Characteristics of Foreshock Activities associated with Large Shallow Intraplate Earthquakes in the Japanese Islands

by

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(Received January 8, 1990 ; Revised April 13, 1990)

Abstract

Characteristics of foreshock activities before large shallow ($M \geq 5$, depth ≤ 30 km) earthquakes in and near the Japanese islands have been investigated. Of 110 main shocks which occurred during the period 1961 through 1988, 41, or 37 per cent, were preceded by foreshock sequences that included events within 30 days of the main shocks. The distance criterion for foreshocks is simply that it be within the $20' \times 20'$ square centered on each main shock. The percentage of earthquakes with foreshocks scarcely changes if we take for criteria 40 days or $30' \times 30'$ square. Last foreshocks most likely occur within a day before the main shocks in close proximity to their epicenters. In the period after 1981, foreshocks were observed for 55 per cent of large earthquakes, while the ratio was 27 per cent for the period 1961-1970, and 37 per cent for the period 1971-1980, which fact shows that hypocenter determination capability of the Japan Meteorological Agency has remarkably improved in recent years. Considerable regional characteristics exist in foreshock activity. One of them is that earthquakes in the Izu region and in Kyushu island are likely to be preceded by foreshocks. In particular, 67 per cent of earthquakes in and near the Izu Peninsula have foreshocks, as compared with only 26 per cent in other regions. Moreover, foreshock sequences in the Izu region and Kyushu island are often swarm-like in contrast to those in other regions which usually contain not more than a few shocks. In most cases the swarm-like foreshock activity in the Izu region becomes quiet two or three hours before the occurrence of the main shock. The phenomenon is considered to imply that stress relaxation occurs in the focal region due to nucleation of fracture just before the occurrence of a large earthquake. Regional characteristics of foreshock activities presented in this study are consistent with the results by Mogi (1963), in which foreshocks for moderate and large earthquakes in and around the Japanese islands during the period 1926 through 1961 were investigated, which fact indicates that the characteristics are intrinsic properties and stem from regional differences of crustal structure and stress accumulation system as pointed out early by Mogi (1963). Time sequences of foreshock activities are classified into 4 Types. Type 1 includes such cases that only one or a few earthquakes occur several to tens days before the main shock. Some events of this Type may not be directly connected to the main shock occurrence. In Type 2 cases one foreshock occurs as in Type 1, but immediately (usually within several minutes) before the main shock occurrence. Foreshocks of this Type may indicate the commencement of fracture which is succeeded by the occurrence of a main shock. Type 3 is represented typically by cases where a moderate earthquake with a magnitude of 4 or so occurs several hours to one day before the main shock, and its aftershocks, sometimes its foreshocks as well, are observed. This seismic activity associated with the moderate earthquake usually disappears a few hours before the main shock. Type 4 corresponds to swarm-like activity. Occurrence of Type 3 and Type 4

foreshock sequences is almost confined to the Izu region, the Fossa Magna area, and the central part of Kyushu island. The appearance of a quiescent period a few hours just before the occurrence of a main shock in Type 3 and in a part of Type 4 sequences, especially in the Izu region, is considered to be a prospective precursory phenomenon for the imminent prediction of large earthquakes.

1. Introduction

There have been a number of studies on foreshock activity. Some of them investigate particular cases in detail (e.g., Bakun *et al.*, 1980; Jones, 1984; Jones *et al.*, 1982; Papazachos, 1973) and others aim to derive common features of foreshock sequences statistically (e.g., Jones, 1985; Jones and Molnar, 1979; von Seggern *et al.*, 1981; Papazachos, 1974; 1975). Furthermore, we have a lot of papers which investigate various physical properties of the earthquake such as wave form, spectrum, mechanism, and damping feature of coda wave, in order to clarify the distinctive features of foreshocks. In spite of these tremendous efforts, it may be said that no effective method of distinguishing foreshock activity from ordinary background seismicity has been found yet. One of the main reasons for this is that each foreshock activity has a specific character and it is difficult to set up general criteria for defining foreshocks by abstracting their common features.

More than a quarter century ago Mogi (1963) studied the patterns of time sequences of seismic activity in and around the Japanese islands and classified them into three types, Type I : main shock- aftershocks sequence, Type II : foreshocks-main shock- aftershocks sequence, and Type III : earthquake swarm. According to Mogi (1963) the spatial distribution of each type of earthquake sequence is related to the crustal structure, and regions where the second and the third type of sequences are observed correspond to volcanic zones in which the degree of heterogeneity in the crust is supposed to be high. Afterwards, Mogi (1967) pointed out that there are also intermediate types of earthquake sequences, and Utsu (1970) proposed a revised classification in which earthquake sequences were divided into twenty types based on Mogi's model. Investigating foreshock activities prior

to earthquakes with $ML \geq 5.0$ that occurred in the San Andreas fault system from 1966 to 1980, Jones (1984) found that 7 main shocks out of 20 are associated with foreshocks. Two of them had a swarm-like character, one was a multiple main shocks type (class IIIa in Utsu, 1970), and the other four foreshock sequences are single events, sometimes with their own aftershocks (class Ib in Utsu, 1970).

Mogi (1963) and Utsu (1970) classified the patterns of earthquake sequences and noted the importance of their regional characteristics, which shows they were farsighted in the study of time sequence of seismic activity in the Japanese islands, but only data of earthquakes until the 1960s were available to them. In this paper foreshock sequences associated with large earthquakes in recent years are investigated, especially noting the specific features of each activity as well as their regional characteristics and their relation to tectonic settings. We propose to classify foreshock sequences into 4 Types and will show that occurrence of so-called swarm-like foreshock activities is confined to a few regions. We consider that the appearance of a quiescent period just before the main shock is an important feature, especially in relation to the imminent prediction of large earthquakes, and investigate the characteristics of the feature in detail with some discussions about possible physical processes of that phenomenon.

