BULLETIN OF THE EARTHQUAKE
RESEARCH INSTITUTE
Vol. 45 (1967), pp. 711-726

37. *Regional Variation of Aftershock Activity.*

By Kiyoo MOGI,

Earthquake Research Institute.

(Read June 22, 1965; April 25, 1967.—Received June 30, 1967.)

Abstract

As a continuation of a previous investigation, great regional variations of aftershock activity in and near Japan are presented by using the difference of magnitudes between the main shock and the largest aftershock as a measure of activity. Even within the outer seismic zone which is one of the most active areas in the circum-Pacific belt, the aftershock activity varies with marked contrast. The rate of decay of aftershock activity and the activity of earthquake swarms are also different in different tectonic regions. The fracture hypothesis of earthquakes suggests that these regionalities in occurrence of aftershocks and earthquake swarms reflect mechanical conditions of the earth's crust. From this standpoint, the mechanical structures of the earth's crust in this area are again discussed based on these new data.

Introduction

Aftershock studies provide fundamental information on the mechanism of earthquake generation. From this point of view, a number of papers have been devoted to the problem. In particular, some important statistical relations[1][2] have been established. However, most researchers have not considered regional variations in aftershock occurrence. In a previous paper[3], the present author systematically discussed the geographical variation of aftershock activity in and near Japan, by using the percentage of earthquakes followed by aftershocks to whole earthquakes in each region as a measure of aftershock activity, with those of earthquake swarms and foreshocks. According to the result, the aftershock activity is greatly different for different regions. If the regional variation is ignored, statistical relations on aftershock phenomena

1) F. ŌMORI, *Rep. Imp. Earthq. Invest. Comm.*, **2** (1894), 103-139.
2) T. UTSU, *Geophys. Mag.*, **30** (1961), 521-605.
3) K. MOGI, *Bull. Earthq. Res. Inst.*, **41** (1963), 615-658.

are often meaningless. The previous study[4] also suggested that statistical parameters in aftershock occurrence have a close relation with physical conditions of the area and their geographical distributions can provide information that is important to deduce the structure of the earth's crust. Accordingly, extensive studies on regional variations in the occurrence of aftershocks and also earthquake swarms are very important.

The previous study gave a reliable result for land area. For sea area where the most active seismic zone is situated, since the result was accompanied by some uncertainty principally due to observational errors, a detailed variation has not been ascertained.

The purpose of the present study is to confirm the previous result on the regional variation of the aftershock activity and the activity of swarm type, and to obtain a more detailed feature on sea area. In this paper, the aftershock activity has been measured by the difference of magnitudes between the main shock and the largest aftershock, which correlates with the ratio of the energy of the main shock to the total energy of aftershocks. Since the aftershock activity in each region can be estimated from a little data by present method, the regional distribution can be obtained from accurate data on large earthquakes only. Furthermore, the rate of decay of aftershock frequency, and the seismic activity in swarm type are discussed based on recent data.

Chapter I. Aftershock activity

1. *Procedure of investigation*

The aftershock activity of an earthquake can be indicated by the ratio of the total energy of aftershocks (E_a) to the energy of the main shock (E_0). Utsu[5] suggested the use of the difference in magnitude between the main shock and the largest aftershock (M_0-M_1), where M_0 and M_1 are the magnitudes of the main shock and the largest aftershock, respectively, as a measure of the aftershock activity. In fact, the M_1 value is nearly proportional to the logarithm of the total aftershocks energy (E_a) (Fig. 1), so that the (M_0-M_1) value can be used instead of the logarithm of the ratio of E_0 to E_a. In this paper, the (M_0-M_1) value is used as a measure of aftershock activity of each earthquake. For all main shocks of magnitude 6 and over of which

4) K. MOGI, *loc. cit.*, 3).
5) T. UTSU, *loc. cit.*, 2).

focal depths do not exceed 60 km, the (M_0-M_1) value has been obtained from the following sources: *Catalogue of the Major earthquakes which occurred in and near Japan (1926–1956)* by Japan Meteorological Agency or JMA and the *Seismological Bulletin of JMA* for the period (1957–1965). These tables list completely all shallow main shocks of magnitude 6 and over that occurred in and near Japan together with most aftershocks of magnitude 4.5 and over. If a major earthquake is not followed by any aftershocks listed in these tables, the magnitude of the largest aftershock of the major earthquake is assumed to be less than 4.5. Some earthquakes of smaller magnitude $(M<6)$ with known M_1 values are also used in the present discussion, because the number of large earthquakes $(M\geq 6)$ are limited, particularly in land area.

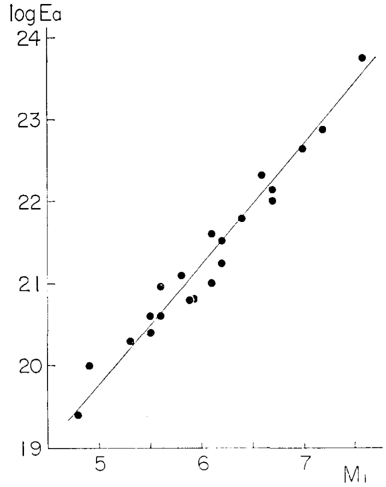

Fig. 1. Relationship between the logarithm of the total energy of aftershocks (E_a) and the magnitude of the largest aftershock (M_1).

This procedure has also been applied to earthquake sequences of the *foreshocks—main shock—aftershocks type* and the *swarm type*, these also forming only a small part of whole earthquakes. In these cases, M_0 and M_1 are the magnitudes of the largest earthquake in each sequence and the largest one among subsequent earthquakes, respectively. In general, the (M_0-M_1) value in earthquake swarms was considerably smaller as compared with that in the *main shock—aftershocks type*. The systematic difference of (M_0-M_1) in sequences of different types will be discussed in Chapter III.

