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EARTHQUAKE PREDICTION FROM MICRO-EARTHQUAKE OBSERVATION IN THE VICINITY OF WAKAYAMA CITY, NORTHWESTERN PART OF THE KII PENINSULA, CENTRAL JAPAN

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A systematic variation in the mode of seismicity is presented as a process accompanying earthquakes of magnitude M ranging from 4.7 to 5.2 occurring periodically with a recurrence time of 8-15 years in the vicinity of Wakayama city, northwestern part of the Kii Peninsula, Central Japan. Earthquakes of magnitude M larger than 4.5 can be reasonably classified into the representative major events in this area where few shallow earthquakes are of magnitude M larger than 5.0.

By a continuous micro-earthquake observation undertaken in the area, a distinct aseismic zone, a so-called seismicity gap, as well as a noticeable lineament of epicentral distributions across the seismicity gap have been confirmed to exist in the area. The seismicity gap, occupying an area of about 50 km^2, appears to be evident 2-3 years before a major earthquake occurrence showing a remarkable contrast to the surrounding area characterized by earthquake swarms. The occurrence of a precursory earthquake of magnitude M as large as 4.3 at the southern border of the seismicity gap is identified as a reliable indication of a subsequent major earthquake to be expected 6-7 months later on a preexisting fault across the seismicity gap.

1. *Introduction*

Small and micro-earthquakes in and around the Kii Peninsula, Central Japan have been precisely located by the Wakayama Micro-earthquake Observatory, E.R.I. (Earthquake Research Institute, Univ. of Tokyo) since the beginning of 1965. Micro-earthquake data thus obtained for a comparatively longer period of time of 13 years are available for the study of seismicity with special reference to an earthquake prediction scheme developed mainly on the basis of a systematic recurrence mode of seismic activity.

It has been found by means of micro-earthquake observation that remarkable swarms of shallow earthquakes in the vicinity of Wakayama city are concentrated within a layer between 3 to 8 km in depth. Earthquakes of magnitude M larger than 4.5 located within the layer can be regarded as major events since few shallow earthquakes are of magnitude M larger than 5.0.

Two distinct crustal interfaces at depths of about 3 and 8 km are derived in the area from a P wave travel time analysis by MIZOUE (1971) which give P wave velocities of 5.3 km/sec, 5.5 km/sec, and 5.8 km/sec for the first superficial (0–3 km), the second (3–8 km), and the third (8–20 km) layers, respectively. The absence of significant seismic activities in the first and the third layers show a remarkable contrast to the pronounced high seismic activities in the second layer.

In the majority of cases, shallow earthquakes in the area have fault plane solutions which are in harmony with wellknown regional stress field of EW compression in the upper part of the crust as described by SHIONO (1977). No geological information is available for the identification of a fault system from the micro-earthquake activity in the area. This is presumably due partly to fault displacements being too small as evaluated by ISHIDA (1974) and partly to a superficial alluvium layer covering the faults in the second layer. Despite the lack of geological confirmation, fault systems are inferred from the seismicity data set of precise epicentral locations through a pattern analysis procedure as described by MIZOUE and NAKAMURA (1976) to detect lineaments of micro-earthquake epicenters. Earthquakes in the area are mainly related to strike slip fault movements along the lineaments of either NE–SW or SE–NW direction which predominate in the northwestern part of the Kii Peninsula.

In the 13 years since the beginning of 1965 when the high magnification seismographic network was established, the following two catastrophic seismic activities took place in the vicinity of Wakayama city, namely the occurrence of an earthquake (M=4.8) on March 30, 1968 and an earthquake (M=4.7) on August 7, 1977. Remarkable aftershock activity was observed along a preexisting fault accompanying the two major events. An earthquake prediction scheme is developed on the basis of nearly identical characteristics of the two events as exemplified by a noticeable similarity of precursory events, aftershock sequences and fault movements. Seismicity data provided by J.M.A. (Japan Meteorological Agency) since the year 1884 are used to examine the recurrence nature of major events for a longer period of time. The long term variation of energy release for felt earthquakes at Wakayama Meteorological Observatory, J.M.A. suggests a periodical occurrence of major events in the vicinity of Wakayama city.

As a reliable indication of a coming major earthquake of magnitude larger than 4.7, a precursory event of magnitude M as large as 4.3 is located at the southern border of the seismicity gap 6–7 months before a major event occurrence. A comparison of sequences of seismic activity at different periods leads to the conclusion that the mode of seismicity in the vicinity of Wakayama city has a recurrence period of 8–15 years related to major earthquake occurrences. Earthquake energy accumulation in the seismicity gap before the occurrence of the precursory event permits an evaluation of the maximum magnitude of a forthcoming major earthquake. The occurrence of precursory earthquakes is interpreted as the approach of earthquake strain energy very close to the critical level, where the ultimate strength of the earth's crust may be exceeded, leading to seismic activity in the seismicity gap. The earthquake prediction scheme so far developed is described along the process applied for the case of the major earthquake which occurred on August 1977 in the neighbourhood of Wakayama city.

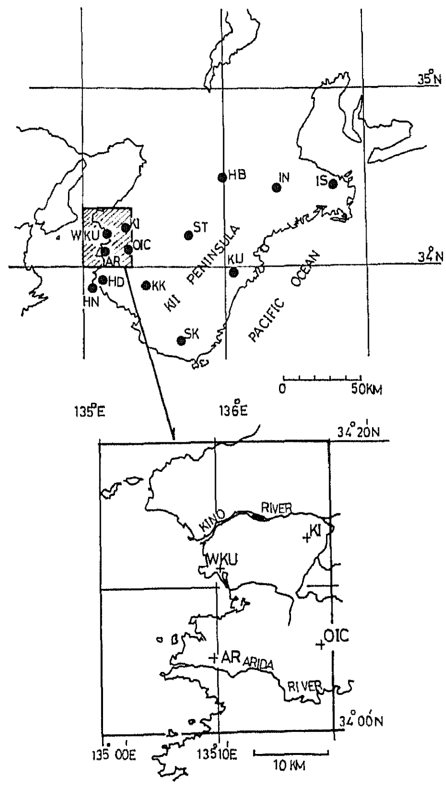

Fig. 1. Station locations of the seismological network of Wakayama Micro-earthquake Observatory, E.R.I. as indicated by closed circles (the upper figure) and enlarged map for northwestern part of the Kii Peninsula (the lower figure).