2. Data

The Earthquake Catalogue of the Japan Meteorological Agency is used to investigate the foreshock activities of large ($M \geq 5.0$) shallow (depth ≤ 30 km) earthquakes which occurred in and near the Japanese islands from 1961, when the hypocenter of earthquakes began to be determined by an electronic computer, through 1988. Figure 1 shows the epicentral distribution of earthquakes whose foreshock

sequences are investigated, and Figure 2 shows the main shocks which are found to be preceded by foreshocks in this study. The aim of this

Fig. 1 Epicentral distribution of large shallow ($M \geq 5$, depth ≤ 30 km) earthquakes whose foreshock sequences are investigated. A broken line indicates the area where we studied seismic activity.

Fig. 2 Epicentral distribution of earthquakes preceded by foreshocks.

study is to clarify the characteristics of foreshock sequences associated with intraplate shallow earthquakes, so that earthquakes occurring to the east of the Pacific coast of the Japanese islands are excluded, because they are considered to occur in the subduction slabs of the Pacific plate and the Philippine Sea plate or interplate coupling zones between these plates and land plates. Exceptions are those earthquakes which occur in and around the Izu Peninsula. Although the Izu Peninsula and small islands to the south of it belong to the Philippine Sea plate, they constitute at the same time a volcanic island arc due to the subduction of the Pacific plate, and earthquakes in these regions are very shallow and have interesting features as shown in this paper. Earthquakes occurring off the west coast of the Japanese islands are included, although some attention should be paid to these earthquakes because the hypothesis has recently been proposed that a newly born subduction zone exists in the east coast of the Sea of Japan (Nakamura, 1983; Kobayashi, 1983). However, they are very few in number, so that the general features of foreshock sequences in the Japanese islands do not change by taking them into consideration.

Whether an earthquake was preceded by a foreshock sequence or not is judged in principle by the JMA Catalogue, and in making the search of foreshocks we used a seismicity analyzing program SEIS-PC for personal computer (Ishikawa *et al.*, 1985). However, even if earthquakes were not found in the Catalogue, when shocks were recorded at local weather observatories and are considered with certainty to have occurred near the epicenters of the main shocks, we regard them as preceded by foreshocks. There are several such earthquakes, which are shown by different symbols from those with foreshocks in the Catalogue (see Figures in § 4). We have included foreshocks regardless of their magnitude. Consequently the percentage of earthquakes with foreshocks apparently increased gradually from the 1960s to the 1980s, owing to the improvement of hypocenter determination capability of the JMA seismological network. However, as will

be demonstrated, the regional characteristics of foreshock activity do not change whether we take into consideration only shocks larger than M 3 or smaller earthquakes as well.

The hypocentral depths of all earthquakes except one investigated in this study are equal to or shallower than 30 km. The exception is the 1964 Niigata earthquake with M 7.5. Although the hypocentral depth of the Niigata earthquake in the Catalogue is 40 km, it is certain that the rupture reached near the surface, so it may be reasonable to include it. Aftershocks, Matsushiro swarm activity, and earthquakes associated with volcanic eruptions (the 1962 Izu-Miyakejima eruption, the 1983 Izu-Miyakejima eruption, and the 1986 Izu-Oshima eruption) are excluded.

3. Analysis

Criterion for defining foreshocks

Earthquakes which occur in the neighborhood of the hypocenter of main shocks shortly before their occurrence are usually called foreshocks. This is a simple criterion, but it is a useful one when we do not know how to define them physically. In this study we also adopt the simple criteria, that is, earthquakes which

occur within a $20' \times 20'$ square centered on each main shock epicenter within 30 days before its occurrence are regarded as foreshocks. Most foreshocks occur in the vicinity of the main shock and even if we extend our spatial criterion of foreshocks to $30' \times 30'$ the number of main shocks preceded by foreshocks does not change at all. Figure 3 shows the distribution of foreshock occurrence as a function of time before main shocks. When two or more foreshocks occur, we take up the one that occurs immediately before the main shock. It is remarkable that 61 per cent of these last foreshocks occur within 24 hours before the main shock. As a criterion of time window a Poisson hypothesis about the distribution of interevent times is sometimes used, in which seismic activity is assumed to be represented by a Poisson process and earthquakes within a critical time before the main shock are regarded as foreshocks. The critical time is chosen so that the probability for the intervals is less than the critical value p_c . For example von Seggern *et al.* (1981) and Bowman and Kisslinger (1984) selected 0.2 as p_c , while Ichikawa (1986) used 0.1 for p_c in analyzing the foreshock activities of earthquakes in the Japanese islands. If we adopt this criterion, at least 20 percent (in the case of $p_c=0.2$) or 10 percent (in the case of $p_c=$

Fig. 3 Foreshock occurrence as a function of time before main shocks. When more than one foreshock is observed, the last foreshock, i.e. the one occurring immediately before each main shock, is taken.