There is some uncertainty in the identification of the largest aftershock in the earthquake lists by JMA. To test this uncertainty the M_1 values determined in the present study have been compared with those given by Utsu[6]. The close agreement between them suggests that uncertainty in determination of the M_1 value based on the same sources is not appreciable and does not cause any serious error in the following discussion.

6) T. UTSU, *loc. cit.*, 2).

2. *Space distribution of* (M_0-M_1)

The (M_0-M_1) values for shallow main shocks are plotted at their epicenters in Fig. 2. Closed, semi-closed, and open circles indicate low,

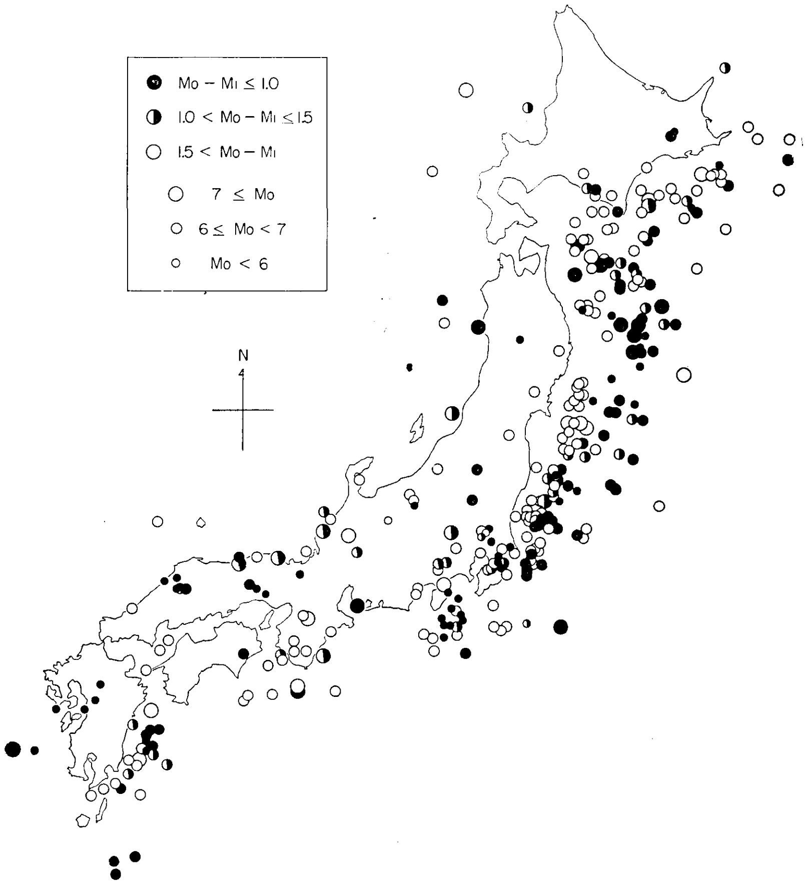

Fig. 2. The (M_0-M_1) values in and near Japan are shown at epicenters of main shocks. M_0: magnitude of a main shock; M_1: magnitude of the largest aftershock.

intermediate and high values of (M_0-M_1), respectively. From this figure, it can be remarked that the (M_0-M_1) value does not distribute at random, but with marked regionality. The systematic variation is most remarkable in the outer seismic zone in Japan, particularly east off northern Japan. Figure 3 shows the frequency distributions of (M_0-M_1) in the two different Regions **A** and **B**. The low values in **A** Region make a marked contrast with the very high values in **B** Region.

Since the (M_0-M_1) value significantly varies in space without large fluctuation, the spatial distribution of (M_0-M_1) can be indicated by contour lines as shown in Fig. 4. According to this result, the aftershock activity is highest in the above-mentioned **A** Region which corresponds to the zone under the steep western slope of the Japan trench, and lowest in **B** Region. Other sea areas where the aftershock activity is appreciably high are situated south off the Izu peninsula along the Fuji volcanic belt and east off southern Kyūshū along the Okinotorishima oceanic ridge (Fig. 5). These results are essentially in agreement with those suggested in the previous study[7].

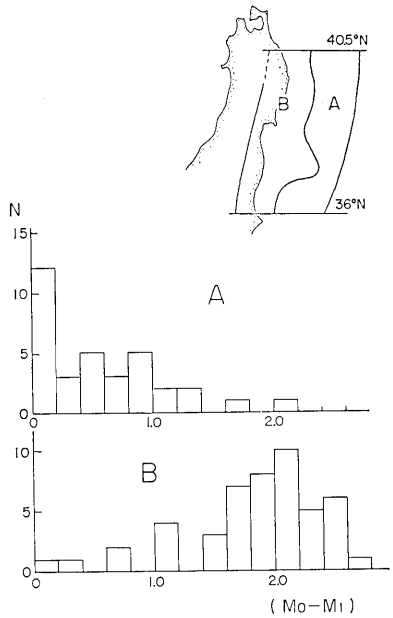

Fig. 3. Frequency distributions of (M_0-M_1) in Regions **A** and **B**.

In land area, the distribution of (M_0-M_1) cannot be determined because data of (M_0-M_1) are insufficient for this purpose, but the previous results obtained by the other method are sufficiently reliable, as mentioned before. Both results of sea area by the present method and of land area by the previous one will be summarized in Chapter III. It is very interesting to discover regionality of aftershock activity in other districts. In Fig. 6, (M_0-M_1) values of large earthquakes in the world are plotted at their epicenters. Although data are clearly insufficient to examine this problem adequately, this preliminary study suggests the fact that the aftershock activity in China and Alaska is systematically lower than that in other regions, as pointed out by Utsu[8].

