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10. *Development of Aftershock Areas of Great Earthquakes.*

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Abstract

Spatial distributions of the aftershock energy of several great shallow earthquakes which occurred in the circum-Pacific seismic belt are discussed. In the interval of one year following the main shock, the active area clearly expanded outward in most cases. The pattern of the expansion, however, is different for different areas, as are the size and the shape of the aftershock area. A sharp contrast in these features of aftershock sequences between Japan and Aleutian-Alaska suggests a difference of the mechanism of aftershock occurrence in both areas. Moreover, a rapid systematic propagation of the aftershock activity during several hours following the main shock was found for the Aleutian Earthquake of 1957 and the Alaska Earthquake of 1964. From the standpoint of the fracture theory of earthquakes, these features in the development of the aftershock region are attributed to the nature of brittle fracture.

1. Introduction

Studies of the aftershock phenomena provide fundamental information on the mechanism of earthquake generation. From this standpoint, statistical features, such as geographical distribution, temporal distribution, and magnitude distribution of aftershocks have been intensely studied (e.g. Omori, 1894; Nasu, 1929; Matuzawa, 1936; Utsu, 1961; Page, 1967). Recently, some detailed features in spatial distribution of aftershocks have been discussed by many investigators. The strain release pattern in the aftershock area has been investigated in various cases [e.g. St. Amand (1956) (for Kern County, 1952), Båth and Benioff (1958) (for Kamchatka, 1952), and Duda (1963) (for Chile, 1960)]. Utsu (1962) studied the geographical variation in the mode of aftershock occurrence within the aftershock area on three Aleutian-Alaska earthquakes. Yamakawa (1967) pointed out for some earthquakes in Japan a concentration of the aftershock energy near the epicenter of the main shock or near a line including the epicenter. The temporal variation of the spatial distribution of aftershocks has been studied by Duda and Båth (1963) (for three California earthquakes), Santō (1964) (for Iturup, 1963) and others. In particular, Murauchi (1949) and Katok (1966) suggested a divergence of the aftershock area after the Nankaidō Earthquake of 1946 and the Khait Earthquake of 1949, respectively.

Although these valuable results have been accumulated, some fundamental characters of aftershock sequences, such as the size and the shape of the aftershock area, the spatial distribution of the aftershock energy, the temporal variation of the aftershock area, etc. have not been fully made clear, because they are variable in various cases and particularly peculier to a region where an aftershock sequence occurred. Thus, further systematic investigations appeared justified.

The object of this paper is to make clear in more general terms these fundamental characters of aftershock sequences for *great shallow earthquakes*. If observational errors in available data are considered, these features can be safely discussed only for some great earthquakes and with a few exceptions in smaller earthquakes. The present analysis was made on great earthquakes which occurred in the circum-Pacific seismic belt since 1933.

In this paper, at first, the size of the aftershock area of great earthquakes was discussed in respect to its regional variation. Moreover, the spatial distribution of the aftershock energy of great earthquakes and their temporal variation have been systematically investigated. One particularly noteworthy result is a sharp contrast in the character of aftershock sequences between Japan and Aleutian-Alaska regions.

In a previous paper (Mogi, 1968), the writer pointed out the high regularity in the occurrence of great earthquakes throughout the world in the past 30 years. The present results of aftershock occurrence of these great earthquakes may give a clue to understanding the nature of great earthquakes.

2. Size of aftershock areas

An aftershock sequence occurs in a limited area including the epicenter of a main shock. In most cases, the area where an aftershock sequence occurred can be defined by a simple boundary and it is usually of circular or elliptic shape. It is well known that there is a close relation between the size of the aftershock area and the magnitude of the main shock. Utsu and Seki (1955) who studied aftershock sequences of 39 earthquakes in and near Japan, obtained the following relation between the aftershock area (A in km^2) and the magnitude (M_0) of the main shock,

$$\log A = 1.02\, M_0 - 4.01. \qquad (1)$$

Utsu (1961) confirmed the relation by aftershock sequences from other areas, and furthermore he obtained the following relation between the linear dimension (D in km) of the aftershock region and the magnitude (M_0) of the main shock for 48 earthquakes in and near Japan, by use of the P-S intervals observed at a certain station,

$$\log D = 0.5\, M_0 - 1.8. \qquad (2)$$

This relation is approximately equivalent to Eq. (1) under the assumption that the aftershock area is circular in shape, which is justified as a first approximation for the considered cases. These formulae were obtained for the range of M_0 from 5 1/2 to 8 1/2, but the considered earthquakes of magnitude 8.0 and larger were only three, and so they are safely applied to earthquakes of moderate magnitude. Now, it is open to question whether or not the A-M_0 relation is also applicable to great earthquakes in various regions. This subject is discussed in this section.

In more detailed investigations, a systematic, but not a large regional variation of the aftershock area in earthquakes in and near Japan was pointed out by Utsu (1957), Yamakawa (1967) and Mogi (1967). Båth and Duda (1963) suggested a different A-M_0 relation for different regions, althogh their data were very few (six aftershock sequences). Such regional variation is discussed for great earthquakes in the following cases.

Result In fifteen great earthquakes which occurred in the circum-Pacific seismic zone, the largest linear dimension (D) of aftershock region and the aftershock area (A) in the interval of one year following the main shock were obtained by plotting epicenters of aftershocks. Now, it may be supposed to be difficult to discriminate aftershocks from other earthquakes. However, in the actual procedure, most aftershocks can be easily defined by comparison with the calm state in the investigated area. The result is summarized in Table 1. The aftershock data were adopted from the following sources: *the Seismological Bulletin* *of the Japan Meteorological Agency* or *JMA*, *the Seismological Bulletin of the U.S. Coast and Geodetic Survey* or *USCGS*, *the United States Earthquakes*, *International Seismological Summary*, and Duda (1963). The errors in determination of epicenters of aftershocks were sometimes serious, particularly for the A values of the aftershock areas which were very long and narrow. Such uncertain cases are parenthesized in Table 1.

Table 1.

Region	Date (G. M. T.)			Lat.	Long.	$\overline{M_0}$	D (km)	A ($\times 10^4$ km^2)
Sanriku-Oki	1933	March	2	39.1° N	144°7° E	8.5	420	5.8
Tōnankai	1944	Dec.	7	33.7° N	136.2° E	8.2	(320)	(2.8)
Nankaidō	1946	Dec.	21	33.0° N	135.6° E	8.2	240	3.4
Tokachi-Oki	1952	March	4	42.15° N	143.85° E	8.3	310	3.1
Bōsō-Oki	1953	Nov.	25	34.3° N	141.8° E	8.0	140	(1.0)
Fukushima-Oki	1938	Nov.	5	37.15° N	141.7° E	7.6	120	
Iturup (Kurile)	1958	Nov.	7	44.3° N	148.5° E	8.2	170	1.3
Iturup (Kurile)	1963	Oct.	13	44.8° N	149.5° E	8.25	600	7.5
Kamchatka	1952	Nov.	4	52.0° N	162.0° E	8.3	900-1000	(19)
Kamchatka	1959	May	4	52.5° N	159.5° E	8.1	(500)	
Aleutian	1957	March	9	51.3° N	175.8° W	8.1	1100	(16)
Aleutian	1965	Feb.	4	51.3° N	178.6° E	7.8	750	12
Alaska	1964	March	28	61.0° N	147.8° W	8.5	900	20
Southern Alaska	1958	July	10	58.5° N	136.0° W	7.9	(450)	
Chile	1960	May	22	39.5° S	74.5° W	8.4	1100-1200	(37)

In Fig. 1, the D values of these great earthquakes are plotted against the magnitude (M_0) of the main shock. Since the magnitude (M_0) of a great earthquake is different for different reporters, the value $\overline{M_0}$ was obtained as the average value of each magnitude (M_0) in the *Catalogue of Major Earthquakes Which Occurred in and near Japan (1926–1956)* by JMA, *Rikanenpyo**, *the Seismological Bulletin of USCGS*, *Seismicity of the Earth* (Gutenberg and Richter, 1954) and Duda (1963). In this figure, $\overline{M_0}$ and the range of M_0 are indicated by an open circle and a bar, respectively. The D-M_0 relation obtained by Utsu (1961) is also indicated as a solid line. According to the present result, the D value of the aftershock area of the great earthquakes of the same

* Science Calendar, Tokyo Astronomical Observatory ed. by Kawasumi (1965) and Hagiwara (1967), Maruzen, Tokyo.

