan Meteorological Agency. Only four A-values (marked with asterisks) are based on the temporary observations, because the data obtained by JMA are insufficient for these sequences.

Logarithm of A in Table 4 is plotted against the magnitude of the main shock M_0 in Figure 45. Open and solid circles indicate sequences which occurred beneath the sea. Open and solid triangles indicate those which occurred in the land area including the shallow sea. Solid circles and triangles refer to ordinary aftershock sequences with few foreshocks, whereas open circles and triangles refer to earthquake swarms or aftershock sequences preceeded by considerable foreshock activities.

The data plotted in Figure 45 exhibit a large scatter, but a correlation between $\log A$ and M_0 is evident. An equation

$$\log \bar{A} = M_0 - 3.7 \tag{14}$$

is employed here to represent the variation of average aftershock area $\bar{A}$ with M_0. This equation gives slightly larger area as compared with equation (13) which is almost equivalent to $\log \bar{A} = M_0 - 3.85$ for M_0 around 7. Equation (14) is just derived from an equation[1)]

$$\log \bar{L} = 0.5\, M_0 - 1.8 \tag{15}$$

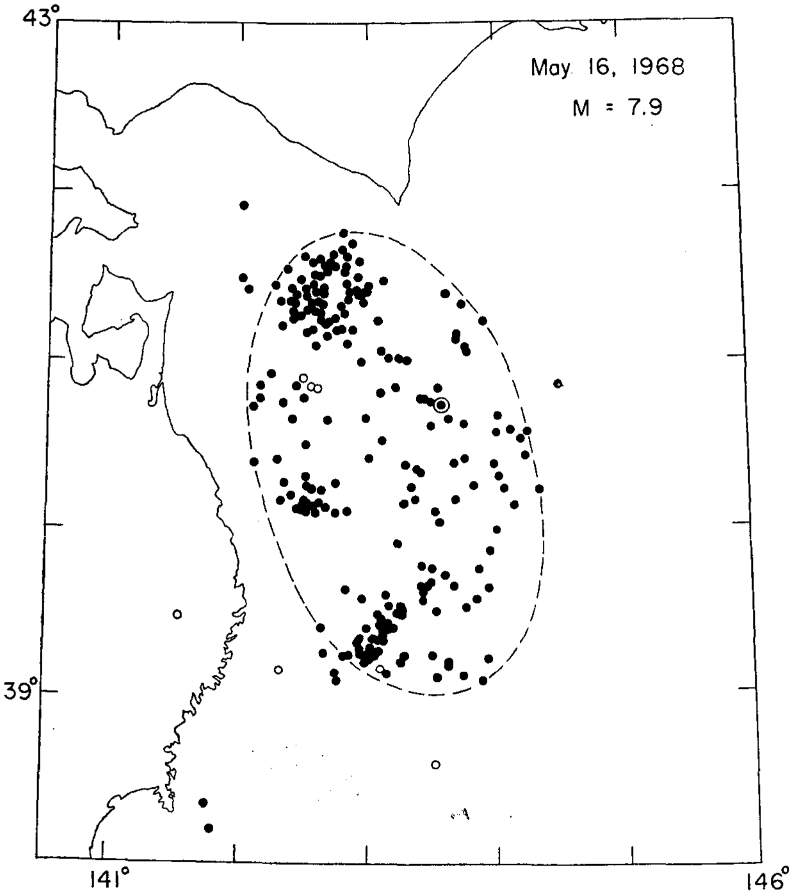


Fig. 42.

which represents the relation between the magnitude M_0 and the linear dimension L of the aftershock region usually estimated from the distribution of S—P intervals observed at a near-by seismic station, if the aftershock area A is on the average equal to the area of a circle with diameter L, i.e., $\bar{A}=(\pi/4)\bar{L}^2$.

A tendency is seen from Figure 45 that the areas for swarms are generally larger than those for ordinary sequences, and the earthquakes occurring off-shore have larger areas than the inland earthquakes. If swarms are excluded, estimated areas at each level of M_0 fall in the range between $(1/5)\bar{A}$ and $5\bar{A}$. Aftershock areas for inland earthquakes accompanied by regular

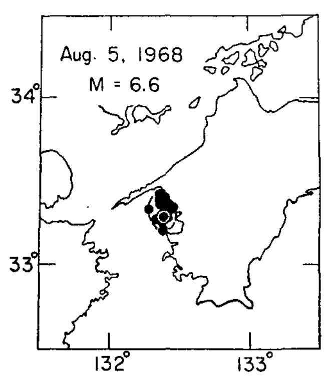


Fig. 43.

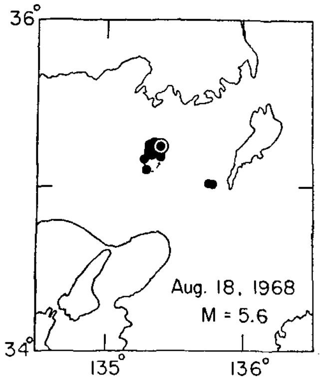


Fig. 44.

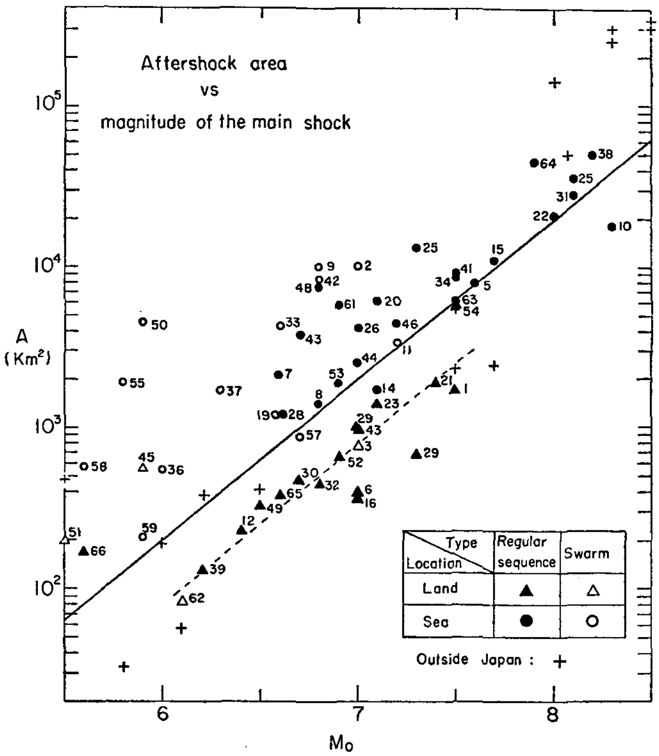


Fig. 45. Aftershock area A plotted against M_0. Circles and triangles refer to earthquakes in the region of Japan listed in Table 4. Crosses refer to earthquakes outside of Japan listed in Table 5. Thick straight line indicates $\log A = M_0 - 3.7$.

aftershock sequences (solid triangles in Figure 45) fit rather closely an equation

$$\log \bar{A}_L = M_0 - 4.1 \tag{16}$$

for $5.5 \leq M_0 \leq 7.5$. This equation is represented by a broken line in Figure 45.