2. *Observational Data Acquisition*

The observational network of Wakayama Micro-earthquake Observatory, E.R.I., which covers the entire region of the *Kii Peninsula*, has been under operation since the year 1965. It consists of more than 11 stations equipped with high magnification short period seismographs, the velocity response of which is nearly flat between 1 Hz and 10 Hz. Station locations are shown in Fig. 1 and are listed in Table 1 together with their elevations. Overall frequency characteristics of seismographs at each of the stations are shown in Fig. 2.

Helical drums with a paper speed of 4 mm/sec comprise the conventional recording system used for routine observations. At Wakaura station (WKU), where the central office of the observatory is located, a time delay and triggering system fed into strip chart recorders in order to obtain high speed seismograms has been introduced since 1974 for WKU as well as for the telemetered stations Oishiyama (OIC), Kishinomiya (KI) and Hinomisaki (HN).

For extensive studies of the mode of seismicity related to unusual activity including the occurrence of major events with magnitude M larger than 4.5,

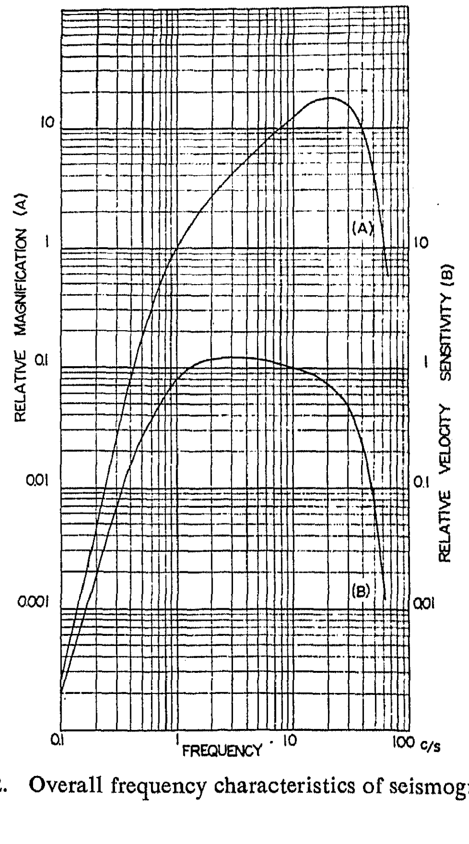

Fig. 2. Overall frequency characteristics of seismographs.

Table 1. Station locations of the seismological network of Wakayama Micro-earthquake Observatory, E.R.I.

No.	Station	Abbr.	Latitude	Longitude	Elevation (km)
			° ′ ″	° ′ ″	
1	Wakaura	WKU	34 11 16.5	135 10 22.7	0.011
2	Oishiyama	OIC	34 05 56.1	135 19 00.1	0.771
3	Arida	AR	34 05 09.2	135 09 42.2	0.041
4	Hinomisaki	HN	33 52 51.8	135 03 58.1	0.191
5	Kainokawa	KK	33 53 55.5	135 26 30.6	0.256
6	Shichikawa	SK	33 35 15.7	135 41 26.8	0.155
7	Sarutani	ST	34 10 34.4	135 44 45.6	0.470
8	Haibara	HB	34 30 10.0	135 59 36.1	0.390
9	Kumano	KU	33 58 10.0	136 03 30.6	0.255
10	Ise	IS	34 27 30.6	136 46 26.3	0.440
11	Kishinomiya	KI	34 13 19.3	135 18 00.0	0.075
12	Iinan	IN	34 26 46.6	136 22 29.2	0.155
13	Hidaka	HD	33 55 33.3	135 08 20.3	0.030

temporary stations have been installed in epicentral area in addition to the stations under routine operations. The temporary observations have significantly contributed to find the detailed features of seismicity in space and time, due mainly to an improvement in the accuracy of locations as well as in the detection capabilities of aftershocks.

Results of routine observations were summarized in the Seismological Bulletins of the observatory for the year 1965. Preliminary results of hypocentral locations and magnitude values of micro-earthquakes detected by the network are available in the form of unpublished computer outputs for the period 1965–1972.

As to earthquakes with magnitude greater than 2.5, locations and magnitude values are given in the form of a standardized earthquake list in the Quarterly Bulletins of the observatory for the period from October, 1974. Locations of earthquakes in and around the Kii Peninsula given by J.M.A. were redetermined by NAKAMURA (1975) for the period 1965–1974 resulting in great improvement in their accuracy mainly due to the high density network and the high accuracy timing system employed by the observatory. In the case of felt earthquakes in the neighbourhood of Wakayama city, precise locations given by NAKAMURA (1977) provide a basic data set for the study of seismicity in the area for the period 1965–1977.

3. *Fault Systems As Inferred from Epicentral Lineaments of Micro-Earthquakes*

No geological information is available for the identification of a fault system related to micro-earthquake activity in the northwestern part of the Kii Peninsula including the area of Wakayama city. Despite the lack of geological confirmation, fault systems in the area are inferred from the seismicity data set of precise epicentral locations through a pattern analysis procedure as given by MIZOUE and NAKAMURA (1976) to detect lineaments of micro-earthquake epicenters.

The epicentral pattern analysis procedure consists of the following two methods:

1) an epicentral linkage pattern analysis method for a relatively short interval of time and
2) an epicentral zonal pattern analysis method with magnitude classifications.