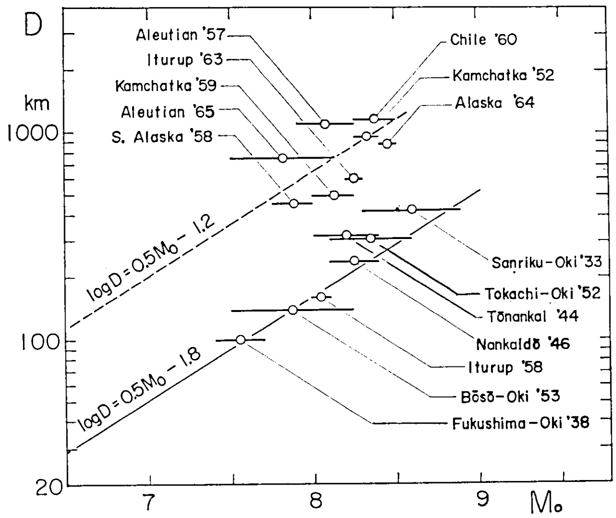

Fig. 1. Length of aftershock area (D) versus magnitude of main shock (M_0).

magnitude is markedly scattered, and so it does not show a close relation to the magnitude M_0. Thus, the following conclusions may be derived:

(i) The formula (2) does not always apply to great earthquakes in different regions. In more detail, the formula (2), however, is nearly applicable to great earthquakes in and near Japan, as shown by Utsu. The linear dimension (D) of aftershock regions in other areas are appreciably larger than expected from Eq. (2), sometimes 1000 km or more.

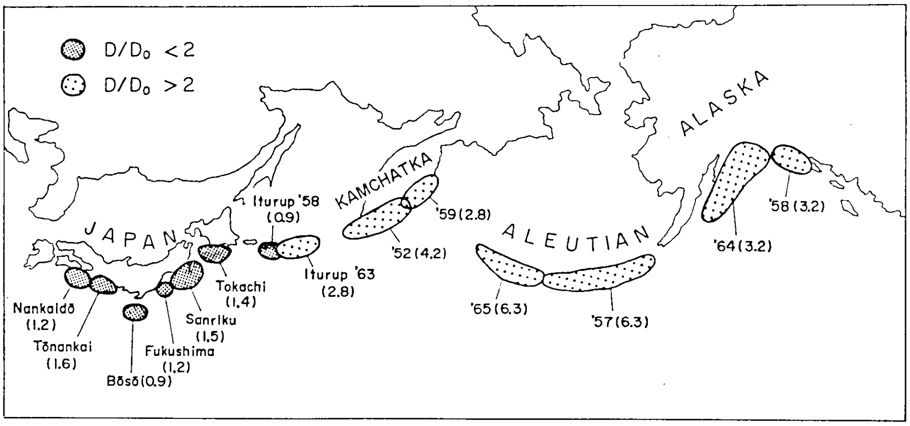

Fig. 2. Geographical distribution of ratio of the length (D) of aftershock area to its standard value (D_0). Parenthesized numerals show D/D_0 values.

(ii) The ratio D/D_0 where D_0 is the D value calculated by Eq. (2) shows a systematic regional variation, as shown in Fig. 2. The marked difference in the size of the aftershock area between Japan and Kamchatka-Aleutian-Alaska suggests the different mechanisms of earthquake occurrence in both regions, as will be mentioned in a later section.

This result on the D value are qualitatively similar on the A value, but the degree of the regional variation is somewhat lower in the A value.

3. Spatial distribution of aftershock energy and its temporal variation

Epicenters of aftershocks do not locate uniformly in the aftershock area, but concentrate at certain places, and their spatial distribution sometimes changes with the lapse of time. To make clear this feature, spatial distributions of aftershock energy in successive periods after the main shock are discussed in this section.

Procedure of investigation The spatial distribution of aftershock energy was obtained by the following procedure: (1) Epicenters of aftershocks are plotted. (2) The area where epicenters of aftershocks are located is divided into square regions with a unit dimension of 20 km. (3) The total energy of aftershocks of which epicenters are located in each square is calculated. (4) The energy of larger aftershocks is distributed to square regions around the epicenters in consideration of the volume where the earthquake energy was stored as the strain energy. The linear dimension of the volume was assumed to be similar to the D value given by Eq. (2) (Tsuboi, 1956).

This spatial distribution of the areal energy density was obtained for the following four periods:

A: one day just after the main shock (24 hours).

B: one month just after the main shock, except for the first day (30 days).

C: one year just after the main shock, except for the first month (11 months).

(**A**+**B**+**C**): one year just after the main shock.

The largest time interval in this analysis was limited to one year, for the reason that in a longer time interval it was difficult in some active regions to discriminate the aftershock activity from the background seismic activity. A set of the energy distributions was obtained for the eight great shallow earthquakes which occurred in the circum-Pacific seismic zone. Since many features of an aftershock sequence are peculiar to each region, as suggested also in the preceding section, the investigated earthquakes are divided into three groups, those in Japan, Aleutian-Alaska, and other regions, in the following description. Earthquakes data were adopted from *the Seismological Bulletin of JMA* (for Japan), *the Seismological Bulletin of USCGS* (for Aleutian-Alaska and Iturup), and Duda (1963) (for Chile).

(I) *Earthquakes in and near Japan*

(1) *The Tokachi-Oki Earthquake of March 4, 1952* ($\overline{M}_0=8.3$).

The main shock was located off south-east coast of Hokkaidō. The

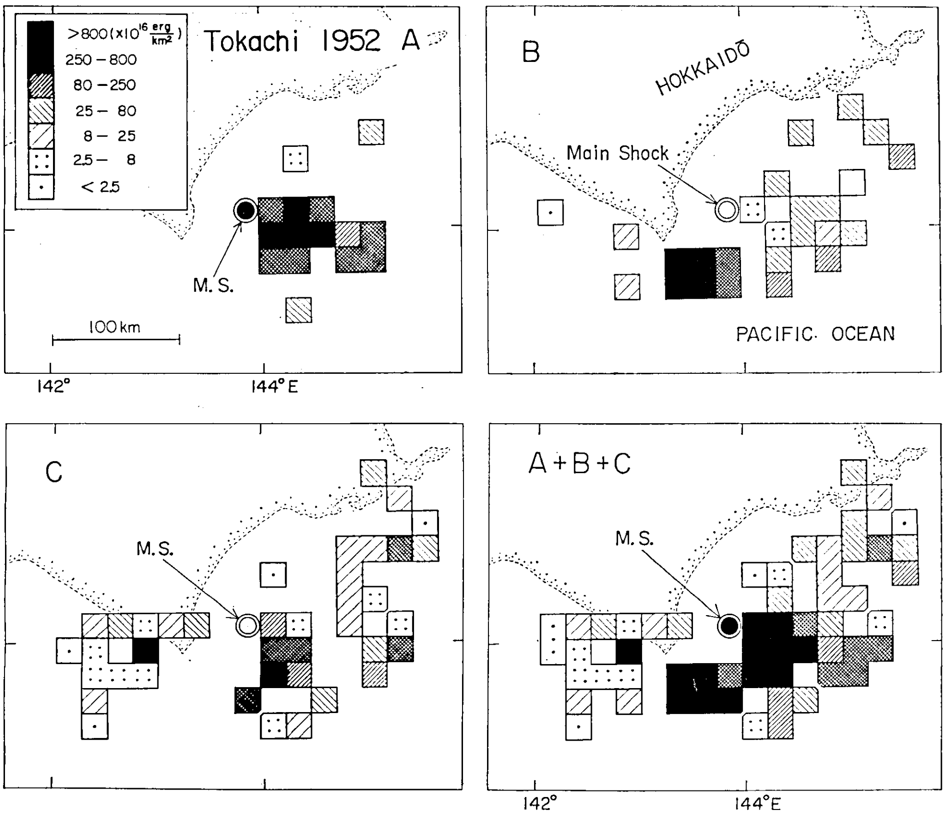

Fig. 3. Distributions of aftershock energy of the Tokachi-Oki Earthquake of 1952 in each period. **A**: one day following the main shock; **B**: one month following the main shock, except for the first day; **C**: one year following the main shock, except for the first month; (**A**+**B**+**C**): one year following the main shock.

spatial distributions of aftershock energy for each period are shown in Fig. 3. In the period **A**, aftershock energy highly concentrates in a limited region near the epicenter of the main shock. In the following periods, **B** and **C**, the active area clearly migrated toward north-east and west. The patterns of the expansion of aftershock area are summarized in Fig. 4. Other noteworthy features are that the aftershock region is located on one side of the main shock, as pointed out by Matuzawa (1936) in many cases, and the southeastern boundary of the aftershock region is definite.

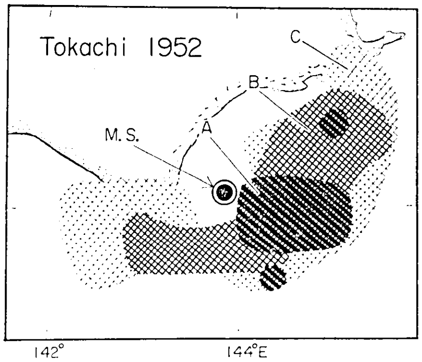

Fig. 4. Successive expansion of aftershock area of the Tokachi-Oki Earthquake of 1952 in the interval of one year following the main shock.

(2) *The Sanriku-Oki Earthquake of March 2, 1933* ($\overline{M_0}=8.5$)

The main shock occurred at the eastern boundary of the circum-Pacific seismic zone in north-eastern Japan, corresponding to the eastern wall of the Japan Trench. The migration of seismic activity in this area during five years since 1930 includes this great earthquake and its aftershock sequence (Mogi, 1968). In the period **A**, the aftershock energy distributes with high concentration in a limited region near the epicenter of the main shock (Fig. 5). The seismic active area markedly extended westward during the following periods **B** and **C**. The successive expansion of the aftershock area is summarized in Fig. 6. Thus, the total aftershock area situated extremely at the west side of the epicenter of the main shock and the eastern boundary of the aftershock region is fairly definite. Another concentration of aftershock energy in the south-western region is due to a large aftershock and the displacement of the active area in the south-west direction corresponds to the above mentioned general migration in this district.