Aftershock areas for earthquakes occurring outside of the Japanese region have been determined by the similar method from the published maps showing aftershock epicenters available to the author.56)-57),60-65),122)-142) These are given in Table 5 and plotted in Figure 45 as crosses. It is remarkable that the aftershock areas for five great earthquakes with magnitude about 8 or more are very large as compared with Japanese sequences with comparable magnitudes. Other earthquakes with $M_0 < 7\,^3/_4$ have aftershock areas not very much different from those of Japanese earthquakes.

Figure 46 is a graph of A plotted against the magnitude of the largest

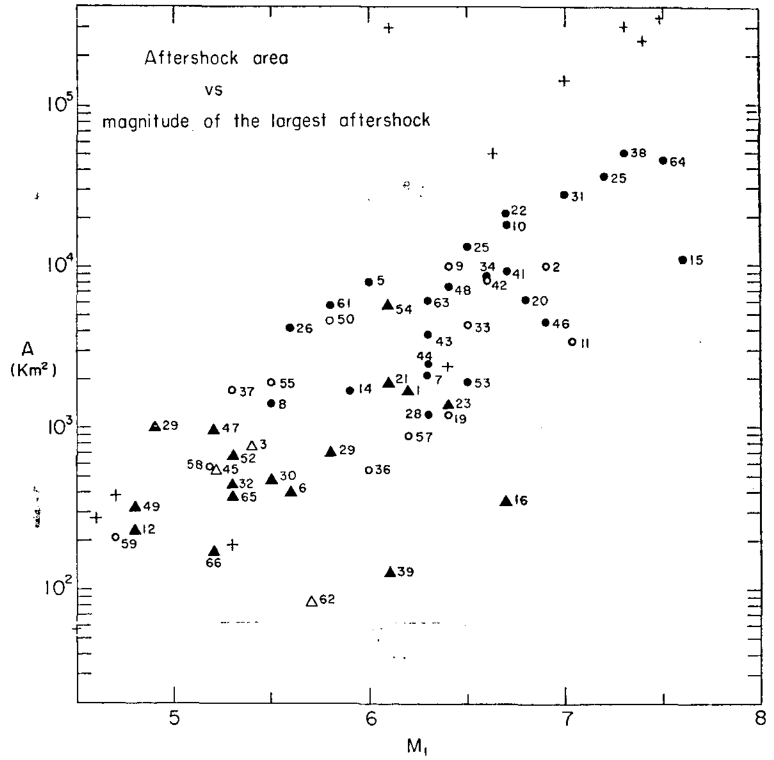


Fig. 46. Aftershock area A plotted against M_1. Marks are the same as in Fig. 45.

aftershock (or the largest foreshock if it is larger than the largest aftershock). The scatter of the plotted points is also considerable, but in contrast with Figure 45, the differences between swarms and ordinary aftershock sequences and between earthquakes occurring beneath the sea and land are not evident. A straight line best fitting to the plotted points is represented by

$$\log \bar{A} = 0.85\, M_1 - 1.8\,. \tag{17}$$

This is somewhat different from equation $\log\ \bar{A} = {}^2/_3 M_1 - 0.4$ which is derived from the combination of equations (4) and (14). This difference is probably due to the fact that the earthquakes treated here, especially those of smaller magnitude, are those followed by rather remarkable aftershock sequence, therefore they are not random samples from a population for which equation (4) is applicable. Aftershock areas for three earthquakes (Nos. 16, 39, and 62) are exceedingly small. Each of these earthquakes was accompanied by a few aftershocks (and foreshocks) of magnitudes not widely different from that of the main shock, but the magnitudes of the other aftershocks are considerably smaller than these large aftershocks.

Figure 47 shows $A/\bar{A}$ as plotted against D_1, p, and c. $A/\bar{A}$ is the ratio of individual aftershock area to the standard value calculated from equation (14). It is recognzied that $A/\bar{A}$ has a tendency to increase with decreasing D_1. Since D_1 is a rough measure of the degree of aftershock activity, $A/\bar{A}$ tends to increase with aftershock activity. This tendency has already pointed out by Mogi22) and Nishi.143). According to them the relation between $L/\bar{L}$ and D_1 is given by

$$\log (L/\bar{L}) = 0.42 - 0.36\, D_1\,, \tag{18}$$

and

$$\log (L/\bar{L}) = 0.26 - 0.22\, D_1 \tag{19}$$

respectively, where L and $\bar{L}$ are the linear dimensions of the aftershock region estimated from observation and calculated from equation (15) respectively. Both equation gives $L/\bar{L} = 1$ at $D_1 = 1.2$. It is seen from Figure 47 that earthquake swarms have generally large $A/\bar{A}$ and small D_1. No clear correlation is evident between $A/\bar{A}$ and p or c, but for small c ($c < 0.2$ day) $A/\bar{A}$ is less than 0.8.

