SEISMIC ACTIVITY IN THE NORTHERN PART OF THE KINKI DISTRICT AND RELATED PROBLEMS (I)

—EARTHQUAKE SWARM ACCOMPANYING THE WACHI EARTHQUAKE OF AUGUST 18, 1968—

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(Received November 18, 1969)

Abstract

An earthquake swarm accompanying the Wachi earthquake of August 18, 1968 was investigated in reference to the time-variation of seismic activity. About 9,000 events observed from February 1968 to April 1969 were classified into three stages, namely, the foreshock sequence, and the first and second parts of the aftershock sequence, according to the mode of their occurrence. These sequences were eventually characterized by the respective portions with a linear, a logarithmic and an exponential relation in the curve of cumulative sum of their daily counts.

As the result of analyses, significant differences in the focal distribution, the focal mechanism and the value of b in the Gutenberg-Richter's formula could be ascertained between the sequences. This fact may indicate that the property of the medium or the regional stress acting on the focal area varied significantly with respect to the sequences. Moreover, a detailed analysis concerning the foreshock sequence showed the interesting fact that the fault of the first major shock of February 14, 1968 lay just on a branch of the Mitoke Fault which was discovered recently by the use of geological methods, whereas during the later part of this sequence the foci of minor shocks gathered at the fault of the main shock, as if they had been prepared for the main rupture of the focal area, thus both of the major faults might form a conjugate set with an angle of intersection of about 75°.

1. Introduction

As can be inferred from the history of earthquakes, the Kinki District may be classified as being one of the seismically active regions in Japan. However, the recent seismicity including minor shocks shows that almost no earthquakes are occurring in the northern part of this district, especially in the vicinity of coast line of the Sea of Japan, despite the fact that severe earthquakes have frequently taken place in this region during the past 1,000 years.

As recently pointed out by one of the present authors (Watanabe [1969]), the earthquakes occurring in the northern part of this district have had a peculiar characteristic in regard to their mode of occurrence. Two prominent shocks are apt to occur successively in a small restricted area within a short time interval, say, several months or about a year; therefore, they were tentatively called "twin earthquakes". Such prominent shocks, however, must have been followed by many subsequent shocks, and an earthquake swarm consisting of them all should have been observed, supposing the focal area to have been covered by a network of stations with highly sensitive seismographs.

With these considerations in mind, we intend to carry out temporary observations of earthquakes with highly sensitive seismographs in such places as the focal areas of the Tango earthquake of 1927 and the Tajima earthquake of 1925 in order to see how the affairs in the past might be related to the present seismicity.

As a preliminary report of these observations, several problems related to the seismicity will be considered in the following sections by using an earthquake swarm associated with the Wachi earthquake of August 18, 1968.

2. Separation of the earthquake swarm

An earthquake swarm occurred from February 1968 to April 1969 in the north part of Kyoto Prefecture, Central Japan. Since the epicenters were surrounded by a network of observation stations of routine basis, we could determine their foci with sufficient accuracy to see the change of focal distribution with time. By using seismograms of the nearest station to the focal region, we could count the daily number of shocks of M as small as zero without exception, even though the foci of these weaker events were not avaliable.

The main shock occurred on August 18, 1968 and was large enogh to be felt all over the Kinki District and sufficient to crack foundations in the vicinity of the epicenter. Its magnitude and focal depth were estimated as 5.6 on the Richter's scale and 10 km respectively. We observed about 9,000 subsequent shocks at one of the routine stations about 25 km distant from the epicenter by the end of April 1969. Prior to this, a major shock of M 4.5 occurred on February 14, 1968 close to the focus of the main shock and was followed by about 600 subsequent minor shocks until the outbreak of the main shock.

