The Relation between Seismic Activities and Earth Tides in the Case of the Matsushiro Earthquake Swarm

By Kazuo OIKE and Keisuke TANIGUCHI

(Manuscript received December 14, 1987)

Abstract

The temporal variations of dilatational strains by solid earth tides were calculated and compared with the variation of seismic activities in the case of the Matsushiro earthquake swarm.

It has been found that in the beginning of each stage of the swarm, major earthquake activity has important relation with the expansive peaks of dilatational strains caused by earth tides. The swarm started on August 3, 1965 with a few events a day. Each group of small felt shocks in the first week began around some of the peaks of dilatational strains. There were four periods in which major earthquake activity occurred around the peak of dilatational strains. These correspond to the beginning of new kinds of seismic activities. The first period was the beginning of the Matsushiro earthquake swarm. The second was that of a larger earthquake series. The third was the period in which the epicentral area extended into a wider area. The fourth was the beginning of the expansion of the seismic area, again.

In these four periods, the type of the seismic activity which occurred was predominantly a large main shock with aftershocks. It suggests that fracturing was beginning in a new area.

Such phenomena show that dilatation causes a decrease in the strength of rocks under the condition of the critical stress level and thus becomes a trigger for the occurrence of earthquakes. Such a synchronization of small events with the dilatational change may be related to the stress level and its changes in the crust.

1. Introduction

The correlation between earthquake occurrences and tidal phases has been studied by many seismologists since 1930. The results have been reviewed by Tanaka (1985)[23].

In an early period of the Ito earthquake swarm in 1930, in the Izu Peninsula, peaks in the burst type of activity occurred at low tide in the region. It was studied and reported by Nasu (1931)[19]. In the same region, a similar phenomenon was detected in a swarm occurring off Kawanazaki in 1980 (Mogi, 1983)[18].

Recently, in the inland regions, microearthquake observation networks have been developed. Very low level activities which corresponded with tidal changes were found by these observations. Kayano (1973)[13] found a correlation between the tidal phase and twelve microearthquakes in Okayama Prefecture. Earthquakes with magnitudes ranging from 1.9 to 3.3 occurred over a period of 10 days, and in the same phase as the ocean tides recorded by a nearby tide gauge.

Ohtake (1970)[20] found that events in a small swarm occurring near Kamikochi, Nagano Prefecture, had a tendency to occur from the time of moonrise to that of southing of the moon.

Klein (1976)[15] analyzed the correlation between peak earthquake activity during swarms and stress orientation of theoretical earth tides. Significant correlation was found in the Reykjanes Peninsula swarm and others. No tidal correlation, however, could be found for the Matsushiro earthquake swarm from the results he obtained.

Heaton (1982)[9] analyzed the correlation between tidal shear stresses and earthquakes whose focal mechanisms were known. From the results, he rejected his own hypothesis that shallow dip-slip earthquakes correlate with tidal shear stresses (Heaton, 1975)[8].

Volcanic earthquakes were also analyzed and a correlation with earth tides was found, especially before and after the eruption (McNutt *et al.*, 1981)[16].

Kilston *et al.* (1983)[14] showed that large earthquakes ($M \geqq 6.0$) in southern California with epicenters between 33° and 36° N had statistically significant 12-hourly, lunar fortnightly and 18.6-year periodicities. Smaller earthquakes ($M < 6.0$) in the same region do not display these periodicities.

Gao *et al.* (1981)[1] and Gao *et al.* (1983)[2] discussed the correlation between earth tides and earthquakes in China. No clear correlation was found between 70 large earthquakes and tidal hydrostatic stresses. Then they classified earthquakes into various types of patterns of activity and showed that isolated shocks have a tendency to occur in dilatational periods of the tidal strains.

It is clear that earthquakes are not always triggered by tidal variations. Triggers are presumed to be effective only at the critical stress level (Oike *et al.*, 1985)[22]. So we must study detailed relations between earthquakes and tidal strains in each stage of a swarm. The purpose of this study is to present a conclusion on the relation between earthquakes and tidal strain variations in the case of the Matsushiro swarm.