3. *Relation between aftershock area and aftershock activity*

A close relation between the size of the area in which aftershocks occur and the magnitude of the main shock was found by Homma and Seki[9] and Utsu and Seki[10]. Recently, Utsu[11] obtained the following

7) K. Mogi, *loc. cit.*, 3).
8) T. Utsu, *Kenshin-jiho*, **28** (1964), 129-136.
9) S. Homma, and A. Seki, *Zisin* (*Journ. Seis. Soc. Japan*), [ii], **3** (1951), 44-48.
10) T. Utsu, and A. Seki, *Zisin* (*Journ. Seis. Soc. Japan*), [ii], **7** (1955), 233-240.
11) T. Utsu, *loc. cit.*, 2).

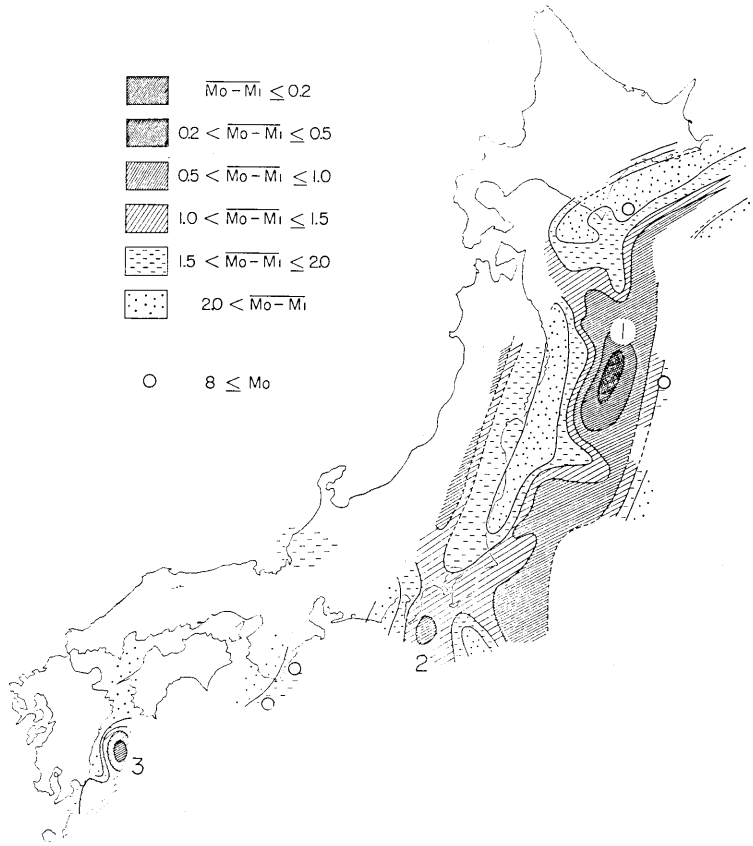

Fig. 4. Spatial distribution of (M_0-M_1) in and near Japan. Epicenters of the largest earthquakes $(M_0 \geq 8)$ in recent years are indicated by open circles. 1: east off Sanriku; 2: south off Izu peninsula; 3: east off southern Kyūshū.

relation between the linear dimension (D in kilometer) of the aftershock area and the magnitude (M_0) of the main shock:

$$\log D = 0.5M_0 - 1.8 \,, \tag{1}$$

for the range of M_0 from $5\frac{1}{2}$ to $8\frac{1}{2}$. However, it may be supposed that the size of the aftershock area depends on the aftershock activity. For example, a considerable number of major earthquakes $(M \geq 6)$ were not followed by any aftershocks observed by the JMA network. The above-mentioned D value for such earthquakes is extremely small or zero. To examine this problem, the logarithm of the ratio of the observed linear dimension (D) of the aftershock area to the one (D_c) calculated from the above-mentioned formula is plotted against $(M_0 - M_1)$ in Fig. 7. This figure indicates a fact that the linear dimension (D) of aftershock area is larger for earthquakes with higher aftershock activity. Although the spread of points is large, their relation is roughly expressed by the following equation:

$$\log \frac{D}{D_c} = 0.42 - 0.36(M_0 - M_1) . \qquad (2)$$

As mentioned before, the aftershock activity shows a

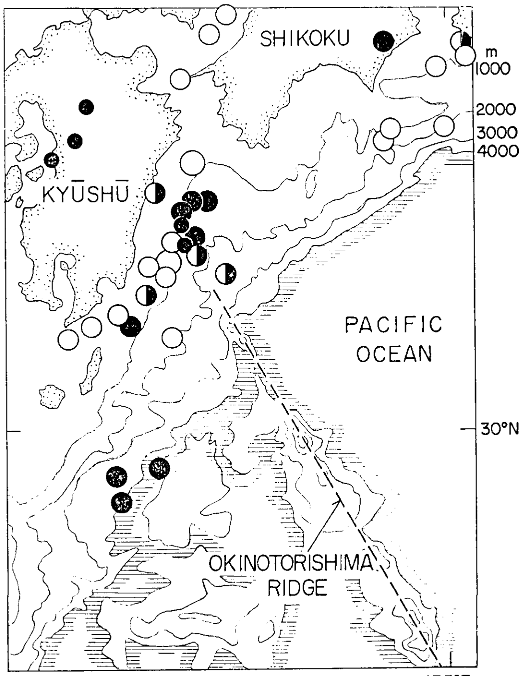

Fig. 5. Submarine topography off the Pacific coast of Kyūshū and Shikoku and the aftershock activity in this area. Closed circle: $(M_0 - M_1) \leq 1.0$; semi-closed circle: $1.0 < (M_0 - M_1) \leq 1.5$; open circle: $(M_0 - M_1) > 1.5$.