The relation between A or L and M_0 in the magnitude range smaller than 5.5 has been examined in several cases. According to the observation by Sasaki and Motoya,144) epicenters of the Rausu, Hokkaido, earthquake

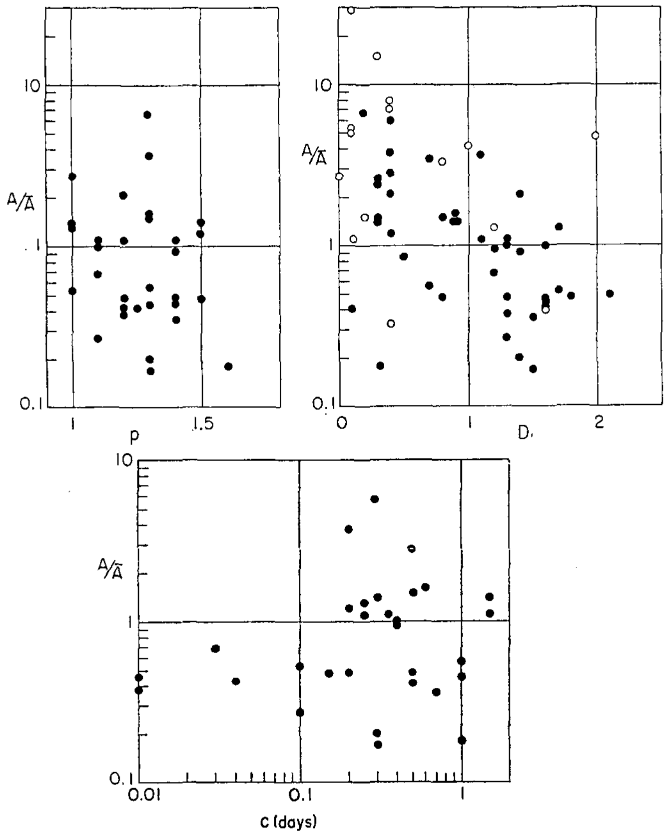


Fig. 47.

swarm in 1964 were distributed over an area of about 110 km^2, which is considerably larger than $\bar{A}$=8 km^2 calculated from equation (14) using the magnitude of the largest shock 4.6. Kishimoto and Hashizume[145] reported that the linear dimension of the focal region of the 1965 Hamasaka swarm in Hyogo Prefecture was about 0.3 to 0.5 km. The largset event has a magnitude of 3.6, which gives $\bar{L}$=1.0 km from equation (15). The linear dimension of the foreshock and aftershock region of the magnitude 3.3 earthquake in Nagano Prefecture in January 1964 was estimated as 2.1 km by Suyehiro et al.,[147] while equation (15) gives $\bar{L}$=0.7 km. Okano and Nakamura[146] found fair agreement between observed and calculated linear dimensions for the aftershock regions of three small earthquakes (M_0: 2.9, 4.0, and 4.1) in the northern part of Osaka Prefecture in 1964 and 1966. The epicentral region of the microearthquake swarm near Mould Bay, Canada in 1965 has been estimated as about 3 km^2 by Smith et al.[148] This is considerably larger than that calculated from equation (14) using the magnitude of the largest event ($M_0=2.9$) assigned by them. The epicentral region of the Matsushiro earthquake swarm of 1965–68 can be estimated from published maps by several authors based on the different type of observations.[149)–154] The area based on the data from the permanent stations of JMA is about 350 km^2, which roughly agrees with the estimated areas from other sources. The largest shock in the swarm has a magnitude of 5.4, then $\bar{A}=50$ km^2 from equation (13). Three earthquakes of magnitude 4.5 to 5.0 which occurred at the southwestern border of the Matsushiro swarm area in 1967 have aftershock areas slightly larger than those estimated from equation (15)[55].

The relation between A and M_0 has been studied by some other seismologists. In some studies the aftershock volume V has been treated together with the aftershock area A. Goto[15] obtained a equation for the minimum aftershock area $A_{\min}$ (in km^2) at each level of magnitude M_0 as

$$\log A_{\min} = 1.74\,M_0 - 9.92 \tag{20}$$

for $M_0>6.5$. He stated that the earthquakes with such minumum aftershock area occur in regions where seqular seismic activity is low. On the other hand aftershock areas for earthquakes occurring in seismically active regions have rather complicated shapes and comparatively large sizes. Similar trend has been described by Yamakawa,[121] who also pointed out that for earthquakes occurring in seismically inactive regions the decay of the aftershock frequency is well represented by the modified Omori formula for a long time, while for earthquakes in active regions the agreement with the modified Omori formula is not so good. Equation (20) seems to give too small value of $A_{\min}$ for $M_0<6.5$. The author proposes an equation

$$\log A_{\min} = M_0 - 4.4 \tag{21}$$

for $5.5<M_0<8$.

Iida[156)–158] obtained a relation between the aftershock volume V and the magnitude of the main shock M_0 from data for 36 Japanese earthquakes as follows.

$$\log V = 1.06\,M_0 - 2.78 \tag{22}$$

where V is expressed in km^3.

The aftershock area of tsunami-genetic earthquakes near Japan is related to M_0 by Iida[157] as

$$\log A = 0.9\,M_0 - 3.0 \tag{23}$$

and by Watanabe[159] as

$$A = 0.83\,A_T + 1500 \tag{24}$$

and

$$\log A_T = 1.22\,M_0 - 5.48 \tag{25}$$

where A_T is the area of tsunami soruce estimated from mareographic observations. Equations (23) and (24) give approximately equal A values to that claculated from equation (14) around $M_0=7$.

The present author[5] in 1957 plotted the size of the tsunami source area and the length of the earthquake fault against the magnitude. Iida[160] expressed the linear dimension L_T (in km) of the tsunami source area by the equation

$$\log L_T = 0.46\,M_0 - 1.82 \tag{26}$$

which is comparable to equation (15). Hatori[161] plotted the linear dimension L_T and area A_T of tsunami source estimated by himself and other investigators against the magnitude for 44 earthquakes near Japan. The plotted points show considerable scatter, but for 12 earthquakes occurring off Sanriku, the relation of A_T and M_0 is well represented by

$$\log A_T = 1.07\,M_0 - 4.2\,. \tag{27}$$

This equation gives almost equal value of A_T to the A-value given by equation (14) for M_0 about 7 to 8. However actual aftershock areas of earthquakes off Sanriku are generally larger than that given by equation (14).