Fig. 1 shows the cumulative sum of their daily counts plotted against time throughout the swarm. The stationary seismic activity near the focal region was properly excluded in plotting the figure as shown later. The arrows in this curve denote the occurrence of the prominent events, say, the first major shock and the main shock and it is noticed that the main shock divides this
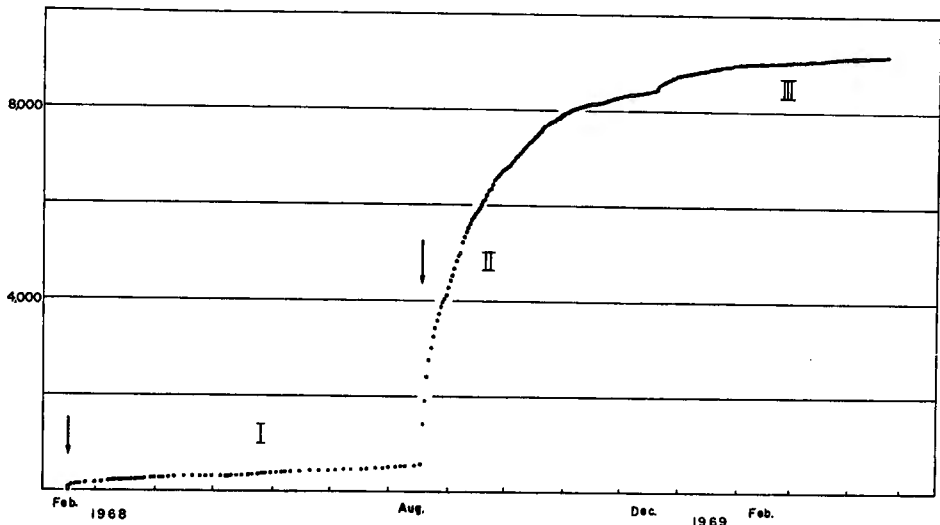
Fig. 1. Cumulative sum of daily counts of shocks. The respective arrows indicate the occurrences of the first major shock and the main shock.
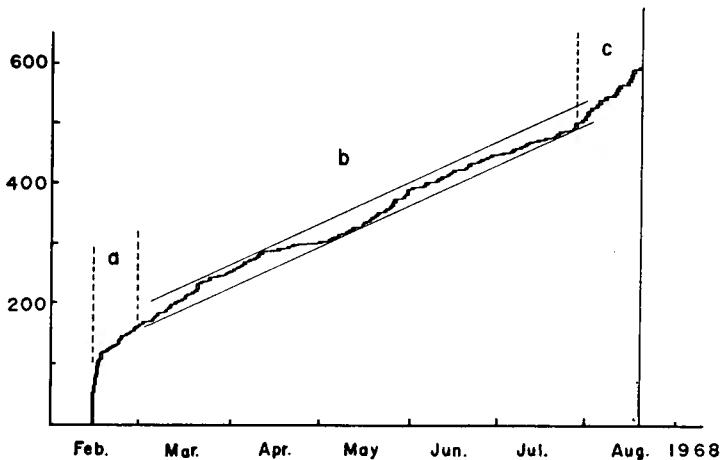

Fig. 2. Cumulative sum of strain released by the minor shocks during the first stage. The portions denoted by a, b and c would coincide with the three stages in rock creep.

swarm into sequences of different types. Therefore, let us consider as a first step this swarm being seperated into two stages. As may be seen from this plot, the mode of seismic activity for the first stage (denoted by I) is quite similar to the foreshock sequence which was previously stated by one of the present authors (Watanabe [1964]) in the case of the other swarms occurring in this district. The linear part of the plot is sure to prevail from the occurrence

of the first major shock and to continue until the outbreak of the main shock, whereas the following part may well represent the mode of seismic activity for the aftershock sequence as fully discussed by many authors. Going into further detail this stage may be divided into two portions according to the slight fold in the middle of this stage, even though no prominent events can be found. These portions divided in this way may certainly correspond to the logarithmic and the exponential parts of the aftershock sequence as proposed by Benioff [e.g., 1951], therefore, let us call them the second stage (II) and the third stage (III) respectively.

In order to see in more detail the characteristics peculiar to the foreshock sequence, we described the strain release curve somewhat minutely in Fig. 2 instead of the cumulative sum of daily count. As inferred from this graph, the linear relation is remarkable also in this expression and the three portions denoted by a, b and c may coincide with the so-called transient, steady state and accelerating creeps of rocks subjected to high pressure.

On the basis of the fact that this swarm is well separated into the three stages according to the mode of occurrence of events, we will consider the questions, in the following sections, as to how the focal distribution, the focal mechanism and some related phenomena did vary with respect to the stages and how they related to each other.