Fig. 4 Foreshock occurrence as a function of time before main shocks which are preceded by foreshock activity within a day. The last foreshock is taken as in Fig. 3

0.1) of all main shocks would have foreshocks. On the other hand it is known that the precursor time of foreshocks and the magnitude of main shocks do not show any relation to each other and, as is shown above, most foreshocks occur shortly before the occurrence of main shocks. Considering these facts, the simple criterion is supposed to be better than those in which the time window is changed according to the degree of seismicity and magnitude of main shocks, especially when we are interested in characteristics of immediate foreshocks. If we extend the time criterion of foreshocks to 40 days, three more earthquakes will be defined as preceded by foreshocks. However, some of these *foreshocks* are not likely to be directly related to the occurrence of main shocks. This may be especially true for such *foreshocks* which occur in a relatively high seismicity region.

Figure 4 shows the distribution of the lengths of time by which the last foreshock precedes a main shock for 24 earthquakes that are accompanied by foreshock activity within a day. We see in Fig. 4 that most of the last foreshocks occur within one hour before the occurrence of a main shock. However, we should not consider that the main shock generally occurs at the culmination of foreshock activity. Statistical analyses of foreshock sequences are in such points sometimes misleading. For example Jones and Molnar (1978) and Papazachos (1974, 1975) insist that foreshock activity gradually becomes high as the time of main shock occurrence approaches, by showing figures in which the time sequences of many foreshock activities are superposed, while Papazachos (1975) proposed a relation in which foreshock activity increases in inverse proportion to the length of time until the main shock. However, the actual time sequence is quite different from such patterns, and usually exhibits quiescence just before the occurrence of a main shock. This feature, we think, is important and will be discussed in detail in § 5.

Percentage of earthquakes preceded by foreshocks

Of the 110 main shocks with a magnitude of

5 or larger, 41 earthquakes were preceded by foreshock activity. The ratio is 37 percent. If we take up only those with a magnitude of 6 or larger, foreshock activity was observed for 13 out of 22 earthquakes, the ratio amounting to 59 percent. It is interesting to compare the results with those by Mogi (1963), in which the foreshock activities of earthquakes in and around the Japanese islands during the period 1926–1961 were investigated. According to Mogi (1963) only 4 per cent of earthquakes are preceded by foreshocks out of about 1500 major earthquakes with $M \geq 4$ in land areas and $M \geq 4.5$ in sea areas. This large difference in the percentage of earthquakes with foreshocks is considered to have several reasons. One of them is that Mogi (1963) investigated foreshock activities for main shocks including those of smaller magnitudes than ours and earthquakes in sea areas as well. Further, Mogi (1963) only noted foreshocks of magnitude 3 or larger, while in this study we adopted all foreshocks in the JMA Catalogue including those of undetermined magnitude. Moreover, we also take into consideration such small shocks which are not in the Catalogue but are recorded at local weather stations of the JMA near the epicenter of the main shock. If we limit ourselves to shocks of magnitude 3 or larger, the ratio of foreshock-preceded earthquakes becomes 25 per cent. Another strong reason for the difference is the fact that the hypocenter determination capability of the seismological network of the Japan Meteorological Agency has remarkably improved in recent years. Actually, the ratio of earthquakes with foreshocks is 27 percent in the period 1961 through 1970, while in the period 1971 through 1980 it is 37 percent, and 55 percent for the period after 1981.

It is a remarkable feature that earthquakes in the Izu region are very often preceded by foreshocks. The ratio amounts to 67 percent. This is very large compared with 26 per cent for other regions. Furthermore, foreshock activities in the Izu region often form a swarm. Another region where swarm-like foreshock activities often appear is Kyushu island. We will discuss the regional characteristics of foreshock activity in detail in the next section.

Fig. 5 Typical pattern for each of the 4 Types of foreshock sequence.

Classification of foreshock sequences

We propose to classify foreshock sequences into 4 Types. Typical patterns for each of the 4 Types are shown in Fig. 5. Type 1 includes such cases where only one or a few shocks occur several to ten or more days before the main shock. Some *foreshocks* of this Type may not be directly related to the occurrence of a main shock. In Type 2 cases also one or two

foreshocks occur as in Type 1, but immediately before, that is, usually within one to several minutes before the main shock in the proximity of its hypocenter. Foreshocks of this Type probably indicate the commencement of fracture which is succeeded by the main shock. Type 3 is represented typically by such cases where a moderate earthquake of magnitude 4 or so occurs several hours to one day before the main shock, and its aftershocks, sometimes its foreshocks as well, are observed. Seismic activities associated with the moderate earthquake usually disappear a few hours before the main shocks. Type 4 includes swarm-like activities. It should be added that we did some simplification in the classification. For example, real earthquake swarms often occur in the Izu region, in which it is difficult to select one main shock, and in Type 3 sequences two or more moderate earthquakes of magnitude 4 or so are sometimes observed to occur in the foreshock activities. Further, besides the above 4 Types, we have another Type, which has no foreshock observed. However, if our seismic network becomes more complete, it may be possible for us to catch some signal indicating the occurrence of large earthquakes before most of them. Of the 41 earthquakes which are found to be preceded by foreshocks, 13 are Type 1 earthquakes, seven are Type 2, five are Type 3, and

Fig. 6 Epicentral distribution of Type 3 and Type 4 earthquakes.

16 are Type 4, although there are several sequences which were difficult to determine whether they are Type 3 or Type 4, and there are a few cases in which Type 2-like foreshocks are observed immediately before main shocks of Type 3 and Type 4. Figure 6 shows the epicentral distribution of earthquakes of Type 3 and Type 4. It is notable that the occurrence of Type 3 and Type 4 foreshock sequences is confined to the Izu region, the Fossa Magna area, and the central part of Kyushu island.

4. Regional characteristics of foreshock activity

Hokkaido island

Fig. 7 Epicenters of large shallow ($M \geq 5$, depth ≤ 30 km) earthquakes in Hokkaido. Foreshock activity was observed in none of these earthquakes.