In the first method, epicentral data plotted on a map for every half month give the basic material for reproducing characteristic epicentral linear patterns. The data processing consists mainly in making linkage systems of consecutive epicenters for each sequence of seismic activity. The method provides an effective technique to enhance lineaments in an epicentral distribution depending on the frequency of recurrence of common patterns.

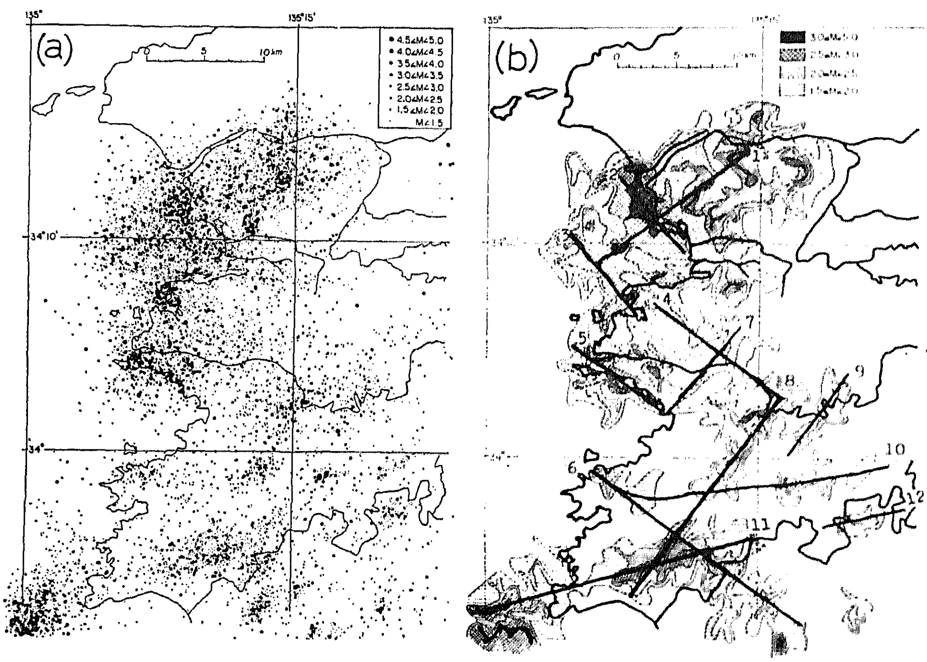

Fig. 3. (a) Micro-earthquake distributions for the period of January, 1965–August, 1972, and (b) fault systems in the north-western part of the Kii Peninsula as inferred from the epicentral lineaments of micro-earthquakes as numbered from 1 to 12 with an epicentral zonal pattern by magnitude classifications.

In the second method, epicentral data for a period of more than a few years are classified into groups with respect to various magnitude ranges. In each of the magnitude ranges, earthquakes are located in separated areas where epicenters are concentrated with a high density after isolated smaller patches of epicentral groups are eliminated. The epicentral distribution thus obtained can be represented as a contour map showing the area where earthquakes of a given magnitude range are distributed. The method provides an effective technique to enhance the epicentral linear patterns which accompany major earthquakes in a seismic region for a comparatively long interval of time.

In spite of the EW trend of the principal geological structures in the Kii Peninsula, the application of the procedure to the observational data indicates that NE-SW and conjugate NW-SE epicentral lineations are predominant in the region. From seismicity data for the period of 1965–1972 as shown in Fig. 3(a), fault systems are inferred from the epicentral lineaments of micro-earthquake numbered from 1 to 12 as shown in Fig. 3(b), which include the remarkable lineament (numbered as 1) across the seismicity gap coincident with the aftershock distribution accompanying the two previously mentioned major earthquakes in the vicinity of Wakayama city.

4. *Comparison of the Mode of Seismicity Associated with Major Earthquakes*

4.1 *Seismicity gap and earthquake energy accumulation*

In the neighbourhood of Wakayama city, the mode of epicentral distribution of micro-earthquakes represents a characteristic zonal arrangement of two earthquake swarm areas separated by a seismicity gap between the two. The seismicity gap is well preserved in a stable mode for 2–3 years until the occurrence of a major earthquake in the seismicity gap produces an abrupt change of the mode of seismicity. Seismic activity accompanying a major earthquake shows a gradual decrease with time over a period of several years. This decrease of seismic activity represents a clear contrast to the stationary swarm activity in the adjoining areas. As seismic activity decreases after a major earthquake occurrence, the seismicity gap recovers its form with slight differences from the previous one depending on the changes of the mode of the seismic activity in the adjoining areas.

Existence of the seismicity gap was confirmed for the first time by a temporary network observation with 18 stations distributed in the northwestern part of the Kii Peninsula undertaken by a joint research project of universities for the period from August 10 to 25, 1965 as described by WATANABE and KUROISO (1967). As shown in Fig. 4(a) no predominant seismic activity was detected in the seismicity gap by the routine network observation of Waka-

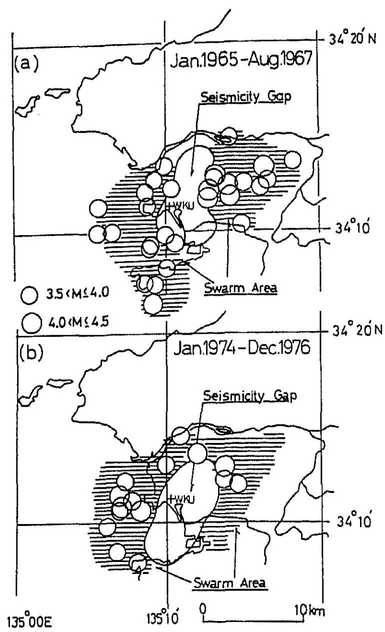

Fig. 4. (a) Seismicity gap for the period from January 1965 to August 1967. (b) Seismicity gap for the period from January 1974 to December 1976. Open circles indicate earthquakes with M more than 3.5. Hatched areas are characterized by the stationary swarm activity.

yama Micro-earthquake Observatory from 1965 up to the time of the occurrence of the precursory earthquake ($M=4.3$) of September 29, 1967 and its accompanying aftershocks. The seismicity gap temporarily disappeared after the catastrophic event for a period of about 5 years.