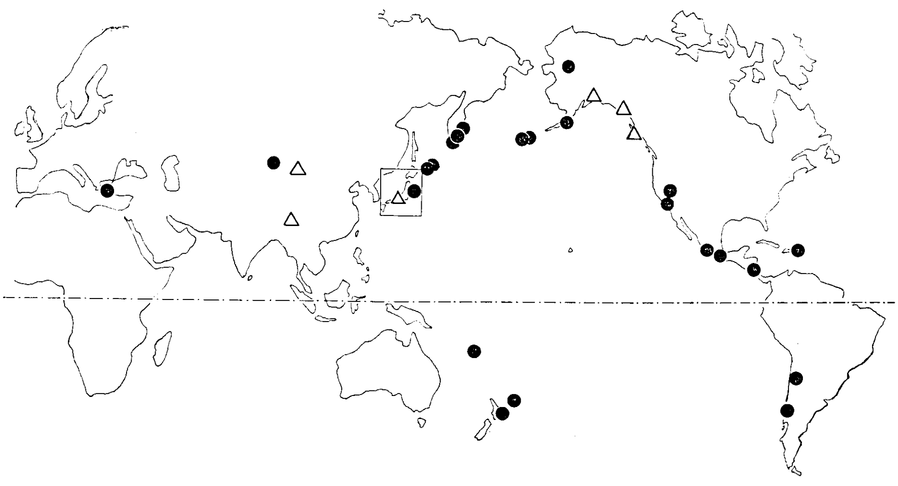

Fig. 6. Aftershock activity of large earthquakes in the world. Closed circle: $(M_0 - M_1) \leq 1.6$; open triangle: $(M_0 - M_1) > 1.6$.

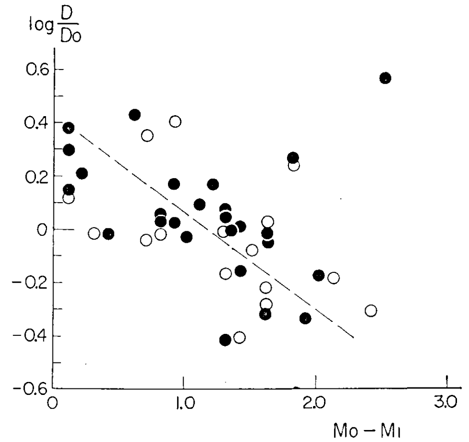

Fig. 7. Relationship between log D/D_0 and $(M_0 - M_1)$. D: observed linear dimension of the aftershock area; D_0: calculated one from Eq. 1. Closed circle: earthquakes occurring in sea area; open circle: those occurring in land area.

systematic geographical distribution, so that, it is deduced that the size of the aftershock area also shows a similar regionality. However, data are inadequate to examine this systematic regionality. The appreciable difference of the aftershock area between the land and the sea areas in and near Japan, pointed out by Utsu[12], seems to be also attributed to the difference in their aftershock activity (see Fig. 7). The larger aftershock area in more seismically active regions, noted by Yamakawa[13], is nearly consistent with the present result.

4. *Rate of frequency decrease in aftershocks*

The frequency of aftershocks decays uniformly in time after the main shock. As is well known, the frequency decay curve of aftershocks can be expressed by the following inverse power formula[14)15)]:

$$n(t) = ct^{-h} , \qquad (3)$$

where $n(t)$ is the frequency of aftershocks per unit of time and t is the elapsed time after a main shock. The h value in this formula indicates the rate of decay of aftershock frequency. Figure 8 indicates the geographic distribution of the

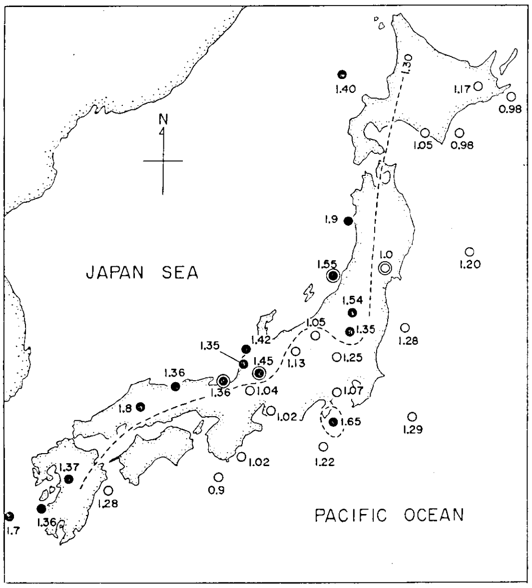

Fig. 8. Space distribution of the h value which indicates the rate of decay of aftershock frequency.

12) T. UTSU, *Zisin* (*Journ. Seis. Soc. Japan*), [ii], **10** (1957), 35–45.
13) N. YAMAKAWA, *Pap. Met. Geophys.*, **18** (1967), 15–26.
14) T. UTSU, *loc. cit.*, 12).
15) K. MOGI, *Bull. Earthq. Res. Inst.*, **40** (1962), 107–124.

h values of large earthquakes. A similar result has already been reported in a previous paper[16], but data of four recent large earthquakes which occurred after the publication of the previous paper, shown by

Table 1.