Shallow seismicity in Hokkaido island is rather low and only 4 earthquakes of magnitude 5 or larger occurred during the period 1961 through 1988. The epicenters of these earthquakes are shown in Fig. 7. For all of these earthquakes no foreshock activity was observed.

Tohoku district

Of 15 main shocks of magnitude 5 or larger which occurred in the Tohoku district from 1961 to 1988, three, or 20 percent, have been preceded by foreshock activities. Table 1 shows

Fig. 8 Epicentral distribution of large shallow ($M \geq 5$, depth ≤ 30 km) earthquakes in the Tohoku district. There are three earthquakes preceded by foreshocks; one is Type 1 and the other two are Type 2.

Table 1 List of earthquakes accompanied by foreshock activity in the Tohoku district.

Year	Month	Day	Name	Hypocenter & Magnitude				Type of Foreshock Activity
				latitude	longitude	depth	M	
1964	5	7	Off-Oga Pen.	40 20	139 00	0 km	6.9	Type 2
1970	10	16	S-E Akita	39 12	140 45	0 km	6.2	Type 2
1983	5	26	Cen. Jap. Sea	40 21.4	139 04.6	14 km	7.7	Type 1 *

A mark * in the last column indicates that the foreshock activity contains earthquake(s) with $M \geq 3$ in the JAM Catalog.

the list of earthquakes accompanied by foreshock activities in the Tohoku district. Two of the three are Type 2, that is, a foreshock was observed just before the occurrence of the main shock, although the foreshocks are not given in the Earthquake Catalogue, but only recorded by local weather stations of the Japan Meteorological Agency. The other Type 1 earthquake is the 1983 Nihonkai-chubu earthquake (M 7.7). For this earthquake an M 5.0 shock occurred in the vicinity of the main shock 12 days before. Precursory seismicity change in the long and middle term in and around the focal region of the earthquake is investigated by Mogi (1985a), which shows that seismic activity in the hypocentral region was low during about 5 years before the earthquake occurrence.

Figure 8 shows the epicentral distribution of earthquakes of M 5 or larger in which earthquakes are plotted by different symbols according to whether they are preceded by foreshocks or not and which Type they are classified into. It is notable that large shallow earthquakes are mostly distributed in the belt-like zone connecting the Oga Peninsula and the Oshika Peninsula. Seismic activities in this zone often exhibit co-occurrence and diffusive pattern in the active periods, which indicates that the zone

Fig. 9 Epicentral distribution of large shallow ($M \geq 5$, depth ≤ 30 km) earthquakes in the Chubu district. Different Types of earthquakes are plotted by different symbols. A broken line indicates the Itoigawa-Shizuoka Tectonic Line which corresponds to the western boundary of the Fossa Magna. N : the 1984 Naganoken-seibu earthquake (M6.8).

Table 2 List of earthquakes accompanied by foreshock activity in the Chubu district.

Year Month Day	Name	Hypocenter & Magnitude				Type of Foreshock Activity
		latitude	longitude	depth	M	
1961 8 19	Kita-Mino	36 01	136 46	0 km	7.0	Type 2
1968 9 21	N Nagano	36 49	138 16	10 km	5.3	Type 3 *
1969 9 2	W Nagano	36 12	137 43	0 km	5.0	Type 3 *
1978 10 7	S-W Nagano	35 47	137 30	0 km	5.3	Type 4 *
1984 9 14	W Nagano	35 49.3	137 33.6	2 km	6.8	Type 1 *
1986 12 30	N Nagano	36 38.2	137 55.5	3 km	5.9	Type 2
1987 3 24	Off S Niigata	37 28.7	137 54.4	22 km	5.9	Type 2 *

A mark * in the last column indicates that the foreshock activity contains earthquake(s) with $M \geq 3$ in the JMA Catalog.

constitutes a mechanical boundary of tectonic blocks (e.g. Mogi, 1985b; Yoshida, 1988; and Yoshida *et al.*, 1988).

Chubu district

In the Chubu district foreshock activities were observed for seven, or 35 percent, of the 20 main shocks of magnitude 5 or larger, in which the Matsushiro swarm is not included. A list of earthquakes accompanied by foreshock activity in the Chubu district is given in Table 2. Figure 9 shows the epicentral distribution of these earthquakes where different Types of earthquakes are plotted by different symbols. Among the seven earthquakes with foreshocks, one is Type 1, three are Type 2, two are Type 3, and one is Type 4. The 1961 Kita-Mino earthquake (M7.0) was recently found to have been accompanied by a foreshock (Hamada, 1987). Not contained in the JMA Catalogue, it occurred one minute before the main shock. Two Type 3 earthquakes in the northern part of the Chubu district are situated in and near the Fossa Magna, which is a large tectonic zone formed in Miocene and is considered to be active even now partially. In one of the Type 3 foreshock sequences (northern one) an M 4.0 earthquake occurred about 4 hours before the main shock and the activities associated with it ceased one and a half hours before the main shock occurrence. In another Type 3 foreshock sequence (southern one), which occurred near an active volcano (Yake-dake), notable seismic activities including an M 4.7 and an M 4.4 earthquake appeared 2 to 1 day before the main shock. The one Type 4 earthquake occurred in October 1978 near the focal region of the 1984 Naganoken-seibu earthquake (M 6.8), where swarm-like activities had continued intermittently since August 1976. The seismic activity was rather low before the 1984 earthquake although several foreshocks were observed during the 30 days before its occurrence. Yoshida (1989) studied the characteristics of seismic activity in the northwestern Chubu district in recent several decades with special reference to the predictability of the 1984 Naganoken-seibu earthquake.