Reappearance of the seismicity gap was identified from the year 1974 until the precursory earthquake ($M=4.3$) of January 16, 1977 filled the seismicity gap with its aftershocks again as shown in Fig. 4(b). The recurrent nature of the appearance and disappearance of the seismicity gap is clearly related to the periodic occurrence of major earthquake located underneath the center of Wakayama city. Existence of the seismicity gap can be interpreted as a manifestation of a subsequent major event to be expected through the process of earthquake energy accumulation in the seismicity gap.

The cumulative sum of earthquake energy release in the adjoining swarm areas increases at a nearly constant rate with time showing a noticeable contrast from a discontinuous stepwise increase of earthquake energy release along the preexisting fault as inferred from an epicentral lineament across the seismicity gap as shown in Fig. 5. The nearly constant rate of the earthquake

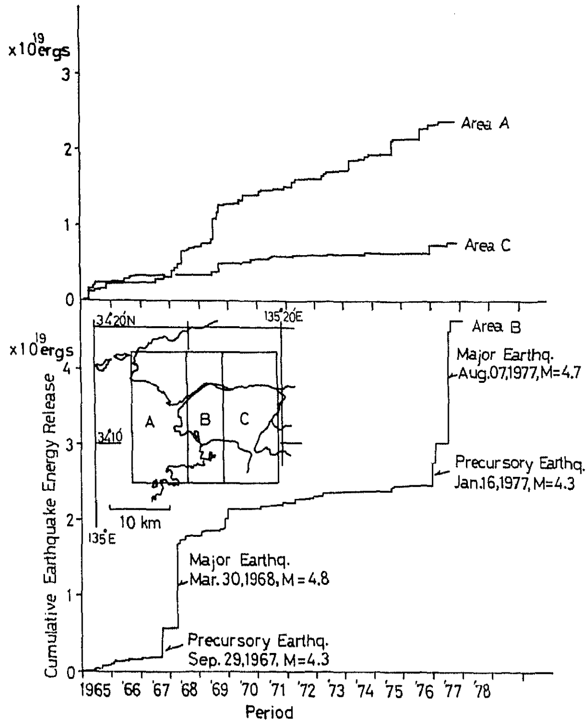

Fig. 5. Cumulative sum of earthquake energy release in the area of (B) including the seismicity gap as compared to those in the adjoining swarm areas of (A) and (C). The two predominant steps on March 1968 and on August 1977 correspond to the occurrence of the major earthquakes.

energy release in the swarm areas, with an appropriate assumption regarding the process of earthquake energy accumulation, can satisfactorily be explained by introducing an equilibrium condition, i.e., earthquake energy release is compensated by the same amount of earthquake energy accumulation within an interval of time far less than the recurrent interval for major earthquake occurrences.

In the swarm area to the west of the seismicity gap, an averaged rate of earthquake energy release δE is estimated to be about 0.9×10^{18} ergs/year from the seismicity data for the period from 1965 to 1976. It is concluded from the evaluation that the earthquake energy E to be released by a forthcoming major earthquake and its accompanying aftershocks can be approximated by the cumulative sum of earthquake energy released in the swarm areas as defined by the equation,

$$E = x \cdot \delta E \cdot T \, ,$$

where the time factor T should be taken as the recurrent interval of major earthquakes. The coefficient x is estimated as 0.8, if it is assumed that an earthquake of magnitude M as large as 4.8 occurs with an interval of 14 years, considering the interval of 14 years between the two major earthquakes of March 22, 1954 ($M=4.7$) and of March 30, 1968 ($M=4.8$).

4.2 Identification of precursory earthquakes

As a reliable indication of a coming major earthquake of magnitude M 4.7–5.2, a precursory event of magnitude M as large as 4.3 takes place 6–7 months before a major earthquake occurrence in the area of Mt. Nagusa, located at the southern border of the seismicity gap. Precursory earthquakes at different periods are found to be nearly identical with respect to their hypocentral locations, magnitude values, aftershock sequences and focal mechanisms. The occurrence of a precursory earthquake can be expected when the energy accumulation in the seismicity gap exceeds the critical level of about 0.7×10^{19} ergs, which is approximately equivalent to the energy released by an earthquake of magnitude M as large as 4.7.

On September 29, 1967 a remarkable earthquake ($M=4.3$) took place in the area of Mt. Nagusa (Fig. 6(a)). The earthquake was accompanied by more than 350 aftershocks covering an area of about 2×2 km^2. Following the earthquake, after an interval of 182 days, the major earthquake ($M=4.8$) occurred on March 30, 1968 in the seismicity gap (Fig. 11(a)). About 8.8 years after the major earthquake occurrence on March 30, 1968, an earthquake ($M=4.3$) occurred on January 16, 1977 in the Mt. Nagusa area at the