Date (J.S.T.)	Location	Epicenter		Magnitude	Rate of Frequency Decay- h
		Longitude (E)	Latitude (N)		
August 19, 1961	Northern part of Mino (Gifu Pref.)	136°46′	36°01′	7.0	1.45
April 30, 1962	Northern part of Miyagi Pref.	141°08′	38°44′	6.5	1.0
March 27, 1963	Off Echizen-misaki	135°46′	35°47′	6.9	1.42
June 16, 1964	Near Niigata	139°11′	38°21′	7.5	1.55

double circles, are added in this figure (Table 1). These new data are well consistent with the systematic space distribution of h in the previous data. Some examples of the frequency curve of aftershocks in the Japan Sea and the Pacific Ocean sides are represented in Fig. 9. This figure also clearly confirms the fact that the aftershock frequency decreases

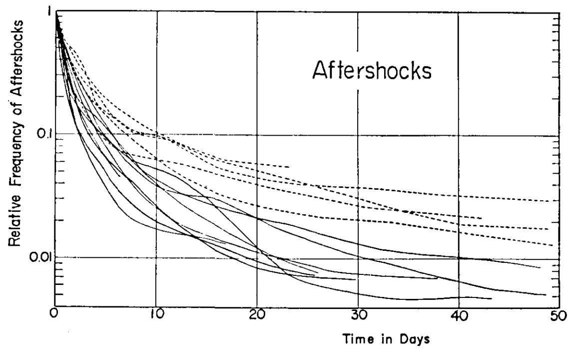

Fig. 9. Relative frequency curves of aftershocks. The solid and the dotted curves indicate curves of earthquakes occurring in the Japan Sea side and in the Pacific Ocean side, respectively.

in time more rapidly in the Japan Sea side than in the Pacific Ocean side. Now, it can be safely concluded that the rate of decay of aftershock activity is significantly different between both regions.

Thus, the degree of the aftershock activity, the rate of decrease of aftershock activity and probably the size of aftershock area, show

16) K. MOGI, *loc. cit.*, 15).

systematic geographical distributions with some relation to tectonic structures in this area.

Chapter II. Earthquake swarms

1. *Space distribution of earthquake swarms*

In the previous paper[17], the patterns of earthquake sequences were classified into the three types. The third type among them is the earthquake swarm where the number and magnitude of earthquakes increase gradually with time and decrease after some duration. In this type, there is no single predominant principal earthquake. The previous study showed that earthquake swarms do not occur accidentally, but

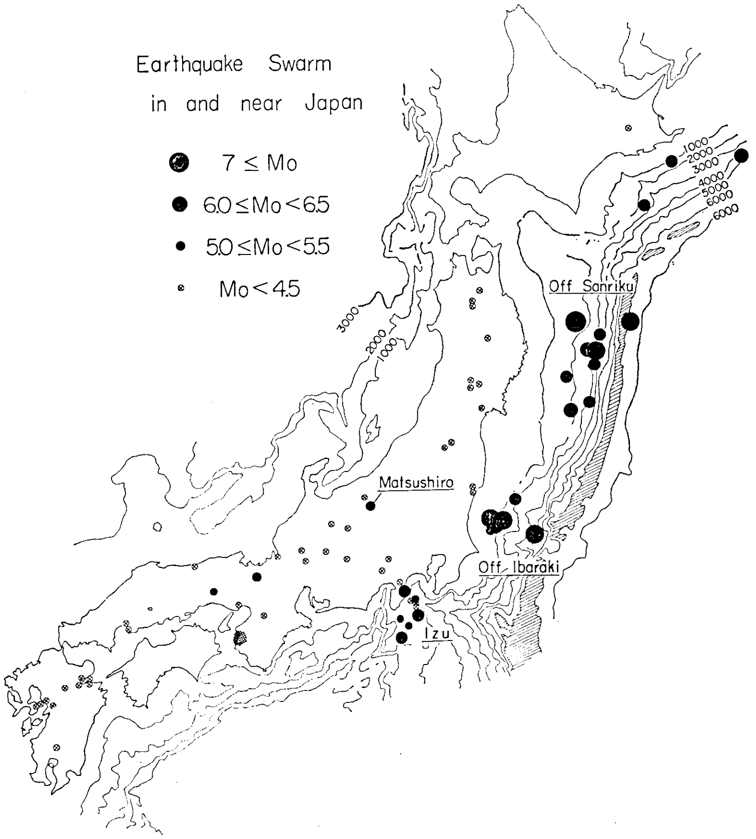

Fig. 10. Earthquake swarms are plotted at epicenters of the largest earthquake in each sequence. The radius of circles shows the magnitude of the largest earthquake.

17) K. Mogi, *loc. cit.*, 3).

occur in groups at certain places. However, the previous procedure of investigation is based on the frequency curve of small earthquakes, so that the method was not applicable to the sea area because of large observational errors. In this paper, earthquake sequences of swarm type have been determined from the frequency distribution of larger earthquakes which are well registered by the JMA network. In Fig. 10, earthquake swarms are plotted at epicenters of the largest earthquake in each sequence. The radius of circles shows the magnitude of the largest earthquake in each sequence, which is a rough measure of the total energy of the earthquake swarm. The crossed circles show epicentral regions of earthquake swarms with small magnitude.

According to this result, earthquake swarms occur also at certain limited regions. Seismic activity in the swarm type is highest east off Sanriku (north-eastern Honshū) and east off Ibaraki (Kwantō), and also high south off the Izu peninsula. These regions coincide well with some of the most active regions of aftershocks. It is noticeable that earthquake swarms in land area, which occurred mainly in volcanic zones, are of smaller magnitudes as compared with those in sea area where the largest magnitude sometimes exceeds 7.