3. Focal distribution and its relation to the Mitoke Fault

The locations of shocks were determined by a graphical method, using P arrival time and $S-P$ time, on the assumptions that most of the foci would be located in a homogeneous semi-infinite medium with V_p of 5.8 km/sec and V_p/V_s of 1.72. Taking the observational error into consideration, this method may give the most probable hypocenters because the epicenters were covered by a network of highly sensitive seismographs. Figs. 3 and 4 express the epicentral distributions for the period before the occurrence of the first major shock and for the first stage respectively. It is confirmed from both of the distributions that there was no shock in the focal region of this swarm before the first stage and that the stationary activity remained almost unvaried. We can certify also the fact that this pattern of seismic activity is peculiar to this region, from the results of routine observations (see, e.g., Kishimoto and Hashizume [1966]). The abrupt appearance of new activity shown in Fig. 4, therefore, can be easily distinguished from the stationary one.

The epicentral distributions of this swarm for the individual periods and stages are listed in Fig. 5 in order to see the change of distribution with time. Focal depths were also obtained by the same method and they were wholly
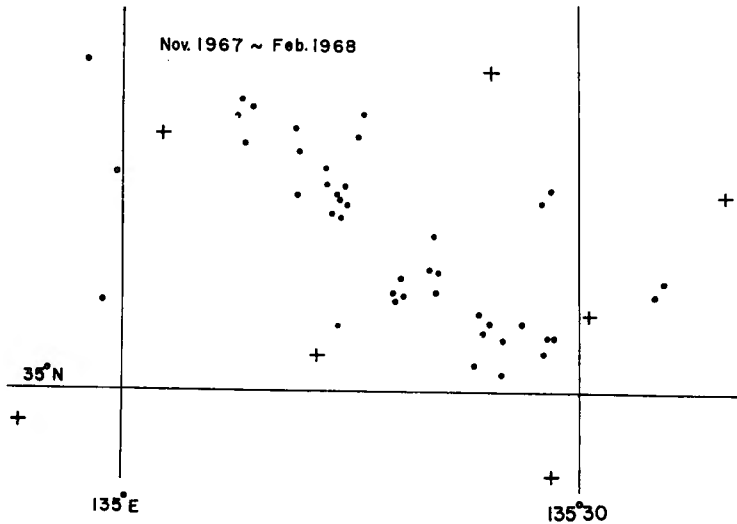
Fig. 3. Epicentral distribution of microearthquakes that occurred in this region during the three months before the occurrence of the first major shock. This may be construed as a stationary activity peculiar to this region, as shown in the text.
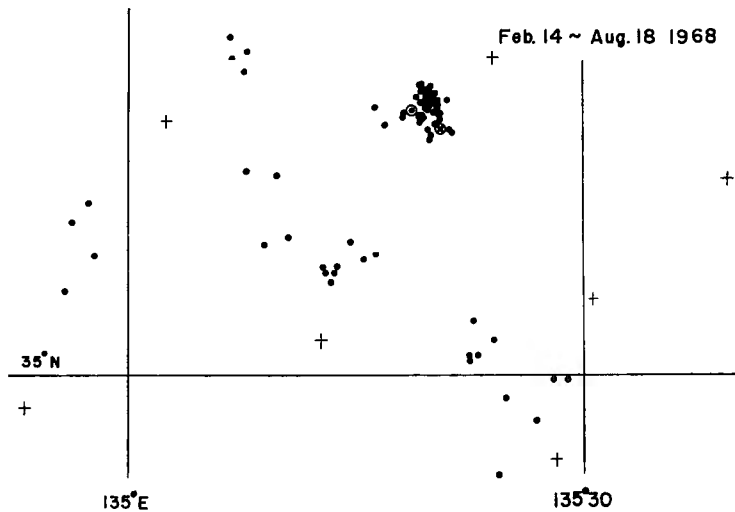
Fig. 4. Epicentral distribution of all shocks that occurred in this region during the first stage.