The following equations by Båth and Duda[162] for the aftershock volume and aftershock area published in 1964 were based on data for only eleven and six earthquakes respectively.

$$\log V = 1.47\,M_0 - 5.42\,, \tag{28}$$

and

$$\log A = 1.21\,M_0 - 5.05\,. \tag{29}$$

Purcaru[21] obtained the following relation from the data on fifteen earthquakes with magnitude ranging from 5 to $8^1/_2$.

$$\log A = 1.08\,M_0 - 4.17\,. \tag{30}$$

The relation between the fault length l (in km) and the magnitude M_0 given by Tocher[163] in 1958 is

$$\log l = 1.02\,M_0 - 5.77\,, \tag{31}$$

and that given by Iida[158] in 1965 is

$$\log l = 1.32\,M_0 - 7.99\,. \tag{32}$$

Wyss and Brune[164] also derived a similar equation for earthquakes in the Parkfield region, California. These equations are not in close agreement with equation (15), whereas an equation for the linear dimension r (in km) of the area where crustal deformation is observed after an inland earthquake of magnitude M_0 proposed by Dambara[165]

$$\log r = 0.51\,M_0 - 2.27 \tag{33}$$

is almost comparable to equation (21), if an equation $A_{\min} = (\pi/4)r^2$ is assumed. According to Otsuka[166] the maximum of the observed fault length accompanying earthquakes with magnitude M_0 is given by

$$\log l_{\max} = 0.5\,M_0 - 1.8 \tag{34}$$

for $M_0 < 7.4$. This is identical with equation (15).

The question whether or not the aftershock area has some connection with the mechanism of the main shock was brought out in Utsu and Seki's paper.[83] It was difficult to connect the aftershock area with the parameters for the mechanism, since the mechanism solutions were not available for many of the earthquakes in question. However it was pointed out that most of the earthquakes occurring in the land area of Japan for which the aftershock areas were defined have such mechanisms that the two orthogonal nodal planes are nearly vertical, i.e., the null vectors are nearly vertical, while the shallow earthquakes occurring off the Pacific coast of Japan which have comparatively large aftershock area seem to have considerably different mechanisms though their solutions are not exactly known. Therefore it is expected that at each level of M_0 the aftershock area has a tendency to increase with decreasing dip of the null vector. Detailed study of this point is a future problem. Pshemikov[167] mentioned that the shape of the aftershock area becomes more oblong as the dip of the null vector for the main shock decreases.

Other important problems concerning the space distribution of aftershocks include (i) spatial concentration of large aftershocks in connection with the mechanism of the main shock and the crustal deformation,[120)-121] (ii) spreading the region of aftershock activity with time,[168)-170),56),154] (iii) increase in seismic and volcanic activities in some separated places (in some cases hundreds of kilometers) from the aftershock area.[171)-174] The definition of the aftershock area employed in this chapter is intended to avoid uncertainty due to such complex characters of aftershock distribution. However these problems should not be neglected in discussions of the phenomena of earthquake generation.

5. Magnitude-frequency relation for aftershocks

It has been generally recognized that the distribution of aftershocks in respect to magnitude in each sequence is represented by Gutenberg-Richter's formula (1) fairly closely. As mentioned in Chapter 2, the main shock usually has too large magnitude to be included in this distribution. On the other hand, the main shock (the largest shock) in an earthquake swarm usually has a suitable magnitude to be included in the same distribution. The values of coefficient b in the formula for 26 aftershock sequences listed in Table 4 were estimated previously.[1] For the others sequences in the table, b-values are estimated by the same method, that is, from the slope of a straight line fitted by eye to the points in a diagram of log $N(M)$ vs M, considerring the result of a discussion on how to obtain the highest accuracy by such a method.[175] $N(M)$ is the number of shocks with magnitude M and larger. These diagrams for 21 sequences are shown in Figures 48–68. The crosses at the top-left of each figure indicate the total number of observed aftershocks during the period of investigation and the average lower limit of magnitude M_z of the observed aftershocks estimated from the distance to the nearest station and the sensitivity of the instrument used there. For sequences in 1965 and later the fact is used to estimate M_z that all stations belonging to JMA report the data on shocks whose double trace amplitude is 1 mm or larger. The definition of

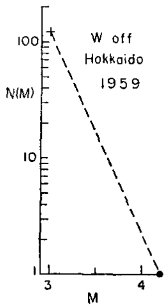


Fig. 48.

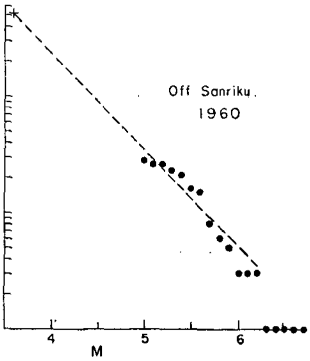


Fig. 49.

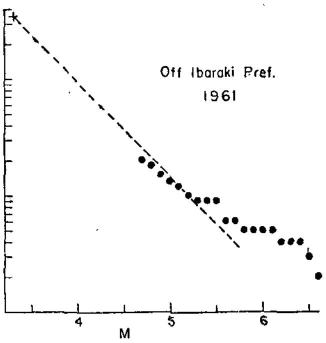


Fig. 50.

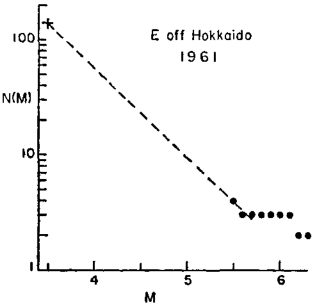


Fig. 51.

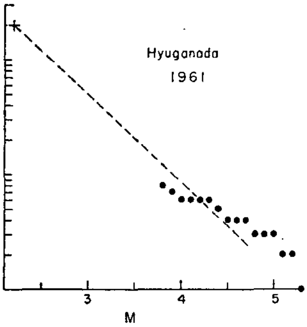


Fig. 52.

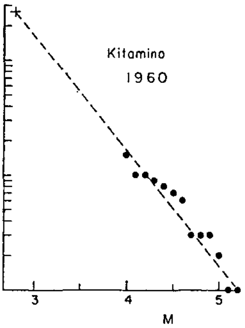


Fig. 53.

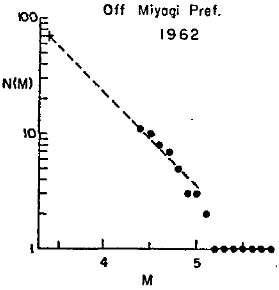


Fig. 54.

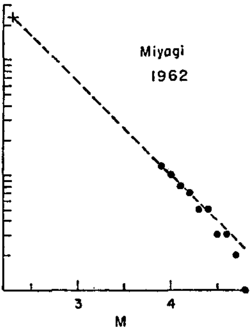


Fig. 55.

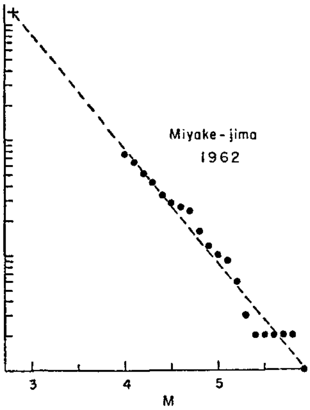


Fig. 56.