(3) *The Nankaidō Earthquake of December 21, 1946* ($\overline{M_0}=8.2$)

The spatial distributions of the aftershock energy in each period and the temporal variation of the aftershock area are shown in Figs. 7 and 8, respectively. The aftershock region is located at the north side of the epicenter of the main shock. The aftershock energy concentrates near the southern boundary of the aftershock area, which limited def-

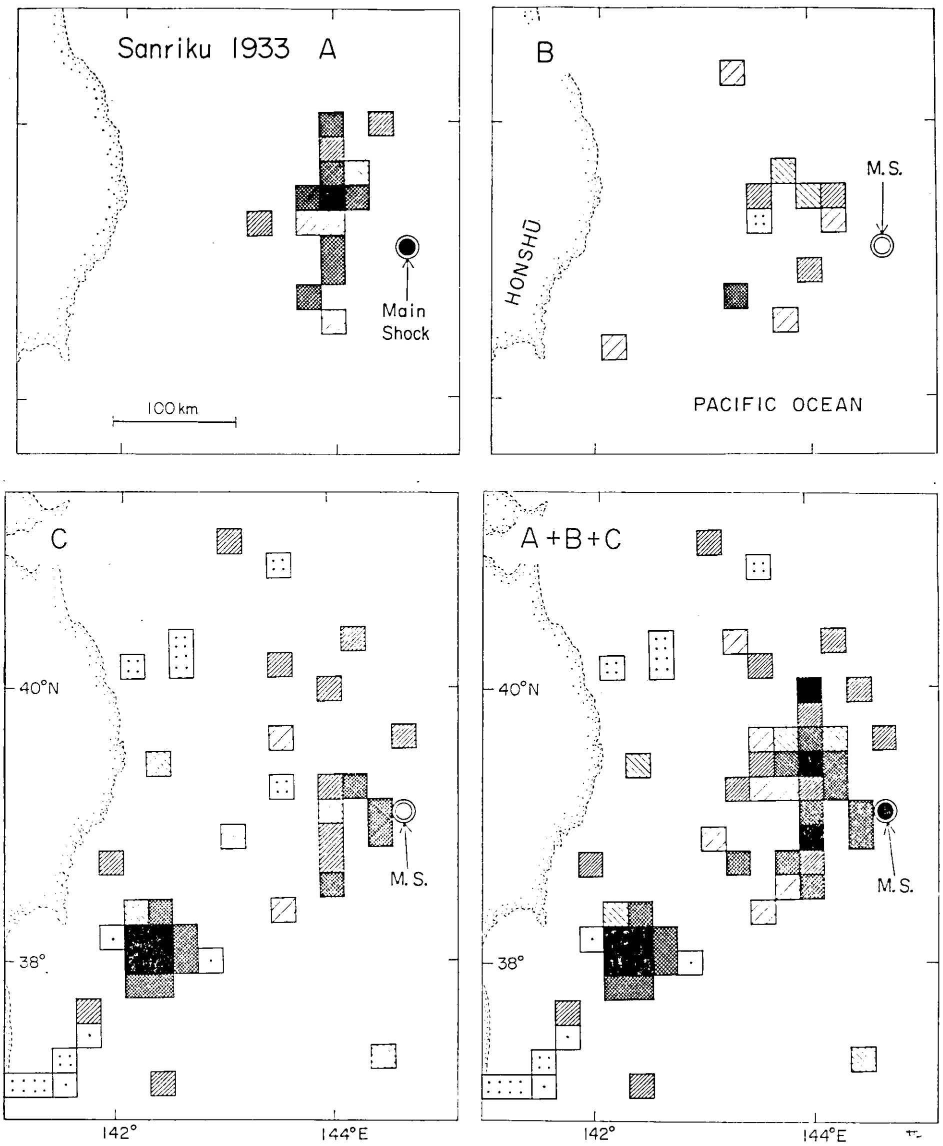

Fig. 5. Distributions of aftershock energy of the Sanriku-Oki Earthquake of 1933 in the periods **A**, **B**, **C** and (**A**+**B**+**C**).

initely the active area.

(4) *The Tōnankai Earthquake of December 7, 1944* ($\overline{M_0}=8.2$)

Figs. 9 and 10 show the spatial distributions of the aftershock energy

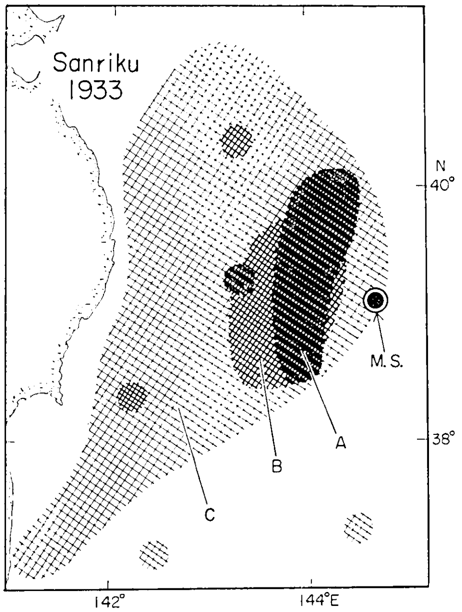

Fig. 6. Successive expansion of aftershock area of the Sanriku-Oki Earthquake of 1933 in the interval of one year following the main shock.

in each period and the successive expansion of the active region, respectively. In this case, the aftershock area extends in the north-east side of the epicenter of the main shock and the pattern of the expansion is very complex. The high energy concentration at the northern part of the aftershock area is due to the Mikawa Earthquake of 1945 which is regarded as another large earthquake.

From these results, the following features are noted as common in these aftershock sequences in and near Japan:

(i) The size of the aftershock area just after the main shock (in the period A) is relatively small.

(ii) There is the marked outward expansion of the aftershock area from the epicenter of the main shock during the successive periods.

(iii) The aftershock energy concentrates in a limited region near the epicenter of the main shock, as pointed out by Yamakawa (1967).

(iv) The difference between the longest and the shortest linear dimension of the aftershock area is not large, that is, the area is nearly circular in shape.

(II) *Earthquakes in Aleutian and Alaska*

(1) *The Aleutian (Rat Island) Earthquake of February 4, 1965* ($\overline{M_0}=7\frac{3}{4}$)

The main shock was preceded by several foreshocks and followed by an intensive aftershock sequence. The spatial distributions of the aftershock energy in each period are shown in Fig. 11. The aftershock area parallel to the Aleutian Island Arc is very long, even in the initial period **A**. The appreciable expansion of the area during the following periods **B** and **C** does not take place in the direction of the long axis, but in the lateral direction. In this case, the aftershock energy highly distributes at a certain region distant from the epicenter of the main shock and along the axis of the aftershock region (Fig. 12).

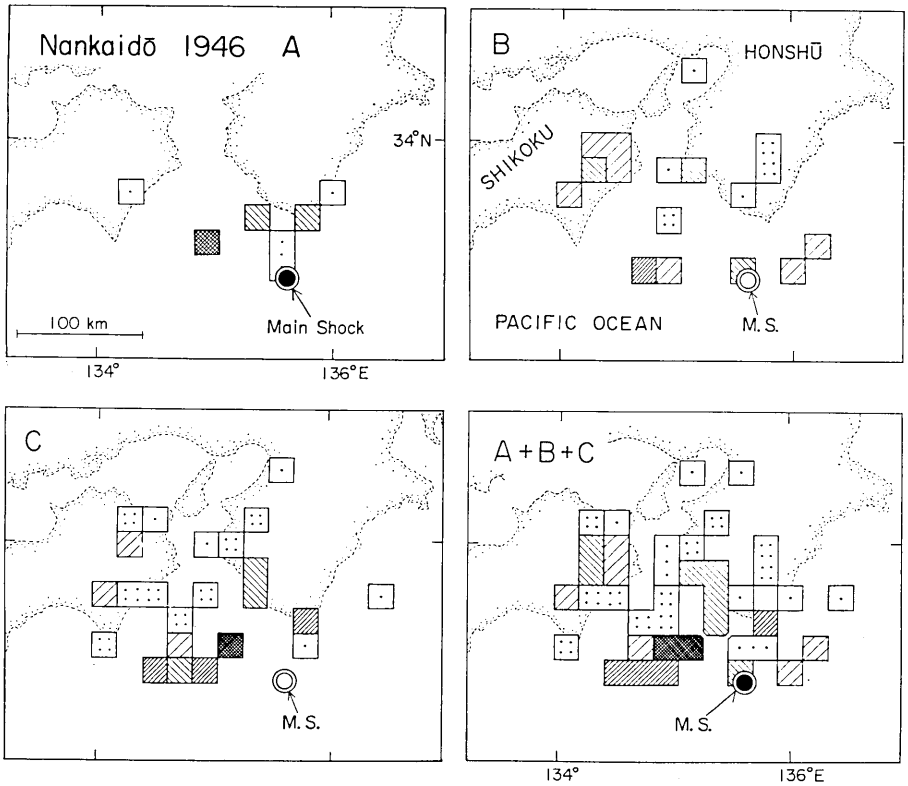

Fig. 7. Distributions of aftershock energy of the Nankaidō Earthquake of 1946 in the periods **A**, **B**, **C** and (**A**+**B**+**C**).