located within a range from 5 km to 12 km, although they are not illustrated here. As may be seen from the upper figures, it seems that epicenters are gathering around the focus of the main shock (centered open circle) during the period corresponding to the transient portion denoted by **a** in Fig. 2, while during the steady state portion (**b**) they were distributed uniformly in a restricted
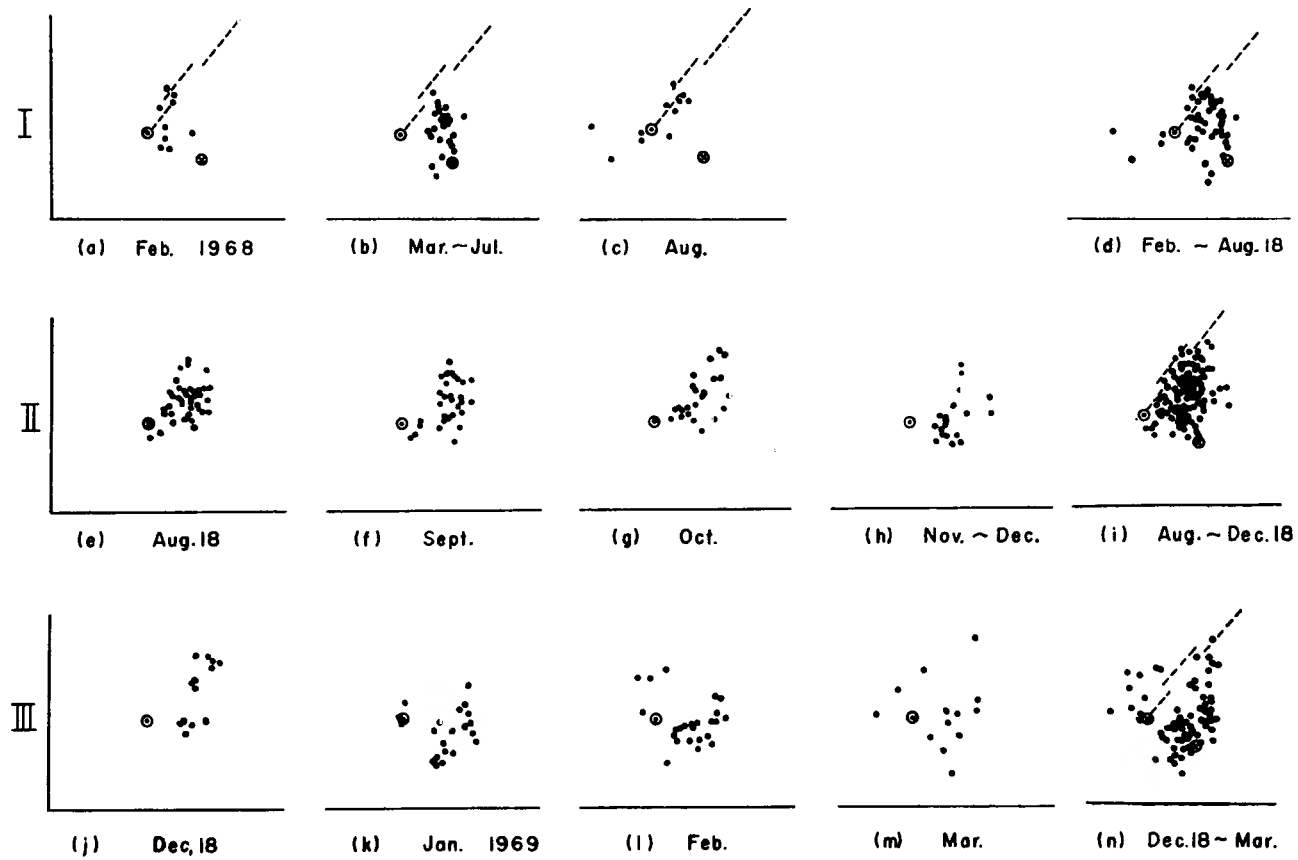
Fig. 5. Epicentral distributions for the individual period and stage. The centered open circle and the circle with a cross represent the locations of the main shock and the first major shock respectively. The dotted line was assumed as the fault associated with the main shock.

area bounded by the epicenters of the first major shock (circle with a cross) and the main shock and also by the dotted line, which was inferred from the focal distribution for the second stage as explained later, whereas epicenters were apt to crowd to this line during the accelerating portion (c). At the very beginning of the second stage, the main shock took place at the southwest end of this line and only on the southeast side of it did the aftershocks occur. Thereafter, they were going away gradually from the line as seen from the middle figures of Figs. 5 (e)–(h). In the third stage, however, new epicenters appeared on the northwest side as well, though they kept a short distance away from the line; then they spread altogether away from the line until thorough activity in this region came to an end.