2. *Frequency distribution*

Frequency curves of earthquake swarms are very complex, different in different cases. Examples of frequency curves are shown in Fig. 11. In this figure, the fact can be pointed out that the number of earth-

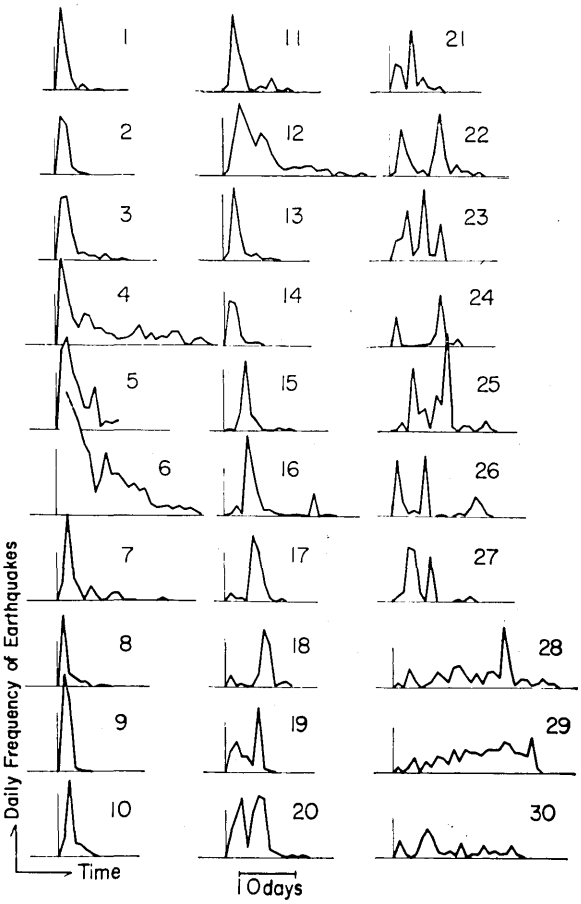

Fig. 11. Daily frequency curves of earthquake swarms.

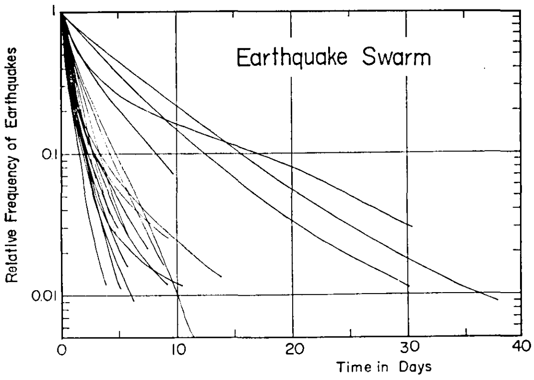

Fig. 12. Frequency decay curves in earthquake swarms.

quakes often decreases with some regularity after a large peak in frequency curve. These frequency curves are shown in semi-logarithmic scale in Fig. 12. They are nearly straight and clearly different from those of aftershocks shown in Fig. 9. The difference of curve shape between earthquake swarms and aftershocks suggests the difference of stress states between these sequences[18].

Chapter III. Structural states of the earth's crust

1. *Relation between the patterns of earthquake sequences and the structural states of the earth's crust*

As mentioned above, the patterns of earthquake sequences can be classified into the three types[19], which are schematically shown in Fig. 13. The model experiments based on fracture hypothesis of earthquakes suggest that the type changes systematically with the degree of fracturing from Type (1) to Type (3). The (M_0-M_1) value is large in Type (1) and small in Type (3) and probably intermediate in Type (2). Therefore, the (M_0-M_1) value may decrease with the degree of fracturing of the medium. Based on this hypothesis, the structural states of the earth's crust in and near Japan are discussed from the above-mentioned results on aftershocks and earthquake swarms.

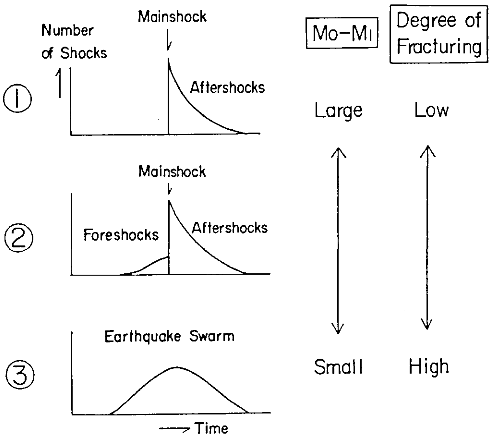

Fig. 13. Three types of earthquake sequences and their relation to the (M_0-M_1) value and the structural state of the earth's crust.

18) K. MOGI, *Bull. Earthq. Res. Inst.*, **40** (1962), 125-173.
19) K. MOGI, *loc. cit.*, 3).

2. *Seismic active zone off the Pacific coast of northern Japan*

The region off the Pacific coast of northern Japan is one of the most active ones in the circum-Pacific seismic belt, and its tectonic feature is of typical island arcs. The seismic activity in this area is shown by the areal density of shallow earthquakes with magnitude 6 and over in Fig. 14. The activity in this seismic zone is not uniform, but concentrates in a narrow zone. The boundary of the fractured region where (M_0-M_1) is smaller than 1.5 is also drawn in this figure. It is very interesting that the seismic active regions do not completely coincide with the fractured regions. The aftershock activity in two vertical sections perpendicular to the Japan trench is shown in Fig. 15. Closed, semi-closed and open circles indicate the degree of aftershock activity of large earthquakes, as in Fig. 2. Small open circles and crosses in the figure indicate foci of deeper earthquakes of unknown magnitudes and aftershocks of magnitude 6 and over at shallower depths. The hypocentral distributions in these sections are similar to those in other regions in island arcs. The zone of deeper earthquakes continues to the deep earthquake zone under the Japan Sea. However, marked variations of aftershock activity in these sections suggest that structural states similarly vary in this section. In the **A-B** section, the two active zones are situated separately at the fractured and the unfractured regions. In the **C-D** section, the boundary of both regions is seismically most active. Figure 16 shows schematically the structural state and the seismic activity in these sections. The shaded area corresponds to the fractured region and open circles indicate earthquake foci. From this seismic feature, the region may be divided into the