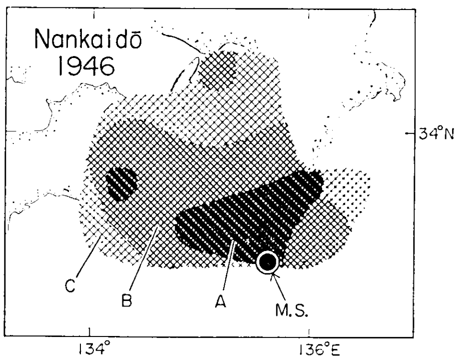

Fig. 8. Successive expansion of aftershock area of the Nankaidō Earthquake of 1946 in the interval of one year following the main shock.

The aftershock sequence of *the Aleutian Earthquake of 1957*, which was studied by Utsu (1962) and will be also discussed in a later section, seems to show some analogous characteristics.

(2) *The Alaska Earthquake of March 27, 1964* ($\overline{M_0}=8.5$)

The aftershock region is located parallel to the Aleutian Trench and the volcanic arc from the Aleutian Islands. In the period **A**, the aftershock area is very long, but limited to a narrow zone

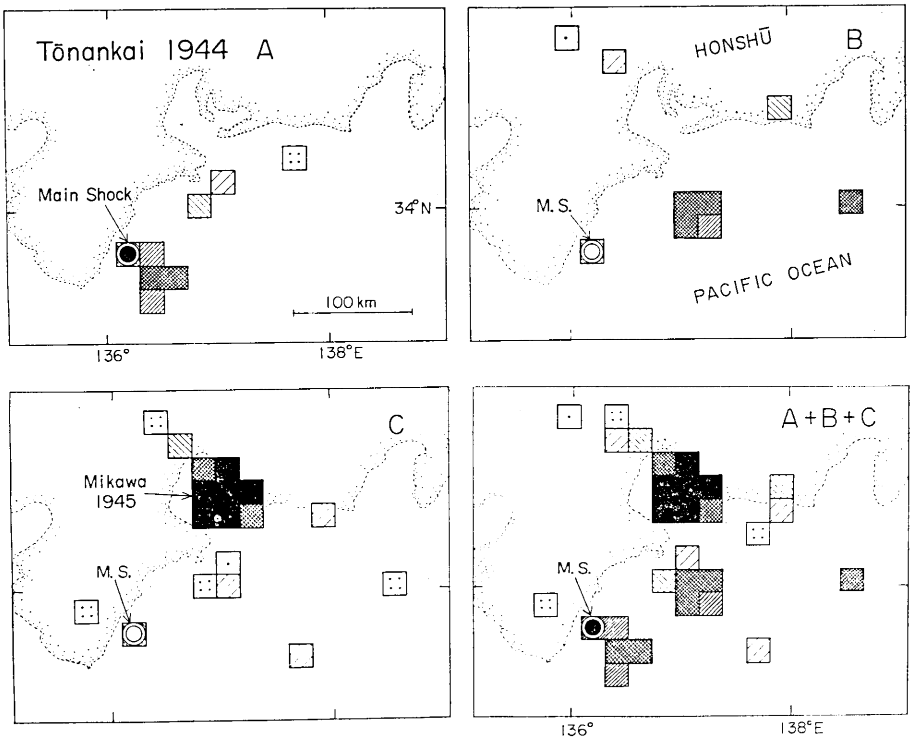

Fig. 9. Distributions of aftershock energy of the Tōnankai Earthquake of 1944 in the periods **A**, **B**, **C** and (**A**+**B**+**C**).

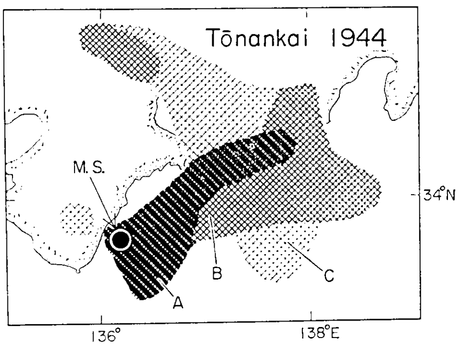

Fig. 10. Successive expansion of aftershock area of the Tōnankai Earthquake of 1944 in the interval of one year following the main shock.

(Fig. 13). The gradual dispersion of the aftershock activity in a lateral direction is noticeable during the following periods **B** and **C**. In this case, there is no marked concentration of aftershock activity.

As common characteristics of aftershock sequences in the Aleutian and Alaska region, the following features may be noted.

(i) The aftershock area is already very long in the initial period **A**.

(ii) The aftershock activity

disperses in a lateral direction during the periods **B** and **C.**

(iii) The aftershock energy highly distributes at a certain region distant from the epicenter of the main shock rather than near the epicenter of the main shock. However, in some cases such as the Aleutian Earthquake of 1957, the energy concentrates also around the epicenter of the main shock.

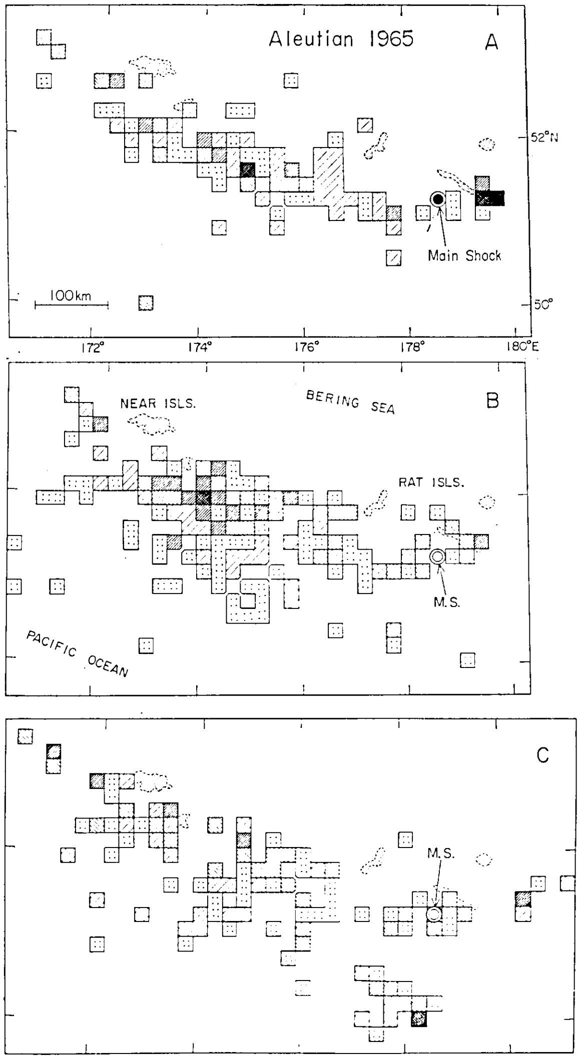

Fig. 11a. Distributions of aftershock energy of the Aleutian Earthquake of 1965 in the periods **A**, **B**, and **C**.

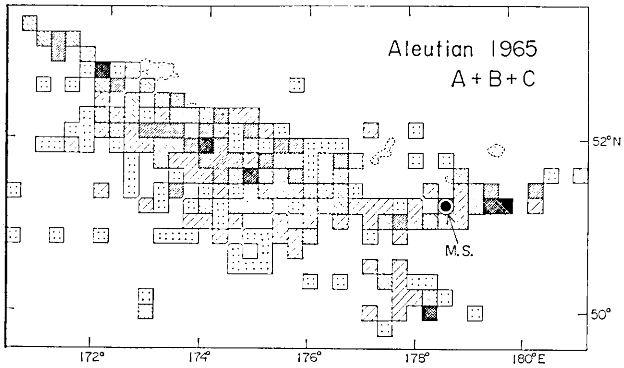

Fig. 11b. Distribution of aftershock energy of the Aleutian Earthquake of 1965 in the period (**A**+**B**+**C**).

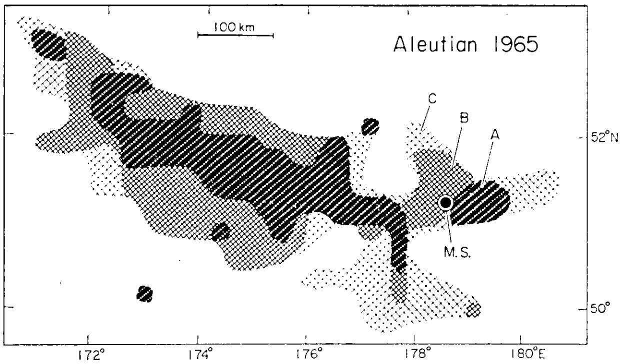

Fig. 12. Successive expansion of aftershock area of the Aleutian Earthquake of 1965 in the interval of one year following the main shock.