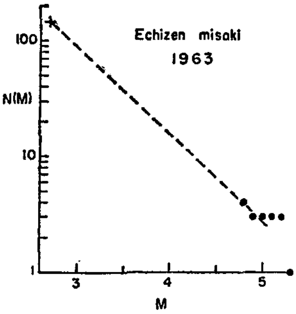


Fig. 57.

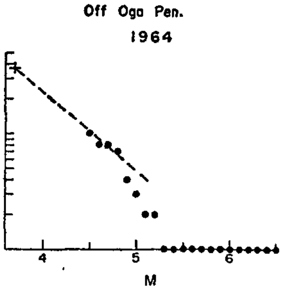


Fig. 58.

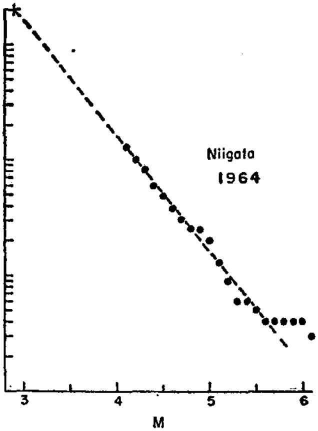


Fig. 59.

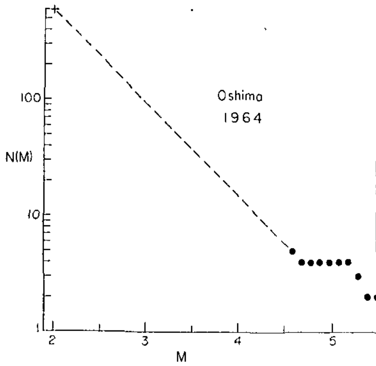


Fig. 60.

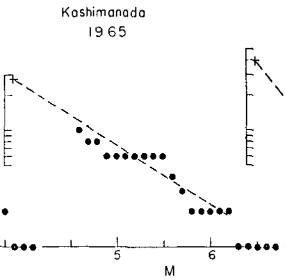


Fig. 61.

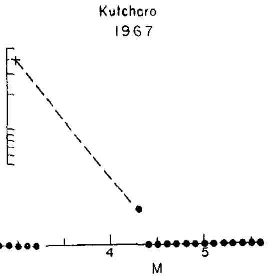


Fig. 62.

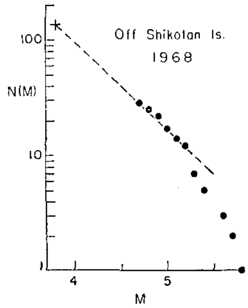


Fig. 63.

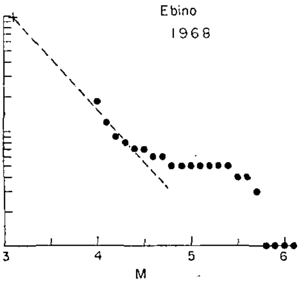


Fig. 64.

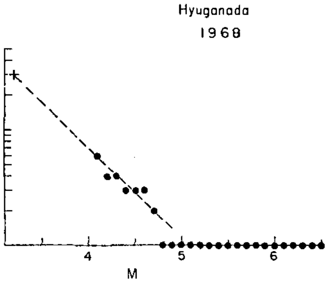


Fig. 65.

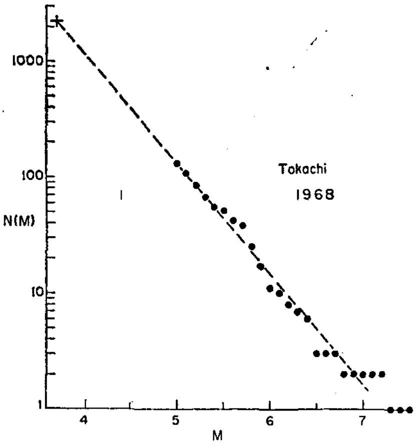


Fig. 66.

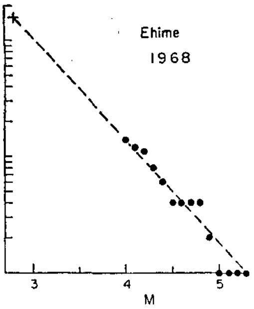


Fig. 67.

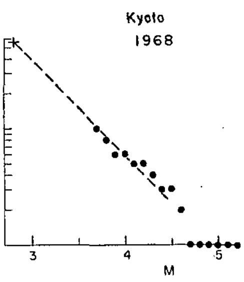


Fig. 68.

aftershocks here is the same as used in Chapter 3 (p. 147) The error in b-value thus determined is difficult to estimate accurately, but a previous study175) shows that the standard deviation of b is roughly $1.5b/\sqrt{N(M_z)}$, if there is no error in the estimate of M_z relative to the magnitude assigned to the larger aftershocks. However M_z may be in error by about 0.3. It is not practicable to test the significance of the difference in b-value for all combinations of two sequences picked up from Table 4, then the tests are performed for every pair of sequences in which magnitudes of more than 30 largest shocks are available by using a method described by Utsu.177) The results are shown in Table 6.

Table 6. Values of b for 11 aftershock sequences (including two swarms, No. 1, and No. 9) and the result of a test of the difference in b-value between every combination of two sequences. $\hat{b}$ is the maximum likelihood estimate of b, and s is the total number of shocks with magnitudes M_s and larger.

No.	Date (GMT) and name of the main shock		M_s	s	$\hat{b}$	Significantly different sequences
1	1928 May 27	Off Sanriku	5.3	43	0.51	At 2% significance level: No. 1 - No. 3, No. 1 - No. 10, No. 1 - No. 11.
2	1933 Mar. 2	Off Sanriku	5.6	32	1.05	
3	1937 Jan. 5	Hyuganada	4.0	30	1.33	
4	1938 Nov. 5	Off Fukushima Pref.	5.7	32	0.74	
5	1945 Jan. 12	Mikawa	4.6	37	0.81	
6	1946 Dec. 20	Nankaido	5.0	37	0.71	At 10% significance level: In addition to the above three pairs, No. 1 - No. 2, No. 1 - No. 7, No. 1 - No. 9, No. 3 - No. 6.
7	1952 Mar. 4	Off Tokachi	5.4	37	1.05	
8	1953 Nov. 25	Off Boso	5.0	42	0.82	
9	1962 Aug. 26	Miyake-jima	4.0	174	0.87	
10	1964 June 16	Niigata	4.0	162	0.99	
11	1968 May 16	Off Tokachi	5.0	31	0.92	

Values of b for aftershock sequences outside of Japanese region listed in Table 5 has been published in some papers.1),9),57)-66),125)-127,137)-139),176) It should be mentioned here that the b-value depends on the magnitude scale employed. Actually the b-values shown in Table 5 are based on various magnitude scales, i.e., body wave magnitude m, surface wave magnitude M_S, Richter's original scale M_L, and other similar scales. Therefore the comparisons of b-values in Table 5 do not always give a meaningful result, wheras the magnitude of the Japanese shocks are based on the same scale.