From those facts stated above, it is noticed that the line of boundary deduced from the focal distribution of the aftershocks would probably coincide with the fault accompanying the main shock as inferred from the fault plane solution shown in the following section. We must emphasize also the fact that the foreshocks were crowding to the eventual fault just before the outbreak of main rupture accompanying the main shock. Furthermore, we are still very interested in the facts that the main shock occurred at the *end* of fault and the aftershocks were distributed within an area on *one side* of the fault and *spread*
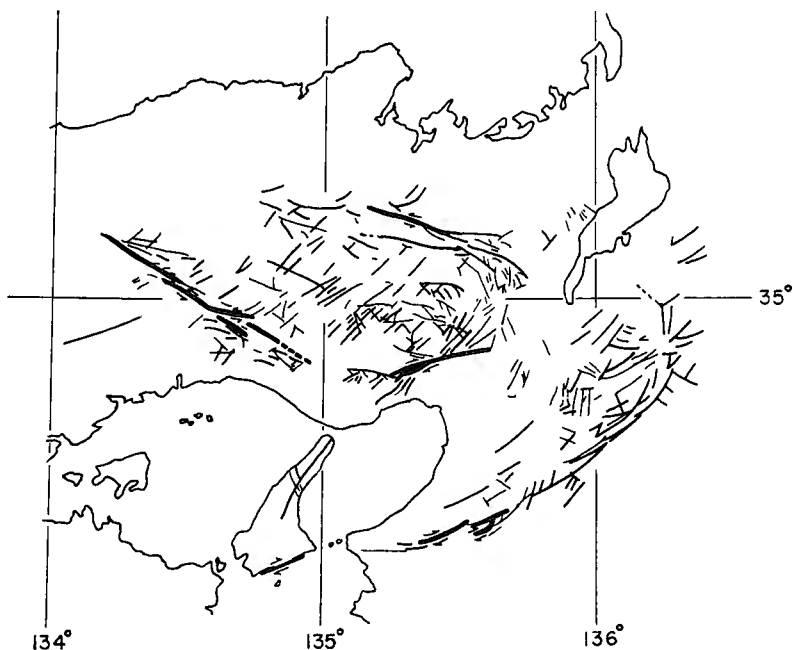

Fig. 6. Map of the northern part of the Kinki District, showing the fault system (thick line) and the large scale fracturing system (thin line). (after Huzita [1969])

gradually with time.

Fig. 6 is a map showing the fault system in the northern part of this district. The thick traces are clear strike-slip faults discovered recently and compiled by Huzita [1969] by using the topographical and the geomorphological methods. The distribution of these faults together with the large scale fracturing system shown by the thin lines may coincide well with the seismic activity as a whole. Therefore, it is of further interest to study how the seismicity relates to the tectonic structure on a limited scale as small as several kilometers. A detailed description of the Mitoke Fault in the connecting area with
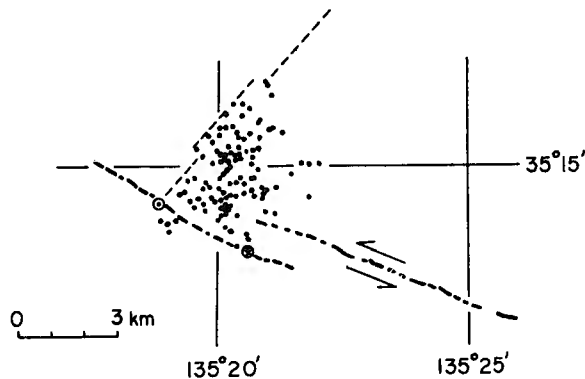

Fig. 7.   Detailed traces of the Mitoke Fault with the epicentral distribution of the aftershocks. The dotted line is the same as those shown in Fig. 5.