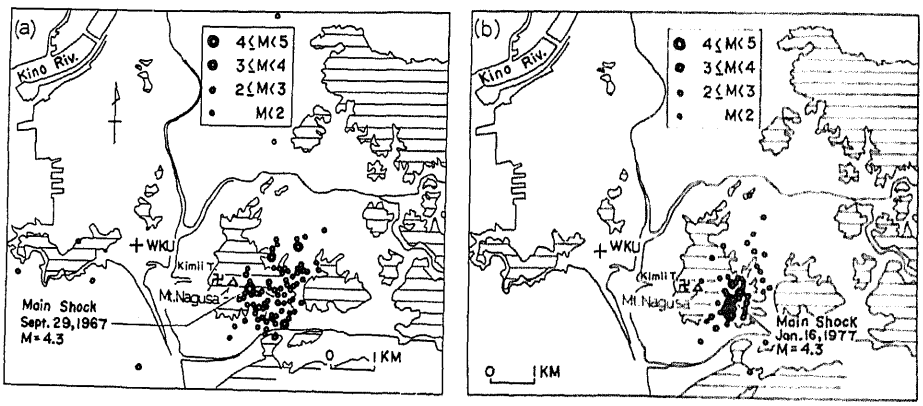

Fig. 6. (a) Locations of the precursory earthquake ($M=4.3$) of September 29, 1967 and its accompanying aftershocks. (b) Locations of the precursory earthquake ($M=4.3$) of January 16, 1977 and its accompanying foreshocks and aftershocks. Locations of WKU station and Mt. Nagusa are shown by a cross and a triangle. Chrystalline rocks are exposed in the hatched areas.

same place where the precursory earthquake of September 29, 1967 was located (Fig. 6(b)).

The earthquake (M=4.3) of January 16, 1977 was accompanied by at least 35 foreshocks, different from the previous event in this respect, as well as by more than 400 aftershocks. As shown in Figs. 6, 7, and 8, the earthquake was identified as a precursory earthquake because of its nearly identical characteristics of location, magnitude value, aftershock sequence and focal mechanism to the previous precursory event of September 29, 1967 which preceded the major earthquake (M=4.8) of March 30, 1968. It is noteworthy that the focal mechanism of the precursory events with vertical slip

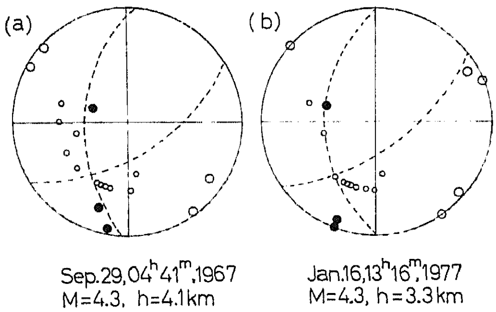

Fig. 7. Initial P wave motion data, showing dilatation with closed circles, and compression with open circles, projected on the upper hemisphere of Wulff's net for the precursory earthquakes of (a) September 29, 1967 and (b) January 16, 1977.

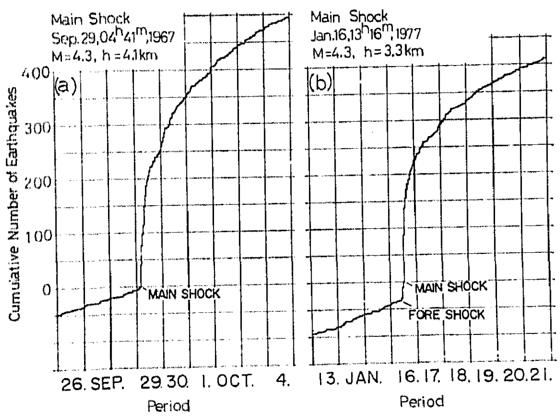

Fig. 8. Cumulative sum of the number of earthquakes for the sequence related to the precursory earthquakes of (a) September 29, 1967 and (b) January 16, 1977.

components is of a different type from the strike slip movements observed ordinarily in the area.

Earthquake energy accumulation in the seismicity gap is estimated to be 0.63×10^{19} ergs at the time of the occurrence of the precursory earthquake ($M=4.3$) of January 16, 1977. The interval T of 8.8 years since the occurrence of the major earthquake ($M=4.8$) of March 30, 1968 is applied in the evaluation by using the equation given in the previous section. Judging from the amount of the earthquake energy accumulation, it was expected that another major earthquake with magnitude M of about 4.7 would take place on the preexisting fault across the seismicity gap about 6 months after the occurrence of the precursory earthquake of January 16, 1977. The foreseen major earthquake occurred on August 7, 1977 with magnitude M 4.7 on the NE portion of the preexisting fault across the seismicity gap (Fig. 11(b)). The interval of 202 days between the precursory earthquake of January 16, 1977 and the major earthquake of August 7, 1977 compares favorably with the previous case of 182 day interval.

4.3 Major earthquakes and accompanying aftershocks

In the 13 years since 1965 when the high magnification network was established, major seismic activity took place twice on a preexisting fault across the seismicity gap in the area of Wakayama city, namely the occurrence of the earthquake ($M=4.8$) of March 30, 1968 and the earthquake ($M=4.7$) of August 7, 1977. As described in the previous section, a precursory earthquake occurred preceding both of the two earthquakes described in the previous section. These two earthquakes, themselves large enough to be classified as major earthquakes group in the area, were accompanied by remarkable aftershock activity. In the second case, the main shock was preceded by foreshocks. The seismic sequences related to the major events in the seismicity gap have entirely different processes from those of earthquake swarms in the areas adjoining the seismicity gap.

In the first case the following results were obtained by Wakayama Microearthquake Observatory, E.R.I. for the origin of the main shock of March 30, 1968:

Origin time$=04^h04^m31^s81$, Magnitude $M=4.8$,
Epicentral coordinates: $X=17.73$ km, $Y=23.48$ km,
Focal depth $H=4.61$ km,

where epicentral coordinates X and Y are measured towards east and north, respectively from the point (135°E, 34°N). The main shock, which registered intensity IV on the J.M.A. scale at Wakayama Meteorological Observatory (WKY), was felt at distances within about 100 km from the epicenter. The focal mechanism of the main shock as derived from the initial P wave motion represents a typical strike slip fault movement under the pronounced regional EW compressional stress field as shown in Fig. 9(a).