In Figures 69–71 relations between b and other parameters M_0, D_1, p, c, and $A/\bar{A}$ are exhibited. No correlation is found between b and three parameters M_0, c, and $A/\bar{A}$. However Figure 69 indicates that b tends to increase with D_1, even if open circles which represent earthquake swarms

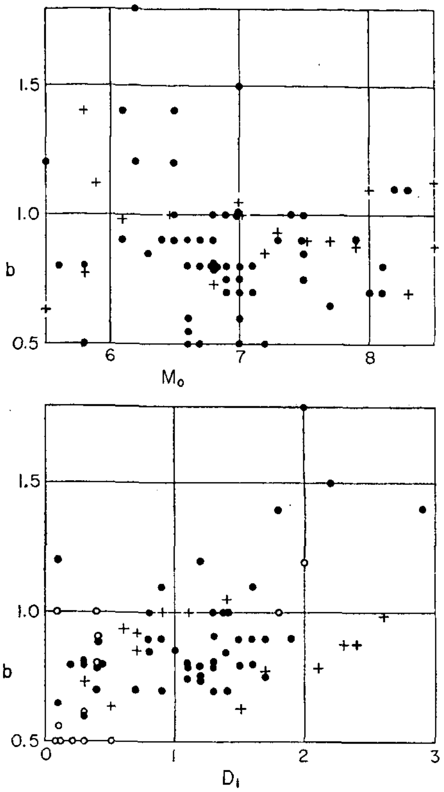
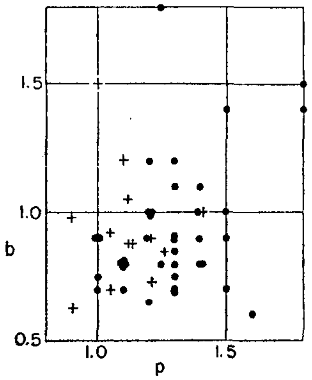


Fig. 69.



Pig. 70.

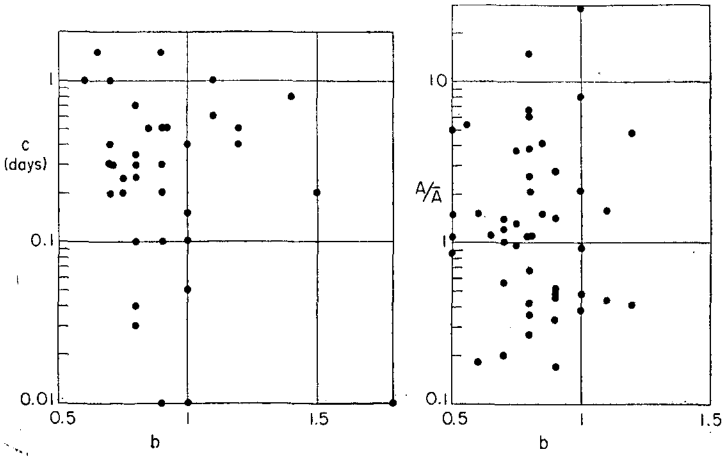


Fig. 71.

are disregarded. From Figure 70 a slight indication of positive correlation between p and b is seen.

The values of b in Table 4 range from 0.5 to 1.5 with a median of about 0.85. It is well known that the value of m in Ishimoto-Iida's formula for the distribution of maximum amplitude a recorded at a certain seismic station

$$n\,(a) = k\,a^{-m} \tag{35}$$

is connected with b by the equation

$$m = b + 1\,. \tag{36}$$

Values of m for aftershocks of Japanese earthquakes with $M_0 \geq 6$ during 1926–1958 and with $M_0 \geq 5.5$ during 1959–1968 reported by various investigators[180)-185)] are tabulated in Table 7. The median of these m values are about 1.85 as is expected from equation (36), but the b and m values in Table 4 and 7 for individual sequence do not completely satisfy equation (36).

Table 7. Values of m for some Japanese sequences reported by some investigators.

Date (GMT) Name	Station	m	Ref.	Date (GMT) Name	Station	m	Ref.
1927 Mar. 7 Tango		1.86	183)	1949 Dec. 25 Imaichi	Nikko	1.8	182)
	Ine	1.95	184)		Nikko	1.79	184)
	Maiduru	2.06		1959 Jan. 30 Teshikaga	Teshikaga	1.902	108)
	Kinosaki	1.84					
1943 Sept. 10 Tottori	Tottori	1.82	97)	1962 Aug. 26 Miyakejima		1.86	114)
	Shikano	1.88			Miyakejima	1.99	
	Kurayoshi	1.79				2.24	
1946 Dec. 20 Nankaido	Tanabe	1.70	180)	1964 May 7 Off Oga Pen.	Fukura	2.05	51)
	Shirahama	1.79			Ogura	2.20	
	Muroto	1.62			Akita	2.14	
	Tanabe	1.85	184)	1964 June 16 Niigata	Onabe	2.0	185)
	Shirahama	1.80			Nakaura	2.0	
	Muroto	1.77			Deyu	2.0	
1948 June 28 Fukui	Yamanaka	1.9	181)				
	Yamanaka	1.69	184)	1967 Nov. 4 Lake Kutcharo	Kushiro	1.74	48)
	Iburibashi	2.17					
	Kawai	1.77					
	Fukui	1.85					
	Shioya	1.92		1968 Jan. 29 Off Shikotan	Kami-kineusu	1.67	49)
	Daishoji	1.87					

The median of $b = 0.85$ is slightly smaller than $b = 1.0$ determined for the whole Japanese shallow earthquakes of $M \geq 6$ using data supplied from JMA.[1),23),186-188)] However Mogi[188)] showed that when aftershocks are selected out of the whole Japanese shallow earthquakes their magnitude distribution fits the formula with $b = 1.3$. The apparent difference between the two values (0.85 and 1.3) may be explained by considering the structure of the magnitude-frequency distribution of the whole earthquakes as discussed in the second part of this paper.