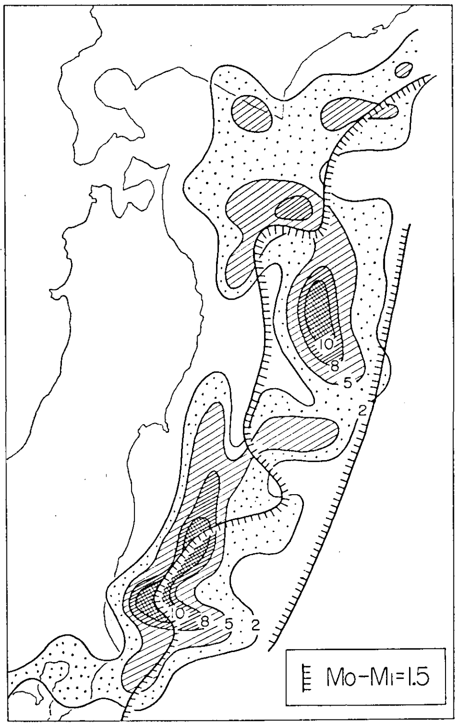

Fig. 14. Spatial distributions of the seismic activity and the aftershock activity. Contour lines indicate the areal density of earthquake epicenters ($M \geq 6$).

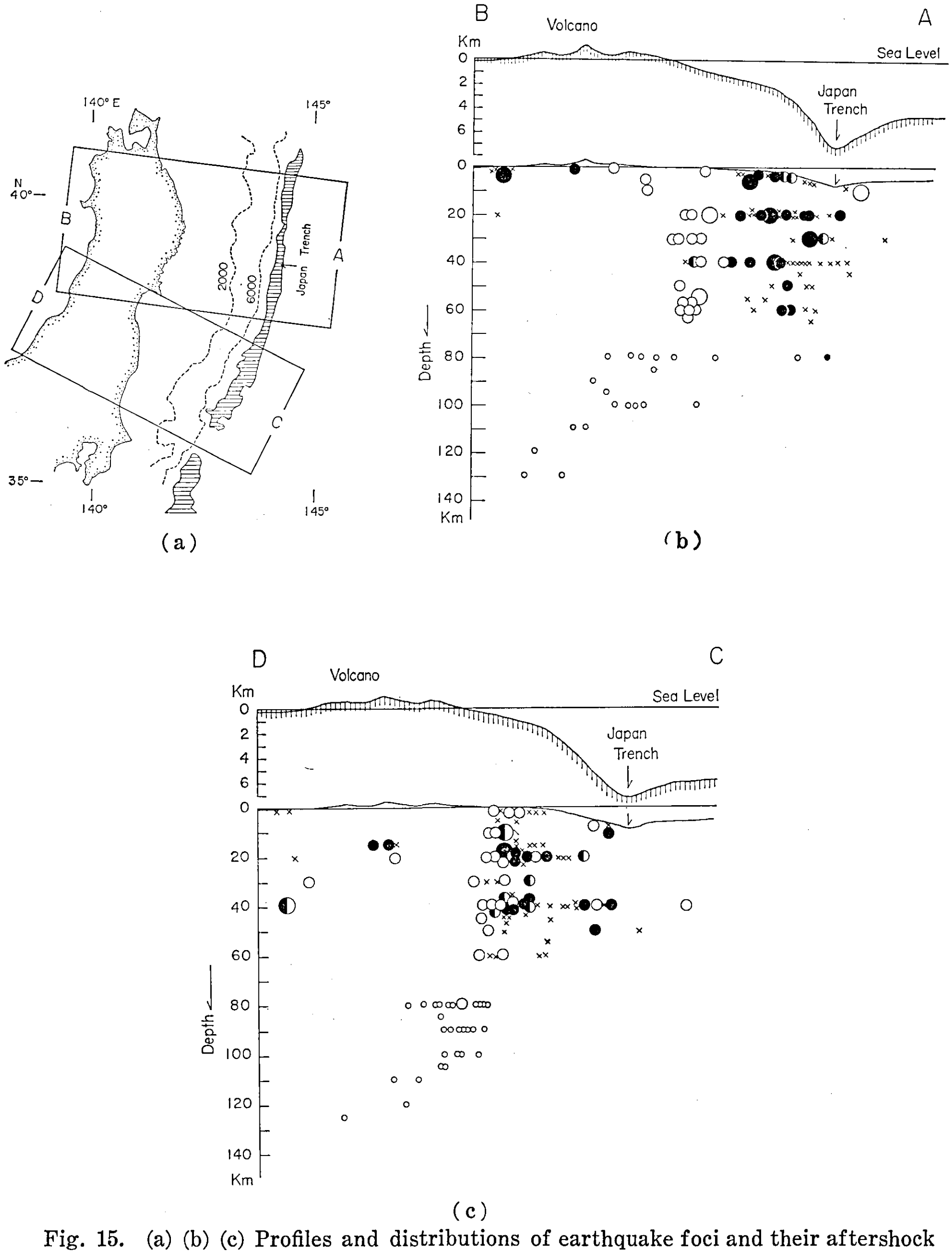

Fig. 15. (a) (b) (c) Profiles and distributions of earthquake foci and their aftershock activity in the vertical sections AB and CD, across the Japan trench. Closed, semi-closed and open larger circles indicate the following range of (M_0-M_1): $(M_0-M_1)\leq 1.0$, $1.0<(M_0-M_1)\leq 1.5$, $(M_0-M_1)>1.5$. Cross: aftershocks; small open circle: deeper earthquakes with unknown magnitude.

following different zones parallel to the Japan trench (Fig. 16):

Region (1): seismically active and highly fractured.