No evident foreshocks were detected, but, more than 650 aftershocks, including 3 events of magnitude M larger than 3.5, were observed. Remarkable aftershock activity continued for about one week. The cumulative sum of the number of earthquakes at Wakaura station (WKU) for the sequence in

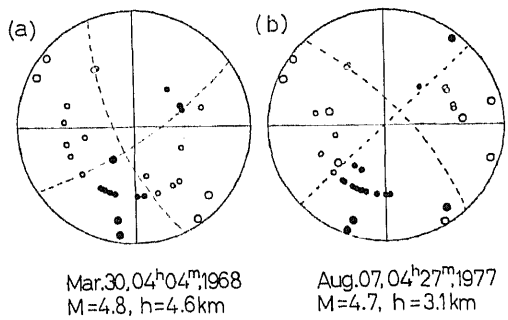

Fig. 9. Initial P wave motion data, showing dilatation with closed circles, and compression with open circles, projected on the upper hemisphere of Wulff's net for the major earthquakes of (a) March 30, 1968 (M=4.8) and of (b) August 7, 1977 (M=4.7).

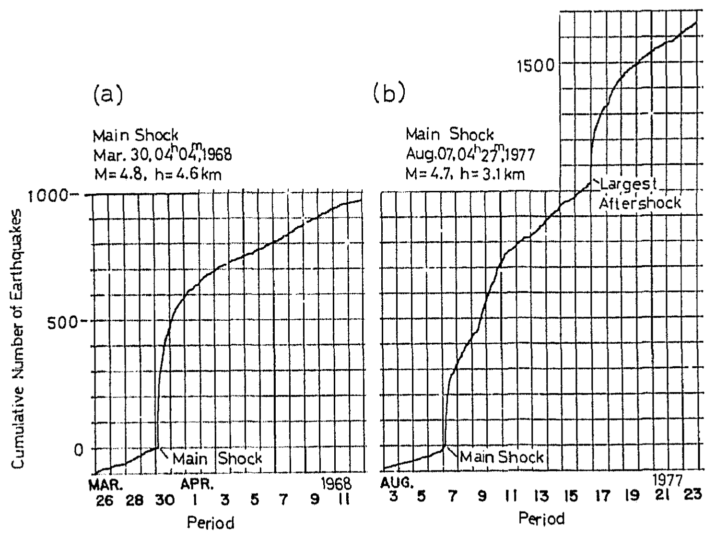

Fig. 10. Cumulative sum of the number of earthquakes at Wakaura station (WKU) for the sequence in the period covering the aftershock activity accompanying the major earthquakes of (a) March 30, 1968 (M=4.8) and of (b) August 7, 1977 (M=4.7).

the period covering the aftershock activity is given in Fig. 10(a). The NE-SW trend of the aftershock distribution is in harmony with the result of the focal mechanism analysis for the main shock, suggesting a right lateral strike slip fault movement. The aftershocks extended unilaterally on the SW portion of the preexisting fault about 5.0 km in length towards the SW direction starting from the middle part of the seismicity gap where the main shock is located. The aftershock distributions are illustrated in Fig. 11(a).

In the second case, the following results were obtained as in the previous case for the origin of the main shock of August 7, 1977, i.e.,

Origin time $=04^{h}27^{m}16^{s}88$, Magnitude $M=4.7$,

Epicentral coordinates: $X=19.89$ km, $Y=24.02$ km,

Focal depth $H=3.05$ km.

The epicenter of the main shock is located at about 2.3 km east of the epicenter of the earthquake ($M=4.8$) of March 30, 1968. The main shock, which registered intensity IV on the J.M.A. scale at WKY, was also felt at distances within about 70 km from the epicenter as in the case of the earthquake ($M=4.8$) of March 30, 1968. The focal mechanism of the main shock from the initial P wave motion is almost identical to that for the previous major earthquake ($M=4.8$) of March 30, 1968 as shown in Fig. 9(b).

The main shock was preceded by at least 26 foreshocks including a remarkable event of magnitude M 3.6. The sequence of the foreshocks is given in Fig. 10(b) and epicenters of the foreshocks and the main shock are plotted in Fig. 11(b). The foreshock activities started at 13.3 hours before the occurrence of the main shock. It seems to be possible to discriminate the foreshocks, if any, from stationary swarm activity when the characteristics of the foreshock sequence are specifically examined. The foreshock activity in the

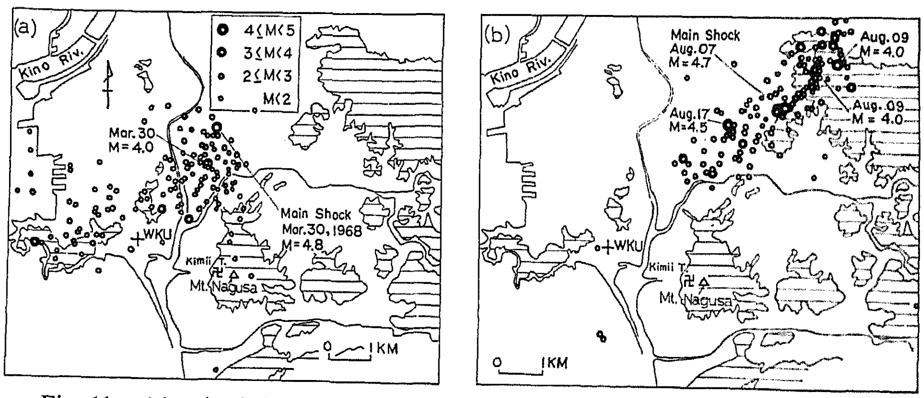

Fig. 11. Aftershock distributions accompanying the major earthquakes of (a) March 30, 1968($M=4.8$) and (b) August 7, 1977 ($M=4.7$). Locations of WKU station and Mt. Nagusa are shown by a cross and a triangle. Chrystalline rocks are exposed in the hatched areas.

seismicity gap is characterized by an acute concentration of relatively large earthquakes in the restricted zone on the preexisting fault associated with major earthquakes. An abrupt decrease of foreshock activity at about 1 hour before the occurrence of the main shock provides information for the most extreme case of short range prediction of major earthquakes in the area.