(iv) The aftershock area is very long and relatively narrow.

(III) *Earthquakes in other regions*

(1) *The Iturup (Kurile Islands) Earthquake of October 13, 1963* ($\overline{M_0}=8\frac{1}{4}$)

This earthquake was preceded by a marked foreshock sequence. The epicentral distribution of the fore- and aftershocks in successive periods has been discussed by Santō (1965). Figs. 15 and 16 show the spatial distributions on the earthquake energy in this sequence and the temporal variation. The active area gradually extended in a north-east direction, and the high earthquake energy distributes around the epicenter of the main shock.

(2) *The Chilean Earthquake of May 22, 1960* ($\overline{M_0}=8.4$)

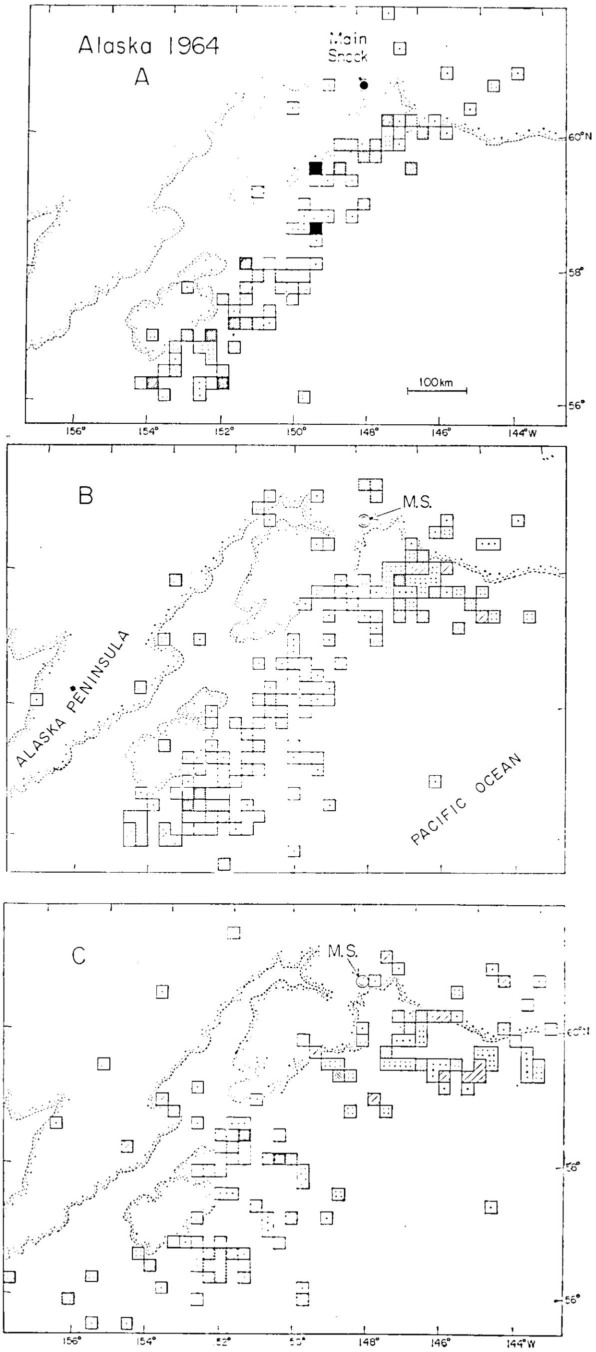

Fig. 13a. Distributions of aftershock energy of the Alaska Earthquake of 1964 in the periods **A**, **B**, and **C**.

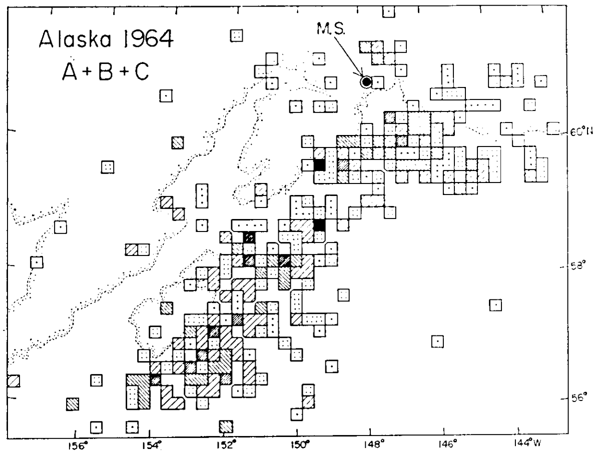

Fig. 13b. Distribution of aftershock energy of the Alaska Earthquake of 1964 in the period (**A**+**B**+**C**).

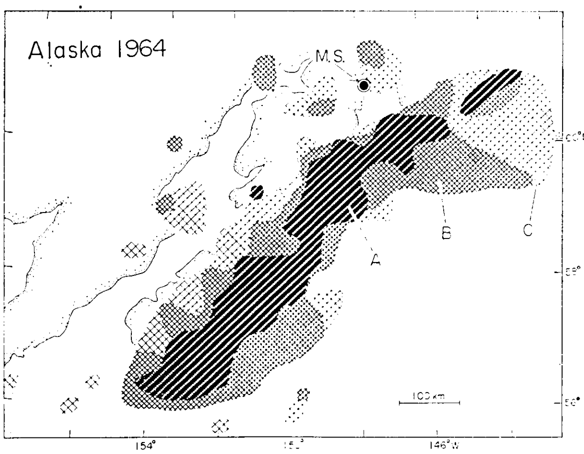

Fig. 14. Successive expansion of aftershock area of the Alaska Earthquake of 1964 in the interval of one year following the main shock.

This earthquake was preceded by intensive foreshocks and followed by moderate aftershocks. Because of insufficient data available, the spatial distributions of the earthquake energy is obtained for a larger unit square ($50\times 50\,km^2$) (Fig. 17). The aftershock area is very long along the continental margin. The active area in the foreshocks-main shock-aftershocks sequence displaced southward during the considered

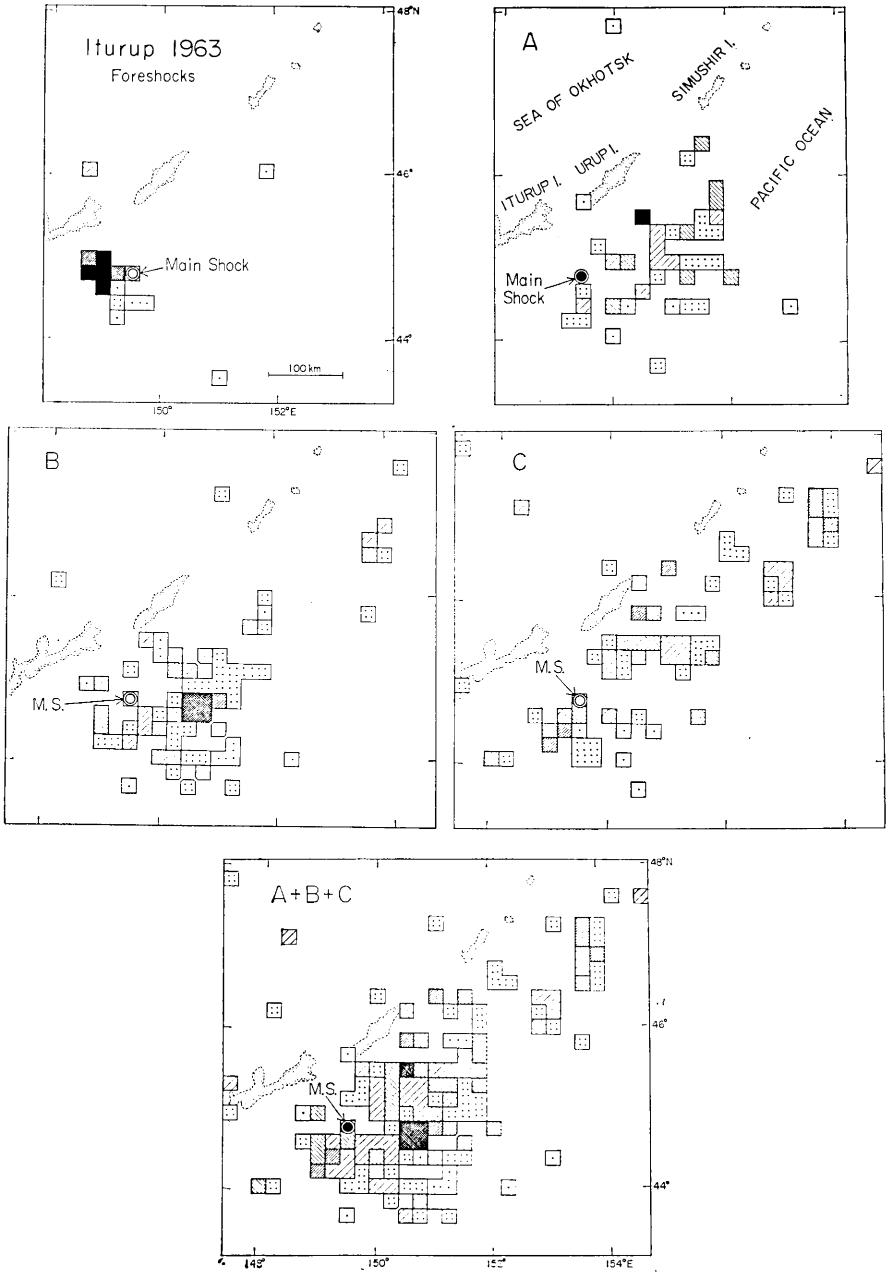

Fig. 15. Distributions of foreshock and aftershock energy of the Iturup Earthquake of October 13, 1963 in each period. The time interval for *foreshocks* is from October 9 to the time just before the main shock.