Izu region

Figure 10 shows the epicentral distribution of earthquakes of magnitude 5 or larger during the period 1961–1988 in and around the Izu Peninsula. It is notable that many earthquakes in this region are associated with foreshock activity, that is, 20 out of the 30 earthquakes have foreshocks, the ratio amounting to 67 percent. Further, foreshock activities in the Izu region are often swarm-like. Actually, as is seen in Table 3 where earthquakes accompanied by foreshock activities are listed, 11 out of 20 earthquakes with foreshocks, that is, more than half, are Type 4 and two are Type 3, while six are classified into Type 1 and the remaining one is Type 2. All of the eleven Type 4 earthquakes are distributed in the sea area near and to the south of the Izu Peninsula. Besides these earthquakes swarm activity has been frequently observed in this area including those which accompanied the 1962 and the 1983 Izu-Miyakejima volcanic eruption and the 1986 Izu-Oshima volcanic eruption. The two Type 3

Fig. 10 Epicentral distribution of large shallow ($M \geq 5$, depth ≤ 30 km) earthquakes in the Izu region. Different Types of earthquakes are shown by different symbols. Y : the 1976 Yamanashiken-tobu earthquake (M 5.5), S : the 1988 Saitamaken-nambu earthquake (M 5.0), K : the 1976 Kawazu earthquake (M 5.4).

Table 3 List of earthquakes accompanied by foreshock activity in the Izu region.

Year	Month	Day	Name	Hypocenter latitude	Magnitude longitude	depth	M	Type of Foreshock Activity
1964	11	3	S Izu Pen.	34 38	138 48	0 km	5.4	Type 2
1964	12	9	Near Izu-Oshima	34 35	139 18	0 km	5.8	Type 4
1965	4	20	Shizuoka	34 53	138 18	20 km	6.1	Type 1
1965	11	6	Near Kozujima	34 03	139 01	20 km	5.6	Type 4 *
1967	4	6	Near Kozujima	34 13	139 09	10 km	5.3	Type 1 *
1968	2	25	Near Kozujima	34 14	139 15	0 km	5.0	Type 4 *
1971	7	4	S Off Shizuoka	33 41	138 36	30 km	5.1	Type 4 *
1976	6	16	E Yamanashi	35 30	139 00	20 km	5.5	Type 3 *
1976	8	18	Izu Kawazu	34 47	138 57	0 km	5.4	Type 1
1978	1	14	Izu-Oshima-kinkai	34 46	139 15	0 km	7.0	Type 4 *
1978	12	3	E-off Izu Pen.	34 53	139 11	20 km	5.4	Type 4 *
1980	6	29	E-off Izu Pen.	34 55	139 14	10 km	6.7	Type 4 *
1980	9	10	W-off Miyakejima	34 01	139 00	20 km	5.6	Type 4 *
1982	12	27	Near Miyakejima	33 45	139 23	20 km	5.4	Type 4 *
1983	8	8	E Yamanashi	35 31.1	139 01.5	22 km	6.0	Type 1 *
1984	2	14	E Yamanashi	35 35.1	139 06.4	25 km	5.2	Type 1
1987	5	11	E-off Izu Pen.	34 55.7	139 15.5	15 km	5.0	Type 4 *
1988	7	31	E-off Izu Pen.	34 57.8	139 13.0	5 km	5.2	Type 4 *
1988	9	5	E Yamanashi	35 29.8	138 59.2	30 km	5.6	Type 1 *
1988	9	29	W Saitama	35 55.1	139 11.4	15 km	5.0	Type 3 *

A mark * in the last column indicates that the foreshock activity contains earthquake(s) with $M \geq 3$ in the JMA Catalog.

earthquakes in the northern part of this region are the 1976 Yamanashiken-tobu earthquake (M 5.5) and the 1988 Saitamaken-nambu earthquake (M 5.0). For the 1976 Kawazu earthquake (M 5.4) only one shock was recorded at a local weather station of the JMA near the epicenter, but more shocks were caught by the seismologi-

cal network of the Earthquake Research Institute, University of Tokyo (Tsumura et al., 1977), and it is suggested that the foreshock sequence might be Type 3 (see Fig.18). It should be noted that quiescence appears 2 to 3 hours before the main shock for many of the foreshock sequences of the Type 3 and the Type 4

Table 4 List of earthquakes accompanied by foreshock activity in the Kinki district.

Year	Month	Day	Name	Hypocenter & Magnitude				Type of Foreshock Activity
				latitude	longitude	depth	M	
1968	3	30	Near Wakayama	34 10	135 10	0 km	5.0	Type 1 *
1984	5	30	Yamasaki Fault	34 57.6	134 35.6	17 km	5.6	Type 1
1987	5	9	N-E Wakayama	34 08.6	135 24.5	8 km	5.6	Type 1

A mark * in the last column indicates that the foreshock activity contains earthquake(s) with $M \geq 3$ in the JMA Catalog.

Fig. 11 Epicentral distribution of large shallow ($M \geq 5$, depth ≤ 30 km) earthquakes in the Kinki district. All the three earthquakes preceded by foreshocks are Type 1.

in this region. In the next section we will show several typical examples of such sequences and discuss the physical meaning of the phenomenon.