the Wachi earthquake is shown in Fig. 7, together with the focal distribution of aftershocks. The thick lines indicate the surface traces of the Fault described by Huzita [1969]. The fault as deduced from the focal distribution of aftershocks and also from the focal plane solution was again drawn by a dotted line. It is noticed from this figure that both of the prominent shocks are located just on a branch of the Fault, which in turn coincides well with one of the boundaries of the focal distribution. The fault accompanying the first major shock, therefore, might lie on this branch of the Fault. Another interesting event is a relation between the seismic activity and the strike-slip movements along the Fault. This earthquake swarm indeed occurred on the Fault, but within a section where the movements measured topographically were rather slight and the traces of the Fault were extremely confused. Eventually an anticorrelation might be noticed between them. The same fact may be recognized concerning the other strike-slip faults shown in Fig. 6 and will be discussed in a future paper.

4. Focal mechanism

As mentioned above, most of the shocks used in this study were recorded at a sufficient number of stations to determine the focal mechanism of individual shocks. The distributions of initial motion of four principal shocks are given
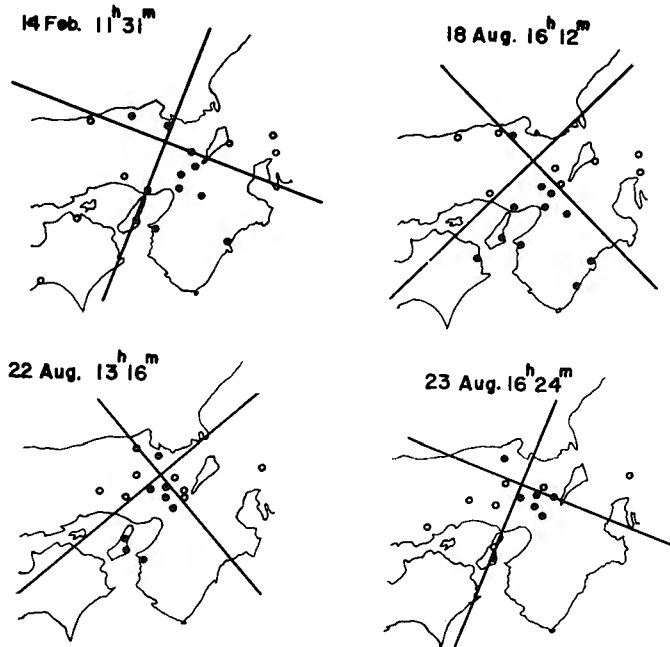

Fig. 8.   Distributions of initial motion for the prominent shocks.

in Fig. 8, indicating the fact that the so-called quadrant type pattern where the earth's surface is divided into four quadrants by two straight lines crossing at the epicenter is valid as generally ascertained in the case of shallow focus earthquake.   As seen from the quadrant type pattern for the main shock (upper right), one of the nodal lines in the direction of NE-SW is in good accordance with the dotted line given in Figs. 5 and 7, which has been assumed as the fault associated with the main shock to explain the clear boundary of the focal distribution of aftershocks.   Similarly, the fault in connection with the first major shock, lying on the branch of the Mitoke Fault, almost coincides with a nodal line in the direction of NW-SE (upper left), though a discrepancy of a few degrees is observed.   Accordingly, both the faults seem to make a conjugate set with an angle of intersection of about 75°, crossing at the focus of the main shock.