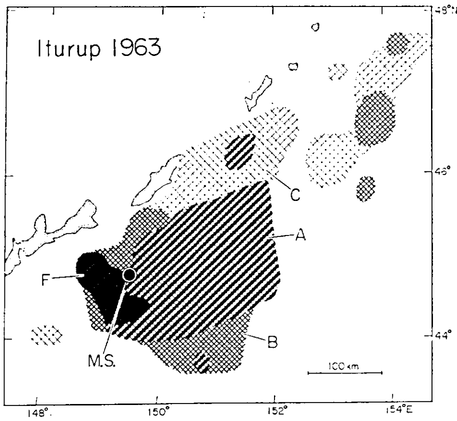

Fig. 16. Foreshock and aftershock regions of the Iturup Earthquake of 1963 in successive periods.

period, and the earthquake energy highly distributes in the northern area and at a certain region in the southern area, as pointed out by Duda (1963).

These aftershock patterns of the Iturup Earthquake and the Chilean Earthquake seem to be characterized as an intermediate type between types in Japan and Aleutian-Alaska.

From the present results, it is concluded that the aftershock area of most great earthquakes gradually is displaced or expanded outward in the interval of one year following the main shock but, however, the mode of expansion of the aftershock area and the pattern of the energy distribution in the area are different for different regions. Fig. 19 summarized the temporal variation of the largest linear dimension (D) of these great earthquakes.

4. Migration of aftershock activity just after the main shock in the Aleutian Earthquake of 1957 and the Alaska Earthquake of 1964

In addition to the above-mentioned gradual displacement or expansion of the aftershock region, a more rapid migration of aftershock activity just after the main shock was found in the following two cases. Although this kind of regularity in aftershock occurrence is not general, it is very suggestive of the mechanism of the generation of aftershocks.

(1) *The Aleutian Earthquake of March 9, 1957*

This earthquake is noticeable for its very long aftershock zone (1100 km) which is situated between the Aleutian Arc and the Aleutian Trench. The epicentral distributions of the main shock and aftershocks based on data taken from *the United States Earthquakes* are shown in Fig. 20a. Before the great earthquake, two earthquake swarms occurred in December, 1956 and in January, 1957 within the above-mentioned aftershock region, as shown in Fig. 20b. The epicenters of these earthquakes in-

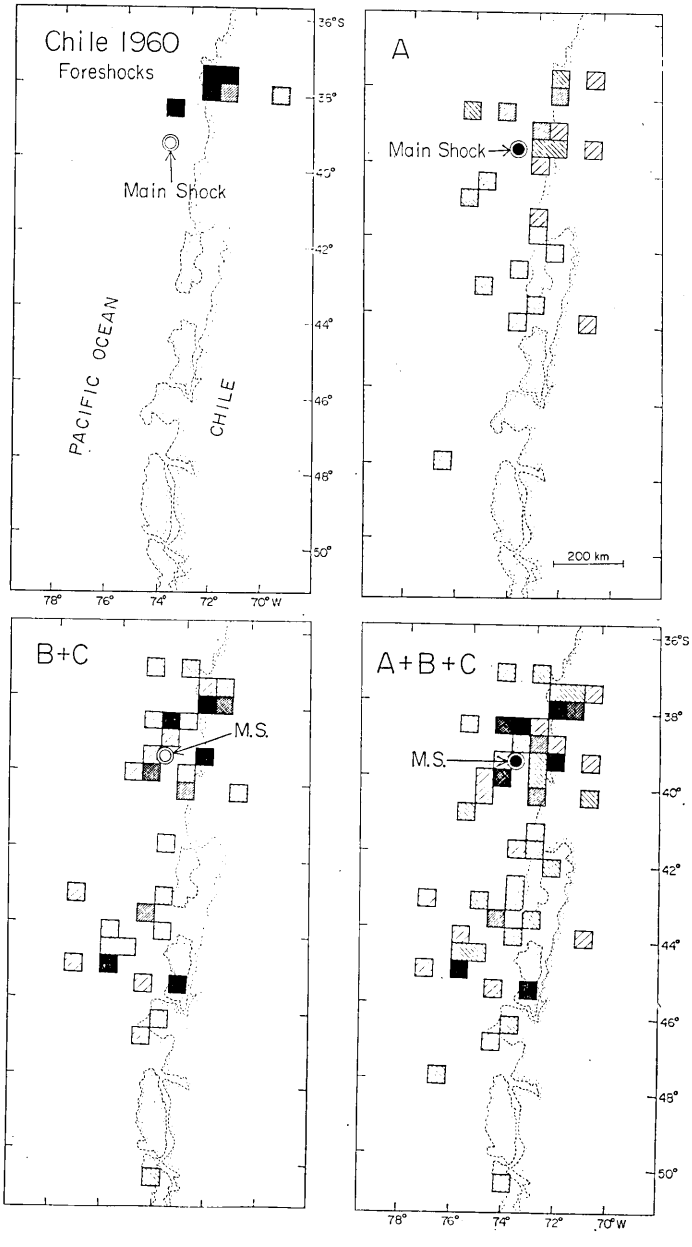

Fig. 17. Distributions of foreshock and aftershock energy of the Chilean Earthquake of May 22, 1960 in each period. The time interval for *foreshocks* is from May 21 to the time just before the main shock.

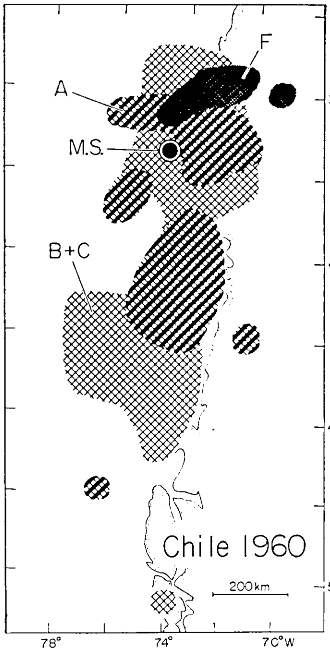

Fig. 18. Foreshock and aftershock regions of the Chilean Earthquake of 1960 in successive periods.

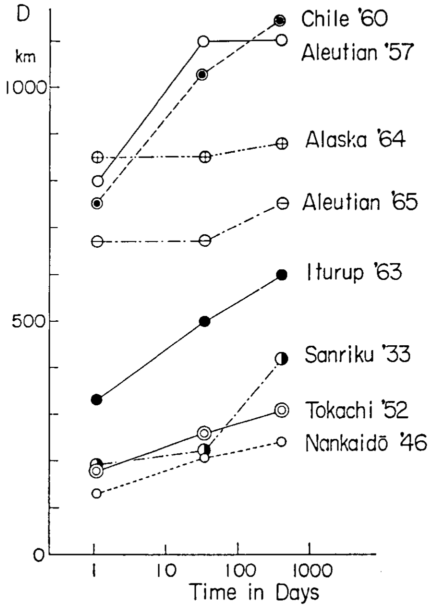

Fig. 19. Length (D) of aftershock area as functions of the time after the main shock.

cluding an earthquake of magnitude 7.0 were located in a limited region 600 km distant from the epicenter of the main shock of March 9, 1957. *The United States Earthquakes* reported epicenters of nine aftershocks including one of magnitude 7.0 (No. 8) which occurred in the interval of eight hours just after the main shock. Although magnitudes of eight of these aftershocks are unknown, they are probably among the larger of the many aftershocks which probably occurred in this time interval. In Fig. 21a, the geographical distribution of the epicenters of the nine aftershocks which are numbered in order of time is shown with those of the main shock and the preceding earthquake swarms. It is evident from this result that the epicentral region of these major aftershocks very systematically migrated in NEE direction. Moreover, it is also interesting that the activity starts from a region near the epicenter of the main shock and terminates at the region where the above-mentioned earthquake swarms had occurred a few months before. In Fig. 21b, the distance from the epicenter of the No. 1 aftershock to