Kinki district

Figure 11 shows the epicentral distribution of earthquakes of magnitude 5 or larger during the period 1961 through 1988 in the Kinki district. Three out of the 15 main shocks were preceded by foreshock activity; the ratio being 20 per cent, and they are all Type 1. Table 4 shows the list of the three earthquakes accompanied by foreshock activity. Two of them occurred near Wakayama city on the western

coast of the Kii Peninsula. Seismicity in that region is high, so it is rather difficult to distinguish foreshocks from shocks of the ordinary activity. The other one is the earthquake along the Yamasaki fault. The area near the fault has been a test field of earthquake prediction research since the mid of the 1970s and various kinds of observation have been carried out there to catch precursory phenomena (e.g. Kishimoto, 1980).

Chugoku-Shikoku district

Epicentral distribution of earthquakes of

Fig. 12 Epicentral distribution of large shallow ($M \geq 5$, depth ≤ 30 km) earthquakes in the Chugoku-Shikoku district. Of the three earthquakes preceded by foreshocks two are Type 1 and one is Type 2.

Table 5 List of earthquakes accompanied by foreshock activity in the Chugoku-Shikoku district.

Year	Month	Day	Name	Hypocenter & Magnitude				Type of Foreshock Activity
				latitude	longitude	depth	M	
1978	6	4	Cen. Shimane	35 05	132 42	0 km	6.1	Type 1 *
1983	10	31	Cen. Tottori	35 24.8	133 55.6	15 km	6.2	Type 2
1984	6	25	N Hiroshima	34 45.4	132 35.2	12 km	5.2	Type 1 *

A mark * in the last column indicates that the foreshock activity contains earthquake(s) with $M \geq 3$ in the JMA Catalog.

$M5$ or larger during the period 1961 through 1988 is shown in Fig. 12. Of the 11 earthquakes, three, or 27 per cent, are preceded by foreshocks in the Chugoku district. One of them is a Type 2 earthquake; the other two are Type 1. The list of earthquakes accompanied by foreshock activities is shown in Table 5.

Kyushu district

Figure 13 shows the epicentral distribution of earthquakes of magnitude 5 or larger in the Kyushu district. Of the 14 earthquakes during the period 1961 through 1988, five, or 36 per cent, were preceded by a foreshock sequence. Table 6 is the list of earthquakes accompanied by foreshock activities. A notable characteristic of foreshock activity in the Kyushu district is that all the observed foreshock sequences are of Type 3 or Type 4. The feature is considered to be related to the specific geological setting of the regions, *i.e.* that they are situated in volcanic zones. Another notable feature of Fig. 13 is that many earthquakes of $M 5$ or larger are distributed in the zone of NE-SW direction in the central part of Kyushu island. Along the zone a conspicuous graben structure develops (Matsumoto, 1979) and a remarkable crustal extension in the N-S direction has been observed (Tada, 1984; 1985). Yoshida (1988) showed that seismic activity in the zone sometimes exhibits co-occurrence and a diffusive pattern, and Yoshida (1990b) found a relationship between shallow seismicity and the occurrence of deep earthquakes. These characteristics are supposed to be closely related to the above-mentioned geological feature and crustal activ-

ity.

5. Discussion

As has been shown in the previous section considerable regionality exists in the foreshock activity of large earthquakes in the Japanese islands. One of the notable features is that earthquakes in the Izu region and in Kyushu island are likely to be associated with foreshocks. Moreover, Type 3 or Type 4 sequences are often observed in these regions in contrast to other regions where only Type 1 or Type 2 sequences occur. These features have already been pointed out by Mogi (1963), in which after-

Fig. 13 Epicentral distribution of large shallow ($M \geq 5$, depth ≤ 30 km) earthquakes in the Kyushu district. It is to be noted that 5 earthquakes preceded by foreshock sequences are all Type 3(1) or Type 4(4), which contain many shocks.

Table 6 List of earthquakes accompanied by foreshock activity in the Kyushu district.

Year	Month	Day	Name	Hypocenter & Magnitude				Type of Foreshock Activity
				latitude	longitude	depth	M	
1961	3	16	N Kagoshima	32 00	130 42	0 km	5.5	Type 4
1968	2	21	Ebino	32 01	130 43	0 km	6.1	Type 4 *
1975	1	23	N-E Kumamoto	33 00	131 08	0 km	6.1	Type 4 *
1977	6	28	Cen. Kumamoto	32 54	130 43	10 km	5.2	Type 3 *
1984	8	6	Shimabara Pen.	32 45.4	130 10.7	7 km	5.7	Type 4 *

A mark * in the last column indicates that the foreshock activity contains earthquake(s) with $M \geq 3$ in the JMA Catalog.

shocks and foreshocks of earthquakes during the period 1926 through 1961 were investigated. Figure 14 and Figure 15 are taken from Mogi

(1963) and show the epicentral distribution of earthquakes associated with foreshocks and the distribution of the percentage of earthquakes

Fig. 14 Epicentral distribution of earthquakes preceded by foreshocks. Open circles show uncertain cases. This figure is taken from Mogi (1963), which investigated the foreshock activities of large and moderate earthquakes in and around the Japanese islands during the period 1926 through 1961.

Fig. 15 This figure is taken from Mogi (1963) and shows the distribution of the ratio of the Type II earthquakes to the sum of the Type I earthquakes and the Type II earthquakes. In Mogi's classification Type I earthquakes represent those which are accompanied by aftershocks and Type II earthquakes correspond to those which are preceded by foreshocks.

with foreshocks. Similarity is remarkable between the distribution of earthquakes in Fig. 14 and in Fig. 2, where earthquakes with foreshocks during the period 1961 through 1988 are plotted. This indicates that the characteristics are intrinsic properties and stem from regional differences in the crustal structure and stress accumulation system. Both the Izu region and Kyushu island correspond to a volcanic zone, and the heterogeneity of the crust in these regions is supposed to be large, which situation should be related to the feature as has been suggested by Mogi (1963).