Now let us consider the question as to how the regional stress was acting on the focal region during the individual stage and throughout the series of
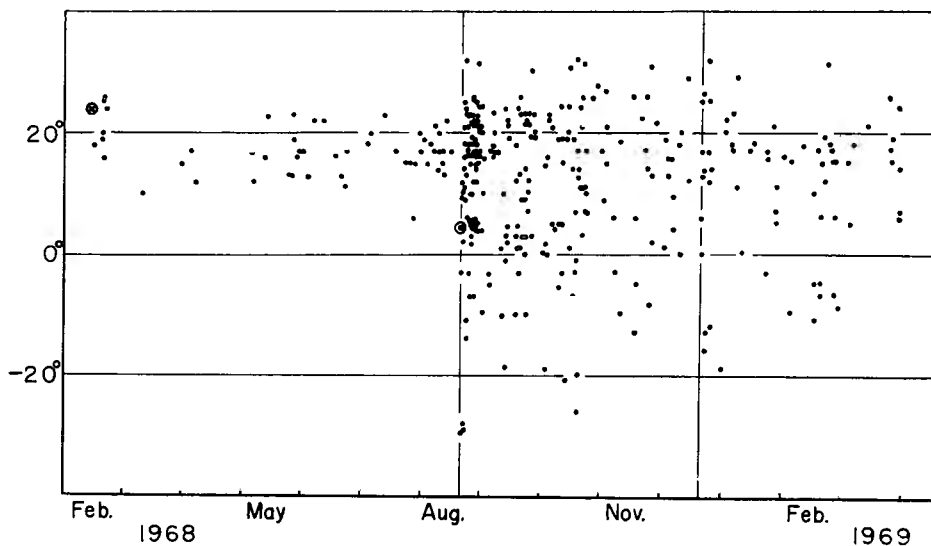
Fig. 9. Directions of principal stress axes plotted against time. The method of how
to determine them is described in the text.

seismic activity. We can easily determine the direction of maximum compres-
sional axis from the quadrant type pattern by cutting the dilatational quadrants
in half through the epicenter, when the frictional effect on the fault surface
can be neglected. The directions of principal axes obtained in this way are
plotted in Fig. 9 in order to see their variation with time. Angles in ordinate
are taken counter-clockwise from the direction of E–W in degree. The centered
open circle and the circle with a cross denote the directions of principal axes
for the main shock and the first major shock respectively. This plot shows
that the directions of principal axes for the first stage are nearly constant
around 17°, whereas, just after the outbreak of main shock those for the second
stage are suddenly scattered over a wider range from −30° to 30°, but the am-
plitude of the scattering is decreasing gradually with time and converging again
to a value around 17° throughout the second and the third stages, though a
slight increase can be recognized at the beginning of the third stage.

A general aspect of these facts may be summarized as follows. During the
first stage the regional stress field which might have caused the first major
shock to occur was preserved and acted almost uniformly over the fracturing
zone nearly parallel to the fault of the first major shock. However, the main
shock disturbed the stress field markedly and the aftershocks occurred in a
confused stress field, such as in a medium crushed into fragments. Thereafter,
the focal area which had suffered a loss of cohesion was gradually restored to its

former state by the secular tectonic stress that might prevail over this region.

Hereupon we should take the effect of frictional strength of the fault into consideration, because the coefficient of friction may not always be negligibly small. As pointed out by many authors (e.g., Kasahara and Sugimura [1964], Hashizume et al. [1966]), the direction of the principal stress axis lies horizontally and almost in the E-W direction in the northern part of the Kinki District. It may be assumed, therefore, that the direction of the principal axis for the main shock, 4.5° from the E-W direction, coincides with the direction of the secular principal axis of this region. On the basis of this assumption, we are able to estimate approximately the coefficient of friction of fault by using the Coulomb-Mohr criterion. In this way, the coefficient of friction for the first major shock was evaluated as 0.70, while in the later part of the first stage the average value of the coefficient was reduced to about 0.45. As a matter of course, the value for the main shock might be extremely low, perhaps not more than 0.1. However, at the end of the third stage it mounted up again to about 0.5, if the inclination of faults of minor shocks was nearly parallel to the fault of the first major shock. Supposing this inference to be acceptable, Fig. 9 might indicate not only the time-variation of the direction of nodal lines but also the change of the average frictional coefficient with time, which is given as the bias, namely, the mean deviation of all samples within an individual time interval from the value for the main shock. As already mentioned, however, the pattern of focal distribution was variable even during the individual stage. The change of the regional stress field and/or the frictional strength of the faults, therefore, would be related not only to the lapse of time but to the location of foci and perhaps to the property of medium.