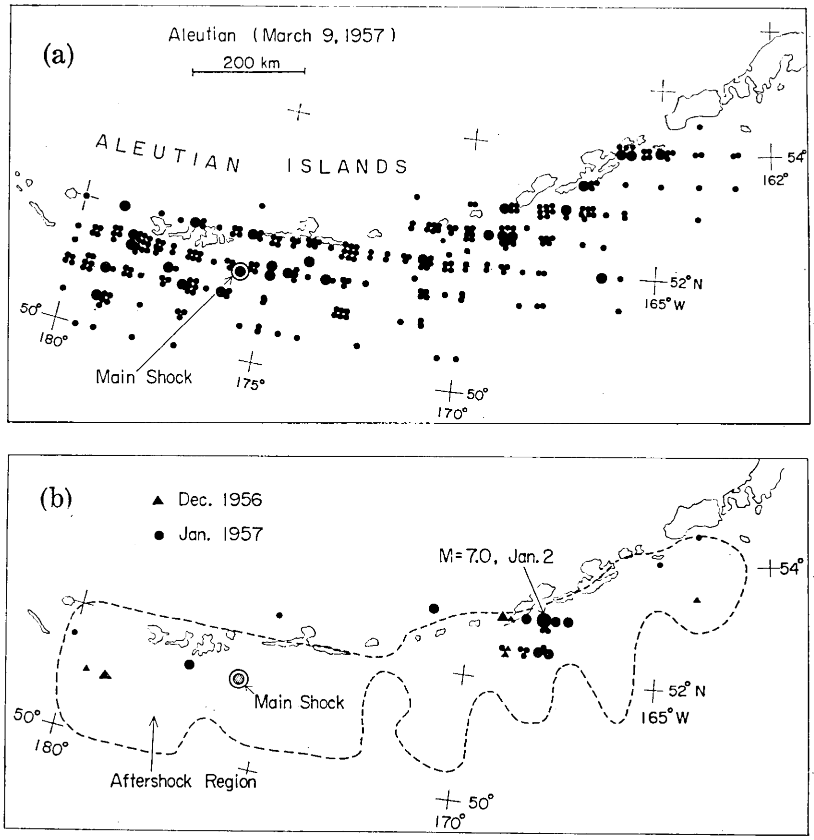

Fig. 20. Distributions of aftershock epicenters of the Aleutian Earthquake of 1957 (above) and of epicenters of swarm earthquakes which occurred before the great earthquake (below).

that of each aftershock are plotted against time as closed circles. Figs. 21a and b indicate the fact that the migration of aftershock activity temporarily stopped after the No. 4 aftershock and started again from the No. 5 aftershock after a few hours interval. If this time interval is corrected for the later part of the time-distance curve, as indicated by a broken curve in Fig. 21b, the initial part of the solid curve and the broken curve give a continuous time-distance curve. The migration velocity for the linear part of the curve is about 400 km/hour, but it decreases gradually before the termination of migration. After the interval of eight hours following the main shock, aftershocks occurred randomly around the above-mentioned migration path and thereafter the

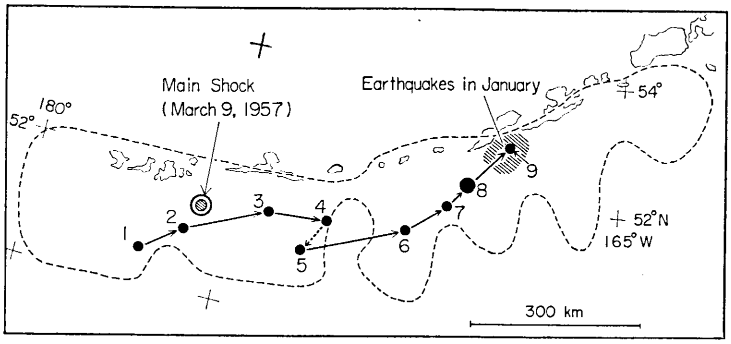

Fig. 21a. Geographical distribution of aftershock epicenters in the interval of nine hours following the Aleutian Earthquake of 1957. Aftershocks are numbered in order of time. A shaded area shows the epicentral region of the earthquake swarm preceding the main shock.

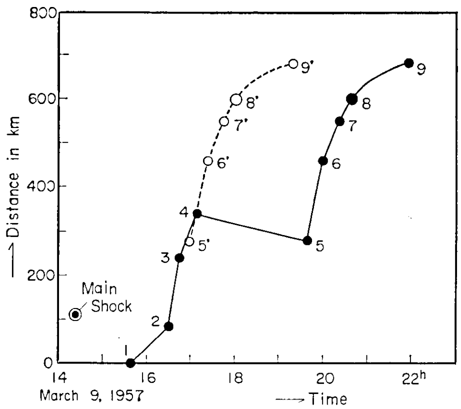

Fig. 21b. Distance from the epicenter of the No. 1 aftershock to each aftershock as a function of time (solid curve). Broken curve: parallel to the solid curve from No. 5 to No. 9.

active area further extended in both directions along the Aleutian Arc.

This noticeable phenomenon may be interpreted from the standpoint of the fracture theory of earthquakes, that earthquakes occur by brittle fracture of the earth's crust or the upper mantle, as follows. Since the focal region of the earthquake swarms directly preceding the great earthquake was in a fractured state at the time of the great earthquake, the rupture following the main shock developed from the epicentral region of the main shock toward the pre-existing weak region, namely the epicentral region of earthquake swarm. The time-distance curve in Fig. 21b suggests the gradual progress of the rupture. The discontinuity in progress of rupture after the No. 4 aftershock suggests the existence of a structural discontinuity which prevented the development of rupture. The abnormal lack of aftershock activity in the considered region suggests this discontinuous structure.

(2) *The Alaska Earthquake of March 27, 1964*

The USCGS located the epicenter of the main shock at 61.0°N,

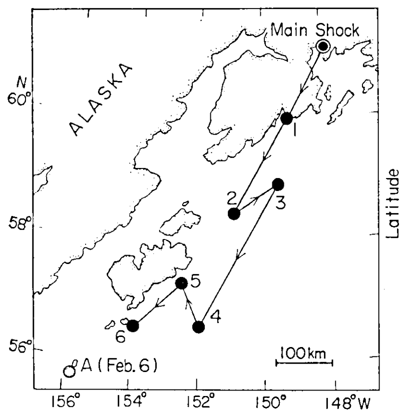

Fig. 22a. Geographical distribution of epicenters of aftershocks with magnitude 6 and larger, following the Alaska Earthquake of 1964.

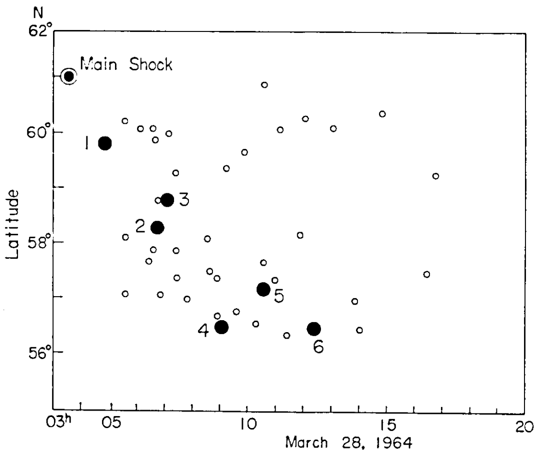

Fig. 22b. Latitude of aftershock epicenters as functions of time. Large solid circle: $M \geq 6$; small open circle: $M < 6$.

147.8° W. Recently, Wyss and Brune (1967) proposed the multiple sources which moved southward from the initial source with a rupture velocity (3.5 km/sec).

According to *the Seismological Bulletin of USCGS*, this earthquake was followed by many small aftershocks, but only six aftershocks of magnitude 6 and larger. All these large aftershocks occurred in the interval of 10 hours following the main shock. Figs. 22a and b show the geographical distribution of the epicenters of these aftershocks and the relation between the latitude of the epicenter of each aftershock and its origin time. The six large aftershocks are numbered in order of time. This result suggests the south-westward migration of aftershock activity from the epicentral region of the main shock to the southwest end of the aftershock zone during the 10 hours just after the main shock. The velocity of migration was about 60 km/hour. In this case, it is also noted that the largest earthquake which occurred in this area during one year before the Alaska Earthquake occurred on February 6, 1964 at the *A* station in Fig. 22a, which is located near the southwest end of the above-mentioned migration pattern.

As mentioned above, Wyss and Brune (1967) suggested the propagation of rupture, from the progress of the multiple sources at the time of the main shock. According to their result, the rupture propagated from the epicenter of the main shock to a region near the epicenter of the No. 1 aftershock, but the further propagation path has not been established. The relation between the gradual migration of the aftershock activity and the rapid propagation of rupture at the time of the main shock, estimated from the seismic body and surface waves, is a very interesting problem for the future.

5. Discussion and conclusion

(1) *Development of the aftershock area*

In the above-mentioned discussion, it has been shown that the aftershock activity of great shallow earthquakes displaced or dispersed rapidly or gradully after the main shock. These patterns of the developments of the active region are very similar to that of the fracture in brittle materials, as pointed out in the preceding section. In the previous paper (Mogi, 1967), the present writer said that various features of the aftershock phenomenon may be attributed to the general nature of a local fracture of the earth's surface layer. The above-mentioned similarity also seems to support this fracture theory of aftershocks.