Except for the Izu region, the Fossa Magna area, and Kyushu island, foreshock sequences are all Type 1 or Type 2, that is, not more than a few shocks are observed. In these cases it is difficult to recognize the occurrence of foreshock unless we find an effective method to

distinguish foreshocks physically. On the other hand, for Type 3 and Type 4 sequences there is a prospective feature which is considered useful for immediate prediction of large earthquakes. That is the appearance of quiescence several hours before the occurrence of a main shock. Some typical examples are presented in the following. Figure 16 shows the time sequence of foreshock activities before the 1978 Izu-

Fig. 16 The upper Figure shows the time sequence of earthquake occurrence before the Izu-Oshima-kinkai earthquake (M7.0) on 14 January 1978. A remarkable activity was observed about 2 hours before the main shock and then it became quiet. The lower Figure is the time sequence of earthquake occurrence before the Izu-hanto-toho-oki earthquake (M6.7) on 29 June 1980. In this case too, noticeable quiescence was observed about 3 hours before the main shock.

Fig. 17 The upper Figure shows the time sequence of foreshock activity before the Izu-hanto-toho-oki earthquake (M5.3) on 3 December 1978, the middle Figure shows the time sequence of foreshock activity before the Izu-hanto-nampo-oki earthquake (M5.6) on 10 September 1980, and the lower Figure shows that before the Naganoken-hokubu earthquake (M5.3) on 21 September 1968. From these Figures it is observed that about 3 hours before each main shock quiescence appeared in the foreshock activity.

Fig. 18 The upper Figure is the temporal change of earthquake occurrence before the Izu-Kawazu earthquake (M5.4) on 18 August 1976, and the lower Figure shows the time sequence of earthquake occurrence before the Izu-Hokkawa earthquake (M3.6) on 9 February of the same year. These figures are drawn by Mogi (1985), and the data are taken from Tsumura *et al.* (1977). In the JMA network these small earthquakes were not caught.

Oshima-kinkai earthquake (M 7.0) and the 1980 Izu-hanto-toho-oki earthquake (M 6.7). It is clear from Fig. 16 that seismicity became quiet 2 hours (for the Izu-Oshima-kinkai earthquake) and 3 hours (for the Izu-hanto-toho-oki earthquake) before the occurrence of the main shocks. In Fig. 17 we can see similar phenomena in the foreshock activities of the 1978 Izu-hanto-toho-oki earthquake (M 5.4), the 1980 Izu-hanto-nampo-oki earthquake (M 5.6), and the 1968 Naganoken-hokubu earthquake (M 5.3). Figure 18 is taken from Mogi (1985c) and shows the time sequences of other earthquakes in the Izu region in which quiescence before the main shock occurrence was recognized. Further, Figure 19 shows the temporal change of the foreshock activity of the 1976 Yamanashiken-tobu earthquake (M 5.5). The duration of the quiescent period varies, as seen

Fig. 19 Temporal change of the foreshock activity before the Yamanashiken-tobu earthquake (M5.5) on 16 June 1976. After SAMC (1977).

in Figs. 16–19, from 2 to 4 hours and no clear relation is recognized between the quiescent period and the magnitude of the main shock. Incidentally it should be noted that the pattern of foreshock sequences as deduced by Papazachos (1975), in which the main shock occurs at the time of culmination of foreshock activity, is not usually observed for the actual sequences.

The appearance of quiescence in foreshock activity just before the main shock is not a new finding, but has already been pointed out sometimes. A famous example may be the case of the 1975 Haicheng earthquake (Raleigh *et al.*, 1977; Jones *et al.*, 1982). Xu *et al.* (1982) present a few other cases for Chinese earthquakes which showed the same pattern. For earthquakes in Japan Mogi (1985c) noted the temporary lull of foreshock activity before the main shock which occurred in and around the Izu Peninsula (see Fig. 18). In this study we found that the phenomenon is more generally observed in Type 3 and Type 4 foreshock activities, although it might be fair to mention that there are also cases where quiescence is not so clear. Almost all of them, however, are swarm activities, in which it is rather difficult to distinguish one main shock.

Scholz (1988) pointed out that there are three types of seismic quiescence: post-seismic quiescence, which occurs in the focal region after an aftershock activity; intermediate-term quiescence, which appears several years prior to a large earthquake; and short-term quiescence, which is observed in the swarm type

foreshock activity several hours before an earthquake. The third type corresponds to the quiescence which we are now discussing. As for the mechanism of the appearance of this type of quiescence, Scholz (1988) proposed the idea that it results from local dilatancy hardening or slip weakening in the nucleation patch. I suggest a third possibility that it may indicate the maturing of the focal region, by which a fracture of large coherency is prepared. Yoshida (1990a) noted that a remarkable feature of the constant average stress drop of earthquakes is related to the feature that the representative coherent length of fracture is proportional to the fault length. That is, the larger the earthquake, the larger the coherency of fracture, which means that non-local conditions not restricted to the hypocentral area may be involved in the preparation of large earthquakes. In any case it is considered that stress softening is more likely to occur in the focal region just before the occurrence of large earthquakes than stress intensifying in consequence of formation of nucleation.