The Matsushiro earthquake swarm was one of the important swarms which have recently occurred in Japan and have been observed in detail. Therefore, the relation of the temporal change of the seismic activity with the tidal phenomena has to be reanalyzed. Especially detailed analyses at each stage of the swarm activity have been done from the viewpoint mentioned above.

2. Data

The first microearthquake of the Matsushiro swarm was recorded on August 3, 1965. The activity increased to the end of the year. The peak of the swarm was in March, 1966, and it decreased gradually to the end of 1970. By that time, 62821 felt earthquakes had been recorded. They included 9 events of intensity V on the JMA scale, 50 of intensity IV and 429 of intensity III (Ohtake, 1976)[21]. The main features of the temporal variations of the swarm activity are sufficiently manifested by these numerous felt earthquakes.

Felt earthquakes were observed and reported by the Seismological observatory of Japan Meteorological Agency at Matsushiro, Nagano Prefecture. Times and intensities used for the present study were taken from these reports. The data for events of comparatively large magnitude used here were obtained by reference to the Bulletin of JMA.

Various kinds of tidal strain components were calculated theoretically using the program written by Harrison (1971)[7] for solid earth tides. Although his program does not include the influences of the load of ocean tides, it is not so important because the Matsushiro region is located at the central mountainous region of Honshu island, and the coast lines are distant enough. The calculated results were compared with the strain changes observed by strainmeters in the tunnel of the Matsushiro Observatory to make sure of the real change of strains in the region.

3. Correlation between Earthquake Occurrences and Dilatational Strains

At the first time variations of various kinds of the areal strain components calculated here were compared with the time series of earthquakes at the beginning stage of the swarm. In **Fig. 1** temporal variations of dilatational strains, maximum shear, extentional strains and activity of earthquakes are shown in comparison with each other. It is seen from the comparison that groups of events began around some of the expansive peaks of dilatational strains.

The phase lag of the strain change observed in the tunnel of the Matsushiro Observatory from the calculated one is very small (Hamada, 1981)[6]. Therefore, the calculated dilatation curves have been used for the analyses through the whole period of the swarm.

The temporal pattern of the Matsushiro swarm which started on August 3, 1965, crustal movements and the variation of water discharge are shown in **Fig. 2,** referring to Ohtake (1976)[21].

Time series of earthquakes from the beginning of August, 1965 to the end of 1966 were compared with the calculated variation of dilatational strains. In quiet

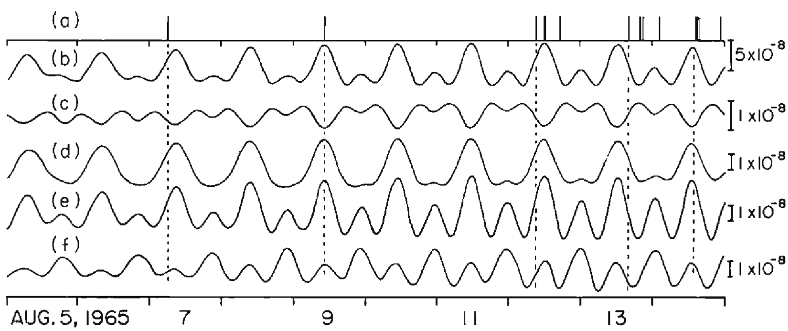

Fig. 1. Relations among felt earthquakes (a) in the beginning stage of the Matsushiro swarm, calculated variations of areal dilatation (b), maximum shear strain (c), strain in the E-W direction (d), that in the N-S direction (e), and differential strain (f) calculated by (e)–(d).