More than 1,600 aftershocks, including 5 events of magnitude M larger than 3.5, were observed. Remarkable aftershock activity continued for about two weeks. As shown in Fig. 10(b), the cumulative sum of the number of earthquakes for the period covering the aftershock activity at Wakaura station (WKU) is divided into three distinct sequences corresponding to the occurrence of the main shock and large aftershocks of magnitude M larger than or equal to 4.0 on August 9 and 17, 1977.

In the first sequence of aftershock activity from $4^{h}27^{m}$, August 7 to $12^{h}38^{m}$, August 9, the distribution of aftershocks was concentrated within a distance of about 1 km from the epicenter of the main shock showing a doubtful pattern of NE-SW trend. In the second sequence from $12^{h}39^{m}$, August 9 to $0^{h}31^{m}$, August 17, the center of the aftershock activity moved towards north-east by about 1.5 km occupying the northeastern end of the aftershock area. In the very early stage of the sequence, two large aftershocks of magnitude M 4.0 occurred successively. In the third sequence from $0^{h}32^{m}$, August 17, the center of the aftershock activities moved towards south-west by about 3.5 km with the largest aftershock of magnitude M 4.5. The aftershock area in the third sequence occupied the south-west end of the aftershock area.

Through the whole sequence of about two weeks of aftershock activity, the aftershock distribution assumed a linear pattern of NE-SW trend about 5.0 km in length as shown in Fig. 11(b). Comparing the linear pattern with

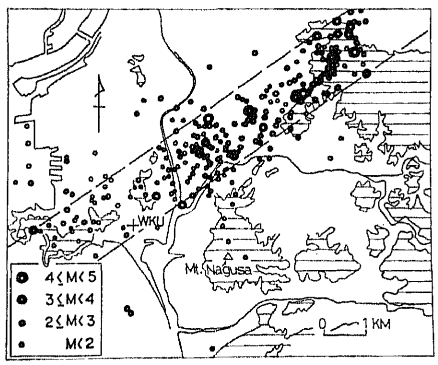

Fig. 12. The pattern of epicentral lineament as revealed by aftershocks accompanying the two major earthquakes of March 30, 1968 and August 7, 1977.

the focal mechanisms of the main shock and its accompanying large aftershocks, the NE-SW trend of the aftershock distribution shows good agreement with one of the nodal lines for the initial P wave motions of these earthquakes, suggesting a right lateral strike slip fault movement.

As illustrated in Fig. 12, the aftershock distributions accompanying the two major earthquakes in the different periods of March 30, 1968 and of August 7, 1977 represented a pattern of epicentral lineament of about 10.0 km in length along the preexisting fault across the seismicity gap. The preexisting fault is found to be divided into the two portions activated in the different periods. Focal mechanisms of the two major earthquakes both reflect the predominant effect of the tectonic stress field of EW compression on the right lateral strike slip fault movements.

5. *Periodic Sequence of Seismic Activity from Felt Earthquake Information*

In addition to the seismicity data currently obtained by the micro-earthquake observation, the felt earthquake sequence is presented in terms of the number of events as well as earthquake energy release to see longer term variations of seismic activities. Unmistakable peaks in the number of earthquakes felt at Wakayama Meteorological Observatory shown in Fig. 13(a)

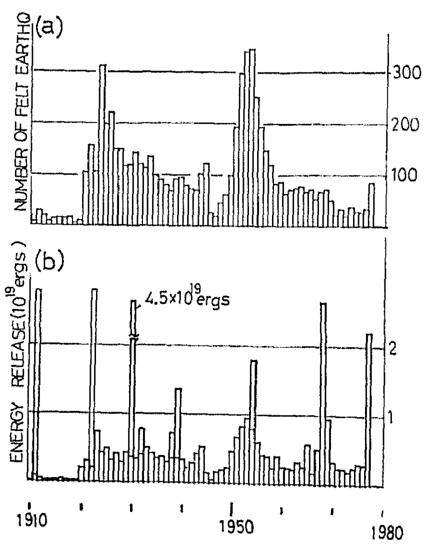

Fig. 13. (a) Number of earthquakes felt at Wakayama Meteorological Observatory (WKY), J.M.A. for the period from 1910 to 1977. (b) Energy released by earthquakes felt at Wakayama Meteorological Observatory (WKY), J.M.A. for the period from 1910 to 1977.

are found for the period from 1920 to 1930 and from 1948 to 1959 reflecting both effects of regional activities in and around the Kii Peninsula and local activities restricted to the neighbourhood of Wakayama city. It should be pointed out that the two outstanding peaks in the number of felt earthquakes are not necessarily related to the increase in the number of major earthquakes in the vicinity of Wakayama city.

As illustrated in Fig. 13(b), longer term variations of seismic activities in earthquake energy release support the idea of a periodic occurrence of major earthquakes in the seismicity gap with an interval of 8–15 years. When the two peaks in 1968 and 1977 for major events are compared with the similar pattern of other peaks in earlier periods, it can be suggested from the amplitudes of predominant peaks that the magnitude M of major events has been in the range from 4.7 to 5.2. Including less reliable informations of felt earthquakes in earlier periods, the occurrence of major earthquakes located in the vicinity of Wakayama city can be traced back to the event of September 5, 1884 as given in Table 2. Periodic occurrence of major earthquakes for the last 93 years since 1884 is shown by taking the interval of earthquakes with magnitude M larger than or equal to 4.7.

Table 2. Major earthquakes ($M \geq 4.5$) in the vicinity of Wakayama city for the period from 1884 to 1977.