6. Conclusion

The characteristics of foreshock activity before large and moderate shallow ($M \geq 5$, depth ≤ 30 km) earthquakes which occurred during the period 1961 through 1988 in and near the Japanese islands are investigated. Of the 110 main shocks 41, or 37 per cent, were preceded by foreshock sequences that included events within 30 days before the main shocks and within a $20' \times 20'$ square centered on each main shock epicenter. Foreshocks most frequently occurs within one day before the main shock, and the last foreshock most likely occurs within one hour before the main shock. However, it should not be considered that the main shock occurs at the time of culmination of foreshock activity as often suggested by statistical investigation of foreshock activity (e.g. Papazachos, 1975). The ratio of earthquakes with a foreshock has increased with years, *i.e.* 27 per cent in the 1960s, 37 per cent in the 1970s, and 55 per cent in the 1980s, which fact shows that hypocenter determination capability of the seis-

mological network of the Japan Meteorological Agency has remarkably improved in recent years.

Foreshock sequences are classified into 4 Types. In Type 1 only one or a few earthquakes occur sporadically several to 10 days before the main shock. Some of these earthquakes may not be related directly to the main shock. A Type 2 foreshock occurs immediately (usually within several minutes) before the main shock in close proximity to the epicenter and it is considered to represent pre-fracture succeeded by the occurrence of main shock. In the Type 3 sequence a moderate earthquake of magnitude 4 or so occurs several hours to one day before the main shock and considerable activities occur accompanying the earthquake. Type 4 corresponds to swarm-like activity.

It should be noted that the same regional characteristics of foreshock activity are found as those derived by Mogi (1963), in which earthquake data during the period 1926–1961 were used. The most conspicuous feature is that earthquakes in the Izu region and in Kyushu island tend to be preceded by foreshocks. In particular the ratio of earthquakes with foreshocks in the Izu region amounts to 67 per cent while it is only 26 per cent for those in other regions. Further, foreshock sequences in the Izu region and in Kyushu island are often swarm-like in contrast to those in other regions which usually contain only one or a few events.

It seems probable that the ratio of earthquakes in which foreshocks are observed will increase in the future, but it will be difficult to recognize foreshocks before the main shock for Type 1 and Type 2 sequences. On the other hand, the appearance of quiescence several hours before the main shock in many of the Type 3 and Type 4 sequences is considered to be a useful phenomenon for immediate prediction of large earthquakes. Regions where Type 3 and Type 4 foreshock sequences appear are restricted to the Izu region, the Fossa Magna area, and Kyushu island, so that it may be difficult to predict all earthquakes in the Japanese islands by using only foreshock activity, although Type 1 and Type 2 foreshocks may also be of some use when they occur in a

region where large earthquakes are expected.

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日本列島及びその周辺の浅い大きな内陸地震に伴った前震活動の特徴

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日本列島とその周辺に発生した浅い大地震($M \geq 5$, 深さ ≤ 30 km)の前震活動の特徴を調べた。1961年から1988年までの期間に発生した110個の本震の中、41個、すなわち37%が前震を伴っていた。ここで定義した前震とは、本震の前30日以内に、本震の震央を中心として $20' \times 20'$ の領域内に発生した地震をいう。前震がみられた地震の割合は、期間を40日とし、また範囲を $30' \times 30'$ に広げてもほとんど変わらない。前震時系列の中の最後の前震は、本震発生前1日以内に、その本震の震央のすぐ近くで発生する場合がほとんどである。1981年以後の期間をとると、前震は55%の地震について観測された。これに対して、1961–1970年の期間では前震を伴った本震の割合は27%、また1971–1980年の期間ではそれは37%である。このことは、近年、気象庁の地震検知力が格段に増大したことを示している。前震活動には著しい地域性が存在する。その注目すべき特徴の一つは、伊豆地域と九州中部に発生する地震には前震が伴いやすいことである。特に、伊豆地域では67%の地震に前震がみられた。他の地域では、この割合は26%である。更に、伊豆地域と九州に発生する地震には、しばしば群発的な前震活動が観測される。他の地域では前震を伴ったとしても、通常は1個ないし2–3個の地震が発生するのみである。なお、伊豆地域にみられる群発的な前震活動では、本震発生の2–3時間前に静穏化が生じることが多い。この現象は、大地震の発生直前に破壊の核が生成されて、震源域における応力が緩和することを示しているものと考えられる。この研究で明らかにされた前震活動の地域的な特徴は、1926年から1961年までの期間に日本とその周辺海域に発生した大・中地震の前震を調査したMogi (1963) の結果と調和的である。この事実は、Mogi (1963) も指摘しているように、これらの特徴が一時的なものではなく、その地域地域毎の地殻構造や応力の集中過程を反映した固有の性質であることを示している。前震の時系列は4つのタイプに分類することができる。タイプ1は、1個ないし2–3個の地震が本震の数日から数10日前に発生するものである。このタイプの前震中には本震の発生と直接関係しないものも含まれている可能性がある。タイプ2もタイプ1と同じように1個ないし2–3個の前震がみられる場合であるが、しかし、これらの前震は本震の直前(通常数分以内)に発生する。このタイプの前震の発生は、本震発生に引き続く破壊の開始を表わしているのかもしれない。タイプ3の典型的な場合は、M4程度の中規模の地震が本震の数時間から1日ほど前に発生してその地震に伴う余震、時には、前震もみられるものである。この中規模の地震に伴う地震活動は、通常、本震発生の2–3時間前には静かになる。タイプ4は群発的な前震活動に対応する。タイプ3とタイプ4の前震活動の発生は、伊豆地域、フォッサ・マグナ地域、九州の中央部にほとんど限られる。これらのタイプの前震活動で、特に伊豆地域においてしばしば見られる本震発生の2–3時間前に生じる静穏化は、大きな地震の直前の予知に有効な前兆現象と考えられる。