One remarkable fact about the magnitude-frequency distribution is that considerably small b valus (0.4~0.65) have been obtained for swarms or aftershock sequences with rather small D_1 occurring off the Pacific coast of northeastern Japan. Six sequences illustrated in Figure 72 and two ones

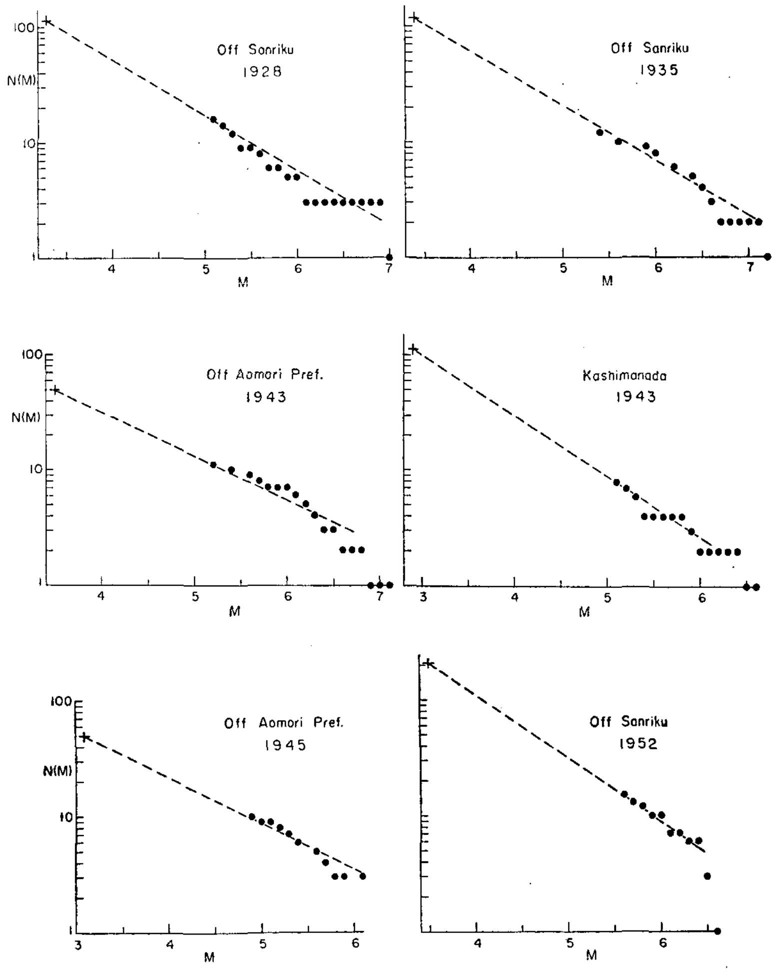


Fig. 72. Magnitude-cumulative frequency distributions for six sequences off the Pacific coast of northeastern Japan showing small slopes (b=0.4~0.65).

(No. 51 and No. 57 in Table 4) come under this category. On the other hand, some sequences occurring in the same region (Nos. 10, 14, 41, 42, and 64) have ordinary b-values ($0.8 \sim 1.0$). Swarms in the Izu Islands region (Nos. 37, 50, 55, etc.) have b-values which is not very small. The nature of these two kinds of swarms will be discussed in a later part.

The variation of b-value with time in an aftershock sequence has been investigated occasionally. Sakuma[189] tested in 1954 the difference in magnitude-frequency distribution between the first day and the later period for six sequences using data by Utsu,[190] and found no significant differences. As mentioned in Chapter 3 the depencence of b-value on time results the dependence of the parameters p and c on the lower limit of magnitude, but such dependence has not been observed clearly in many aftershock sequences studied hitherto.[57] Lomnitz[190] has indicated that the mean magnitude $\overline{M}$ of aftershocks above a certain level M_s does not change significantly with time in an aftershock sequence. This shows the stability of b-value, since[192)-193]

$$\overline{M} = \frac{\log e}{b} + M_s . \tag{37}$$

The temporal variation of b-value in an sequence, if exists, may not be so large that no statistically significant conclusion is achieved unless the very large volume of homogeneous data is available such as in the case of the Matsushiro earthquake swarm, for which a significant variation of b or m values has been reported by some authors.[149)-152]

6. Comments on the relations between parameters

In the previous chapters relations between several parameters characterizing an aftershock sequence have been investigated using data for Japanese sequences with $M_0 \geq 6$ (1926–1958) and $M_0 \geq 5.5$ (1959–1968). Among these parameters, values for p, c, A, and b have been estimated only for sequences listed in Table 4. There are many other sequences for which sufficient data have not been obtained to evaluate these parameters. Therefore the sequences used in the investigation may not be regarded as unbiased samples of the whole Japanese aftershock sequence, but they are mostly such sequences that accompanied by relatively high aftershock activities, and this is especially true for sequences with small M_0. For example, the mean of D_1 of 66 earthquakes in Table 4 is 1.0 and no correlation is found between D_1 and M_0. This is considerably different from the results obtained in Chapter 2 (cf. Figure 2).

Table 8. Correlations between parameters for sequences listed in Table 4. Upper right: Correlation coefficients r. Lower left: Results of t-tests. A mark × indicates that the hypothesis of $r=0$ is not rejected even at a signicance level of 0.1. For other marks see the text.

	M_0	D_1	$\log T_1$	p	$\log c$	$\log A/\bar{A}$	b
M_0		0.06	0.33	−0.18	0.42	−0.35	−0.14
D_1	×		−0.12	0.02	−0.55	−0.49	0.51
$\log T_1$	P	×		−0.53	−0.16	0.06	−0.23
p	×	×	**N**		0.39	−0.20	0.35
$\log c$	P	**N**	×	p		0.15	−0.24
$\log A/\bar{A}$	N	**N**	×	×	×		−0.10
b	×	**P**	×	p	×	×	

Apart from this point, the data in Table 4 show no remarkable mutual correlations except between A and M_0, and A and M_1. However there is slight indication of correlation between some of these parameters, and their correlation coefficients are calculated as shown in Table 8. In this table letters **P** and **N**, P and N, and p and n indicate positive and negative correlations for which the null hypothesis $r=0$ (no correlation) is rejected at significance levels of 0.001, 0.01, and 0.05 respectively. As far as the sequences listed in Table 4 are concerned, correlations between these parameters must be regarded as statistically significant. However, the interpretation of why such correlations exist is more or less complicated considering the situation under which these sequences have been chosen.