No.	Year	Date	Magnitude (M)	Period	Interval T (year)
1	1884	Sep. 5	>4.5		
				Sep. 5, 1884–Mar. 15, 1898	13.5
2	1898	Mar. 15	4.9		
3	1900	Feb. 2	4.9	Mar. 15, 1898–Jan. 5, 1910	11.8
4	1910	Jan. 5	5.1		
				Jan. 5, 1910–Mar. 10, 1922	12.2
5	1922	Mar. 10	5.1		
6	1922	Mar. 11	4.8	Mar. 10, 1922–Feb. 11, 1930	7.9
7	1930	Feb. 11	5.2		
8	1932	Jan. 11	4.5		
9	1938	Oct. 13	4.5	Feb. 11, 1930–Jan. 20, 1939	8.9
10	1939	Jan. 20	4.8		
				Jan. 20, 1939–Mar. 22, 1954	15.2
11	1954	Mar. 22	4.7		
				Mar. 22, 1954–Mar. 30, 1968	14.0
12	1968	Mar. 30	4.8		
				Mar. 30, 1968–Aug. 7, 1977	9.3
13	1977	Aug. 7	4.7		
14	1977	Aug. 17	4.5		

6. *Summary and Conclusion*

As a practical method of earthquake prediction, a process related to major earthquake occurrence is systematized from the view-point of periodic change in the pattern of seismicity. Representative reference modes of seismicity can be defined in the standardized recurrence process of major earthquake occurrence. Observed modes of seismicity from precise location of micro-earthquakes can be compared with the reference modes in the standardized process. When a particular reference mode is specified to be identical to the observed mode, forthcoming seismic process can be predicted for a time range along the line of the standardized process.

Seismicity in the neighbourhood of Wakayama city is systematized as a recurrent process with successive stages in the modes of 1) the seismicity gap, 2) the precursory event occurrence, and 3) or 3′) the major event occurrence, respectively. The recurrence process in the modes of seismicity is summarized along the following lines as schematically illustrated in Fig. 14.

In the first stage, modes of epicentral distribution of micro-earthquakes represent a characteristic zonal arrangement of two swarm areas (A) and (C) separated by an intervening area of seismicity gap (B). A distinct lineament $\overline{PQ}$ of micro-earthquakes runs across the seismicity gap with its strike in the NE-SW direction. Existence of the seismicity gap can be interpreted as a

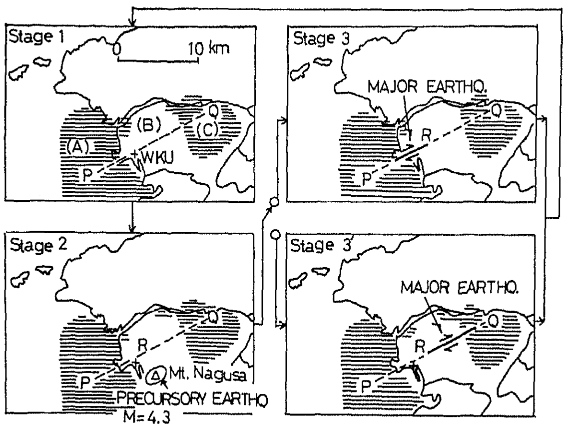

Fig. 14. Schematical representation of the standardized process of seismicity with successive stages in the modes of 1) appearance of seismicity gap, 2) precursory event occurrence, and 3) or 3′) major event occurrence. Swarm areas are designated as (A) and (C) and the seismicity gap is designated as (B). Preexisting fault $\overline{PQ}$ runs across the seismicity gap. Major earthquake occurrences are related with the alternate movements along the fault segment $\overline{PR}$ and $\overline{PQ}$.

manifestation of a subsequent major event taking place through a process of strain energy accumulation over the interval of 8 to 15 years in the seismicity gap. The preexisting fault system related to the occurrence of a major event is inferred from the lineament of micro-earthquakes across the seismicity gap. The seismicity gap is well preserved in a stable mode for more than 3 years until the occurrence of a major event produces an abrupt change of the mode of seismicity by removing the seismicity gap.

In the second stage, a precursory event of magnitude M as large as 4.3 takes place about 6–7 months before a major event occurrence in the area of Mt. Nagusa, located at the southern border of the seismicity gap. The occurrence of the precursory event can be expected when the strain energy accumulation in the seismicity gap exceeds a critical level. The magnitude of the forthcoming major earthquake is estimated from the strain energy accumulation at the time of the occurrence of the precursory earthquakes for the interval since the occurrence of the previous major earthquake. Precursory earthquakes can be identified from their characteristic hypocentral locations, magnitude values, aftershock sequences and focal mechanisms.

In the third stage, a major earthquake of magnitude M as large as 4.7–5.2 takes place in the seismicity gap with a recurrent time of 8–15 years accompanied by remarkable aftershock activity which lasts one or two weeks. The aftershock distribution makes a linear pattern of epicenters with a NE-SW trend coincident with the preexisting fault as inferred from the lineament of stationary micro-earthquake activity. The NE-SW trend of the aftershock distribution is in harmony with the focal mechanism of the major earthquake suggesting a right lateral strike slip fault movement.

The major earthquake of magnitude M as large as 4.7–4.8 is accompanied by aftershocks distributed on either the south-western portion $\overline{PR}$ or the north-eastern portion $\overline{PQ}$ of the preexisting fault $\overline{PQ}$. On the other hand, it seems to be highly probable that a major earthquake of magnitude M as large as 5.1–5.2 will be accompanied by a fault movement along both portions of $\overline{PR}$ and $\overline{RQ}$ at the same time. In such a case, as presumabley occurred in the major earthquake ($M=5.2$) of February 11, 1930, the area affected by the major earthquake will extend along the preexisting fault $\overline{PQ}$ across the seismicity gap as shown in Fig. 14.

Temporary disappearance of the seismicity gap for about 5 years is observed after the occurrence of a major earthquake and its accompanying aftershocks. Reappearance of the seismicity gap for the period preceding the occurrence of a major earthquake by 2–3 years is confirmed as an indication that the seismicity mode in the vicinity of Wakayama city returns to the first stage of the recurrent seismicity process.

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