5. Change of the value of b in the Gutenberg-Richter's formula

Time-variation of the value of b in the formula $\log n(M) = a - bM$, has been fully discussed by many workers, especially in the case of the Matsushiro earthquakes. The data used in this study, however, show that there is not any statistical significance as to the change in the b-value within the individual stages except for the following point. At the very beginning of the first stage as shown by a in Fig. 2, the parameter b falls around 0.8 and it may be rather high in comparison with those in the succeeding portions denoted by b and c. Although we have yet to account for the physical significance of this result, let us simply compare the b-values between the stages to see the possible relation to the mode of seismic activity for the respective sequence.

The representative values determined by the Utsu [1966] method are given in Fig. 10. The slopes of the straight lines do not necessarily express these
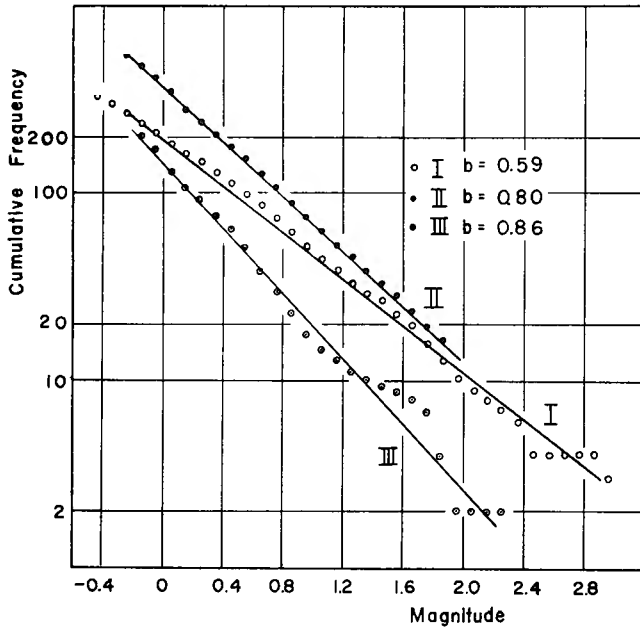
Fig. 10. Magnitude-frequency relations for the three stages. A significant difference in the value of *b* can be recognized between the first and the other stages. The straight lines are drawn by eyefitting. Accordingly, they do not necessarily coincide with those calculated by the Utsu method.

values because they were drawn only in order to fit the plots. The test of the difference in *b*-value proved the change of the values between the first stage and the other stages to be significant statistically. Therefore, the foreshock sequence may be characterized by the lower *b*-value of 0.59.

As suggested by previous workers (e.g., Mogi [1962] and Scholtz [1968]), this fact would probably indicate a change in the property of medium and/or the variety of stress patterns in the focal domain. Whatever the physical significance, the change in the *b*-value seems to be one of the most important observable parameters to indicate the characteristics of earthquake sequences.

6. Concluding remarks

We studied several phenomena associated with the earthquake swarm. One of the most interesting results may be the detailed description of the foreshock sequence, even though its seismic activity was so un-remarkable that it could not have been observed if the observational network on a routine basis had not been set up at that time. As for the regional stress field, it might be almost steady except during the very beginning of this stage. On the other

hand, the foci were wandering in the focal area of the forth-coming aftershocks. Just before the outbreak of the main shock, however, they were gathered on the fault which was to be associated with it, as if they had been prepared for the main rupture.   It is very interesting to note that this fact would perhaps exhibit similarity with the clustering of microfractures on the eventual fault plane observed by Scholtz [1968] in his recent experiment on rock.

Another remarkable event is that the directions of nodal lines deduced from the focal plane solution were markedly scattered in the aftershock sequences, but, afterwards, they were restored to their former state.   According to these conditions at the focal region, the frictional effect on the fault plane might vary significantly.   However, we have no evidence to see whether the Byerlee's [1967] model of friction with wedge shaped asperities would also apply well to this particular case.

In conclusion, we should collect more sufficient evidence for a satisfactory explanation of the spatial and temporal patterns of the seismic activity of the swarm type and their causative relation.   Some of the results of this study, however, should be taken as applicable not only to this swarm but to swarms occurring in other districts.   For example, the Himeji earthquakes (Watanabe [1964]) and even the Matsushiro earthquakes (see, e.g., *Technical report of J. M. A.* [1968]) exhibited several similar features in regard to the mode of seismic activity and the time-variation of focal distribution.   This is an interesting problem for future research.

Acknowledgements

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