(2) *Comparison of aftershock sequences between Japan and Aleutian-Alaska*

As mentioned above, some features of aftershock sequences are different for different seismic regions. In particular, the aftershock sequences in and near Japan show a sharp contrast to those in the Aleutian-Alaska region. Their comparison is summarized as follows:

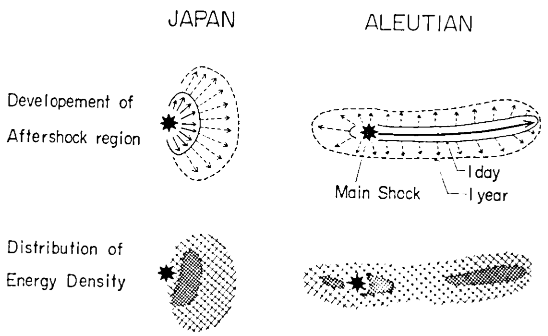

Fig. 23. Typical patterns of development of aftershock area and of spatial distribution of aftershock energy in great shallow earthquakes which occurred in two different areas, Japan and Aleutian-Alaska.

(i) The aftershock area is considerably larger in Aleutian-Alasuka than in Japan.

(ii) The shape of the aftershock region is nearly circular in Japan, but extremely longer in one direction in Aleutian-Alaska.

(iii) In Japan, the aftershock area is relatively small in the period A and markedly increased during the following periods. The development of the area

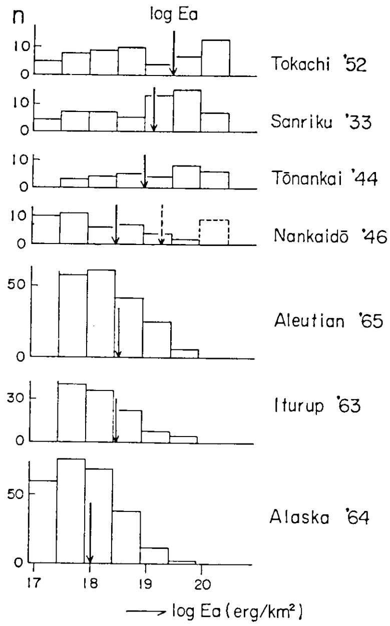

Fig. 24. Histograms of areal density of aftershock energy.

occurs in radial directions from the epicenter of the main shock. On the other hand, the aftershock area in the Aleutian-Alaska region is already very long in the period A and the width of the area increases during the following periods. The modes of development of the aftershock region are schematically shown in Fig. 23.

(iv) There is a high concentration of aftershock energy near the epicenter of the main shock in Japan, but rather at a region distant from the epicenter of the main shock in Aleutian-Alaska (Fig. 23).

(v) The areal density of the aftershock energy is considerably higher in Japan than in Aleutian-Alaska. The histograms of the energy density in a unit area are shown in Fig. 24.

These differences suggest the following difference in the generation mechanism of aftershocks between both areas. In Japan, at the time of the main shock, the fracture occurs at a limited region around the epicenter of the main shock and this fracture pattern develops gradually in radial directions. On the other hand, in the Aleutian-Alaska region, the fracture develops along a long axis of the aftershock zone at the time of the main shock or just after the main shock. Such large and rapid developments of rupture may be due to the pre-existence of a weak large linear structure or a large fault, as in the California Earthquake of 1906 (Benioff, 1962).

(3) *Relation between the main shock and the aftershock area*

According to Tsuboi's hypothesis (1956), the aftershock region is the projection of the earthquake volume, where the energy of the main shock was stored as a strain energy before the earthquake, on the earth's surface. The hypothesis assumed that the mean energy density in the earthquake volume is nearly equal in various cases. However, the above-mentioned regional variation in the size of the aftershock area for earthquakes of the same magnitude suggests that the energy density

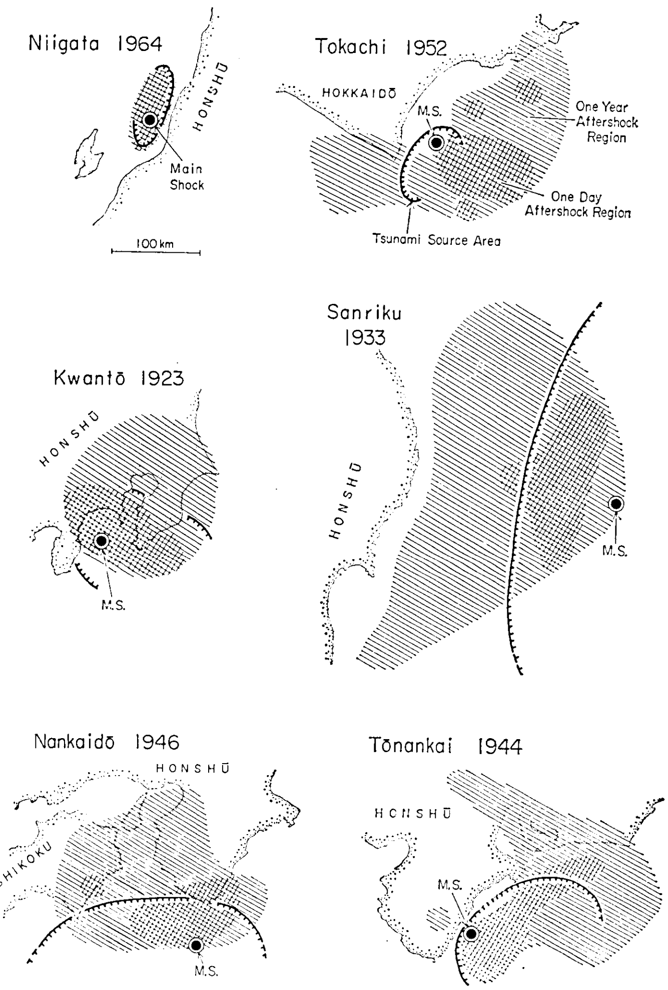

Fig. 25. Localities of the aftershock areas in the intervals of one day and one year following the main shock and the source area of tsunami, in large shallow earthquakes in and near Japan.

is different in different regions.

It has been believed by many investigators that the large part of the strain energy stored in the *aftershock region* was released simultaneously as seismic energy at the time of the main shock. However, some modifications of this hypothesis will have to be made, for the reasons given below.

(i) Some aftershock regions just after the main shock (for example, aftershock regions in the period A in earthquakes in and near Japan) are limited to a small area near the main shock, very different from the total aftershock area in a longer time interval, and thereafter the area gradually increases with time.

(ii) The source area of the tsunami (Hatori, 1965, 1966, 1967), which may correspond to the area strained markedly at the time of the main shock, in and near Japan, more nearly agrees with the aftershock area in the period A than the total aftershock area, as seen in Fig. 25.

From these results, it is deduced that the large part of the energy of the main shock was not always released from the total aftershock region, but from a smaller area which corresponds to the aftershock area just after the main shock or the source area of the tsunami.

In the Niigata Earthquake of June 16, 1964 ($M_0=7.5$), however, the aftershock area in a long time interval agrees with the aftershock area just after the main shock and the tsunami source area (see Fig. 25). In such a case, the aftershock region may correspond to the region where the seismic energy of the main shock was stored before the earthquake.

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10. 大地震の余震域の拡大

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大地震の発生機構を研究する一つの方法として，その余震の発生特性を研究することが考えられる．個々の大地震については，かなり詳しい研究が行なわれてきたのに対して，これらの大地震に共通な特性の系統的な研究は必ずしも十分ではない．本論文では，浅発性の大地震の余震活動の空間的な分布，とくにその時間的な変化を出来るだけ多くの例についてしらべ，大地震の余震の起こり方を明らかにすることを試みた．次にその結果を要約する．

(1) 主に中規模の地震について求められた宇津・関の余震面積と本震のマグニチュードとの関係式は，色々の地域の大地震には必ずしも適合しない．日本地域の地震の余震域のひろがりは，アラスカやアリューシャンなどの他の地域のものに較べて著しく小さく，明瞭な地域性を示す．

(2) 余震域の形にも地域的な特徴がある．日本地域では大体円形に近いが，アラスカ，アリュー

シャンでは非常に細長い.

(3) 余震エネルギーは，しばしばある部分に集中的に分布する．日本地域では，本震の一方の側に，これに近接して集中する場合が多く，アラスカ・アリューシャン地域では，むしろ本震から離れた所に，余震域の軸に沿つて集中する.

(4) 余震域は本震後次第に拡大する傾向があり，余震エネルギーは外方に拡散する傾向を示す．しかし，その様式は，日本地域では，本震を中心として外側に拡大するが，アラスカ・アリューシャン地域では，本震直後すでに非常に長大で，以後次第に幅の方向に拡大する.

(5) 1957 年のアリューシャン地震と 1964 年のアラスカ地震の際に，本震後の数時間内に大きい余震の震源域が本震近傍から余震域の一方の端に向つて系統的に移動する現象が見られた.

(6) 本震のエネルギーは余震域全体に歪エネルギーとして蓄えられていたものであるという考えがあるが，本震のエネルギーは，むしろ本震直後の余震域(時として余震域全体よりも著しく小さい) に蓄えられていたと考えなければならない．このことは，津波の浪源域が余震域全体よりは，本震直後の余震域に符合することからも支持される.

以上の余震の諸特徴を地震の破壊説の立場から考察した.