Region (2): seismically active, but not fractured.

Region (3): moderately active and appreciably fractured. This shallow zone is situated under volcanic regions.

Region (4): no earthquakes occur in this region, which is probably in an unfractured state.

Region (5): seismically inactive and homogeneous in structure.

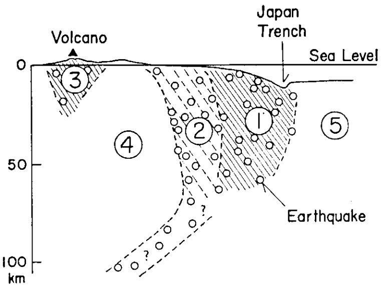

Fig. 16. Schematic diagram showing the seismic activity and the structural state in the vertical section across the Japan trench. Shaded areas represent fractured zones.

Thus, a large number of earthquakes occur in *Region* (1) with a fractured structure and also in *Region* (2) which is not in a highly fractured state, but major earthquakes scarcely occur in *Region* (4) adjacent to *Region* (2). The boundary between *Regions* (2) and (4) is strikingly clear. These results suggest that the fracturing in *Region* (2) is now proceeding, but does not occur in *Region* (4) yet, and that the boundary may correspond to the front of the fracture pattern progressing from east to west.

3. *Mechanical structure of the earth's crust in and near Japan*

In the previous paper[20], the structural state of the earth's crust in and near Japan was deduced from the occurrences of various types of earthquake sequences based on the above-mentioned hypothesis. The mechanical structure revised by the present data, principally on sea area, is shown in Fig. 17. From this result, the following conclusions are made:

(1) The highly fractured zone situated along the Japan trench coincides with the zone under the steep western slope of the trench. This is consistent with other evidences from topographical study and seismic prospecting[21].

(2) Other fractured regions in sea area are situated south off the Izu peninsula and east off southern Kyūshū. These two regions correspond to the places where the Izu-Mariana and the Okinotorishima

20) K. Mogi, *loc. cit.*, 3).

21) W. J. Ludwig et al, *Journ. Geophys. Res.*, **71** (1966), 2121-2137.

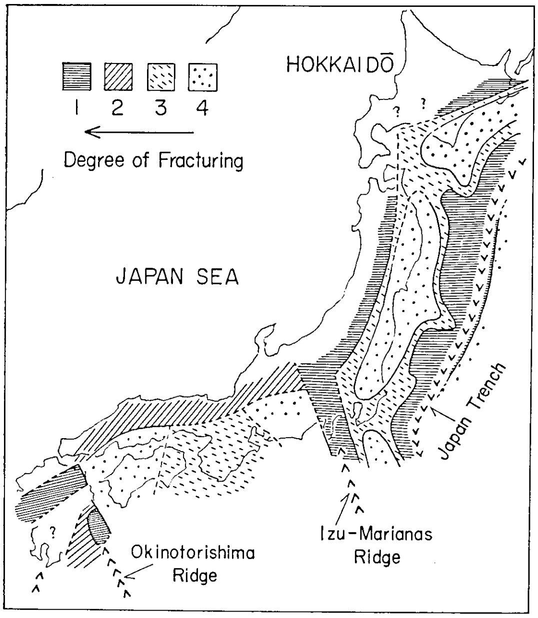

Fig. 17. Mechanical structure of the earth's crust in and near Japan, deduced from the occurrence of aftershocks, foreshocks and earthquake swarms. Shaded areas correspond to highly fractured regions.

oceanic ridges meet to the outer seismic zone in Japan, respectively (see Fig. 5).

(3) An unfractured zone distributes in parallel with the above-mentioned highly fractured zone along the Japan trench, but this zone is discontinuous south off Hokkaidō and east off Kwantō, corresponding to intersecting regions of the island arcs.

(4) Volcanic regions in land area are also in fractured states, as pointed out in the previous paper.

The present mechanical structure of Japanese island is very consistent with tectonic structures deduced independently from geological and geophysical data[22].

---

37. 余震活動の地域性

地震研究所 茂 木 清 夫

さきに，日本付近の余震活動に著しい地域的差異があること，その地理的分布が地殻の構造状態を反映するものであることを論じた．その時は，余震活動度をあらわす尺度として，ある地域に起こる地震 ($M>4\sim4.5$) のうち，余震を伴つた地震のパーセンテージを用いた．この方法は陸地に起こる地震については十分正確な値を与えるが，小さい地震の観測精度の低い海洋地域についてはある程度の誤差を伴う．しかしながら，東北日本外側地震帯をはじめ，日本付近の主な活動地域は海洋地域にある．本論文では，特に海洋地域の余震活動あるいは群発地震活動の詳細を明らかにするために，観測精度の十分高い比較的大きい地震（主として $M\geq6$）に着目し，本震と最大余震のマグニチュードの差 (M_0-M_1) を余震活動度の尺度に用いて，その地域性を調べた．東北日本外帯の地震頻発地域の中でも，余震活動度は系統的に大きく変化している．

さらに，余震頻度の減少速度がやはり明瞭な地域性を示すことを最近の資料を加えて示した．また，群発地震もある特定の地域に起こりやすい傾向を示すが，その規模は海洋地域の地震頻発地帯で著しく大きく，陸地の，主に火山地域に発生するものと対照的である．

前回の結果と総合すると，日本周辺全域の余震及群発地震の起こり方の地域性が明らかになる．これらの結果から，前回と同様に，日本地域の地殻の構造状態が推定される．特に海洋地域における破砕度の著しい所として，日本海溝の西側斜面地域，伊豆半島南東沖，及び日向洋東南方沖が指摘される．

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