It is easily understood that the number of aftershocks with magnitude larger than a certain level is an increasing function of a parameter b as well as c, and also a decreasing function of a parameter D_1 as well as p, if all parameters other than one of these parameters remain the same. All sequences with large M_0 (say $M_0>7.5$) are accompanied by sufficiently large number of observable aftershocks for evaluating parameters p, c, b, A, etc., while for sequences with small M_0 (say $M_0<6$) these parameters are estimated only for those consisting of relatively large number of observable aftershocks, i.e., more probably for those having rather small p or D_1, or large b or c.

Suppose that there is a linear relationship between a quantity X and M_0. The mean and the variance of X are expressed by $\bar{X}=\alpha+\beta M_0$ and $V(X)=\gamma$ (constant) as illustrated in Figure 73 (solid circles plus open circles) when the X-values for all earthquakes are determined. However, as is often in the case with natural earthquakes, data necessary to estimate X-values are available only for a portion of earthquakes with small M_0, especially for earthquakes with rather large X-values, as indicated by open circles in the figure. The regression line (solid line) determined from the position of open circles is not a fair representation of the whole earthquake.

As an example, if X is replaced by log A, A is correlated with D_1 which is a rough measure of the aftershock activity, and there is a tendency that the data necessary to estimate A are more easily collected for earthquakes with higher aftershock activity, thus the regression line determined by the method of least squares will have a slope smaller than that for all earthquakes. As seen from Figure 73, a line $X_{\max}$ may have a slope close to that for all earthquakes (thick broken line), whereas a line $X_{\min}$ has a larger slope. Equations (13) to (34) in Chapter 4 must be reviewed taking such effects into consideration.

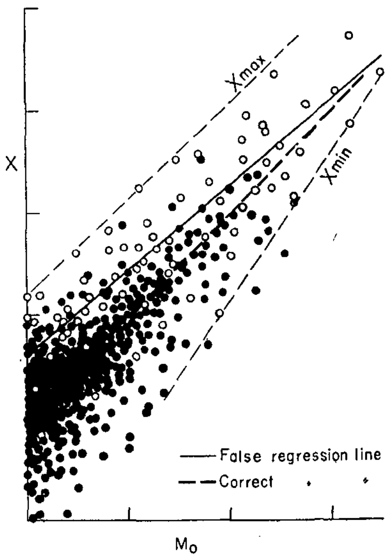


Fig. 73. A graph for an explanation of how a biased selection of data leads to a false regression line. A quantity X may be replaced by M_1, log A, log V, log l, etc. For a range of small M_0 there is a risk that only earthquakes with rather large X-values are selected, because observational data are available only for such earthquakes. The solid line is determined from these data (open circles).

The above description suggests that the interpretation of the correlations between parameters shown in Table 8 is not so simple. Further discussions will be made in a later part.

(1) D_1 and M_0: Although a negative correlation has been indicated

between D_1 and M_0 in Chapter 2, no correlation is found for 66 earthquakes in Table 4. This is due to the effect of data selection mentioned above.

(2) T_1 and M_0: The positive correlation may be a real one, since a positive correlation has been found for nearly complete data as illustrated in Figure 18.

(3) c and M_0: The positive correlation may suggest that the time scale of the aftershock phenomena has a tendency to increase with M_0.

(4) $A/\bar{A}$ and M_0: If equation (14) which defines $\bar{A}$ were determined by the method of least squares using all data in Table 4, the correlation coefficient would be exactly zero. However the equation was employed from another point of view, giving less weight to swarms, considering the harmony with equation (15), etc. The negative correlation is due to the fact that most swarms in Table 4 with large $A/\bar{A}$ have relatively small M_0.

(5) c and D_1: The negative correlation may suggest that for an sequence of high aftershock activity the occurence of aftershocks at an early stage of the sequence is relatively complex resulting a large c value.

(6) $A/\bar{A}$ and D_1: This negative correlation is similar to that has been pointed out by Mogi[22] and Nishi,[143] and can be explained at least partly by an idea that an earthquake with high aftershock activity has relatively large aftershock area.

(7) b and D_1: An explanation of this positive correlation has been given by Utsu.[23] The idea is as follows. If the magnitude of a shock in an aftershock sequence can be regarded as a random sample from a population defined by a function

$$\log N(M) = b\ (M_1{}^* - M) \tag{38}$$

where $N(M)$ is the number of shocks with magnitude M and larger, and b and $D_1{}^*$ ($=M_0-M_1{}^*$) are constant for all sequences (M_0 and M_1 may vary from sequence to sequence), it is easily understood that there is a negative correlation between b (an estimate of b from the magnitude distribution in a range of $M \geq M_s$, $M_s = M_0 -$const.) and D_1 (see Figure 74). Of course the above assumption does not hold exactly. Another explanation is that a sequence with small M_0 and large D_1 is more probably chosen for investigation if its b-value is relatively large. It must also be added that the small b-values for some earthquake swarms and aftershock sequences with small D_1 mentioned in Chapter 5 may contribute to this positive correlation.

(8) p and T_1: The negative correlation is natural, considering that a

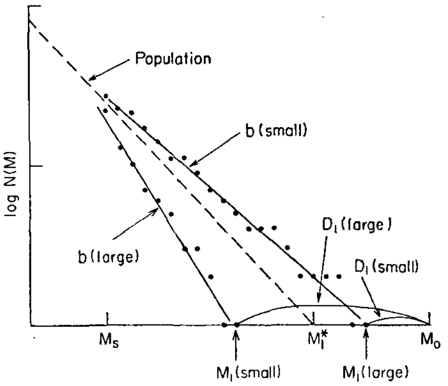


Fig. 74.

small p value means that the decay of the aftershock frequency is slow, then the probability that the largest aftershock occurs in a later stage of the sequence is relatively high.

(9) p and c, p and b: The weak positive correlations seem to be real ones, since the biased selection of sequences yields more probably negative correlations between p and c, and p and b, though the explanation can not readily be provided.

(to be continued)

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