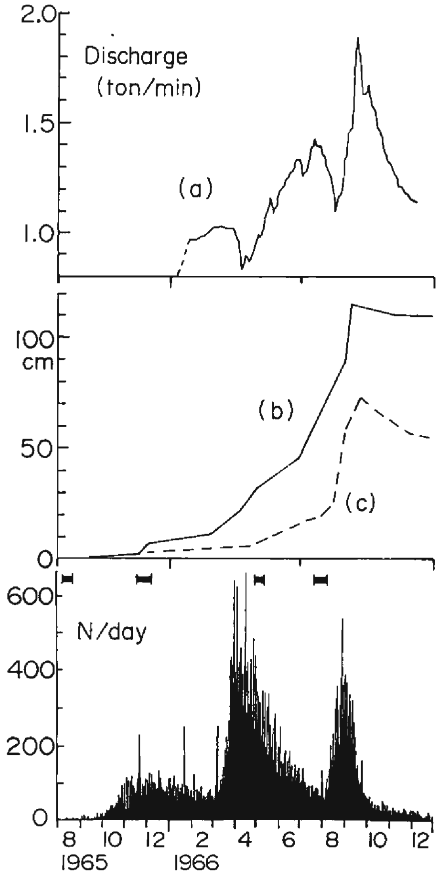

Fig. 2. The variation of water discharged (a), horizontal displacement (b), vertical movement (c) and the temporal pattern of the seismic activity of the Matsushiro swarm. Bars indicate four periods in which some correlations between shocks and peaks of dilatational strains have been found as a result of this study.

periods, time sequences of events were compared with changes of strains one by one. In active periods, the temporal variation of the number of events per hour was compared with the dilatational strains. Some correlations between seismic activities and strain changes were found in the four periods as follows:

3.1 From August 7 to August 14, 1965

This period was the beginning stage of the Matsushiro swarm. The relation between the seismic activity and dilatational change is shown in **Fig. 1.**

The first felt event occurred on Aug. 7, 1965 and the second one occurred on Aug. 9. They occurred around the peak of dilatational strains. The subsequent three groups of felt events occurred from Aug. 12 to 14. They started near the peaks of dilatational strains.

3.2 From November 2 to December 10, 1965

This period was the start of occurrences of large earthquakes at the first stage of the swarm. The relations between the seismic activities and dilatational strains are shown in **Figs. 3** and **4.** **Fig. 3** shows the relation between comparatively large earthquakes and dilatational strains. From the beginning of November, 1965, the

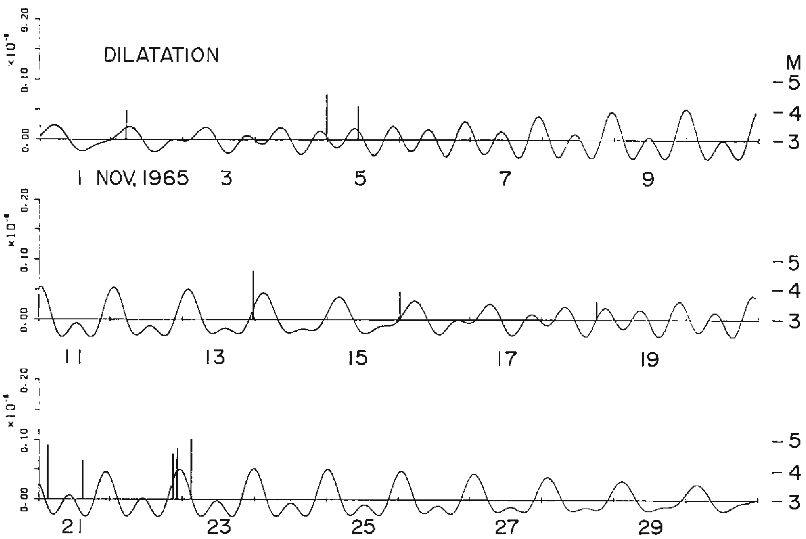

Fig. 3. The relation between comparatively large events (M>3.5) and the dilatational strains at the beginning of occurrences of the larger earthquakes in the first stage.

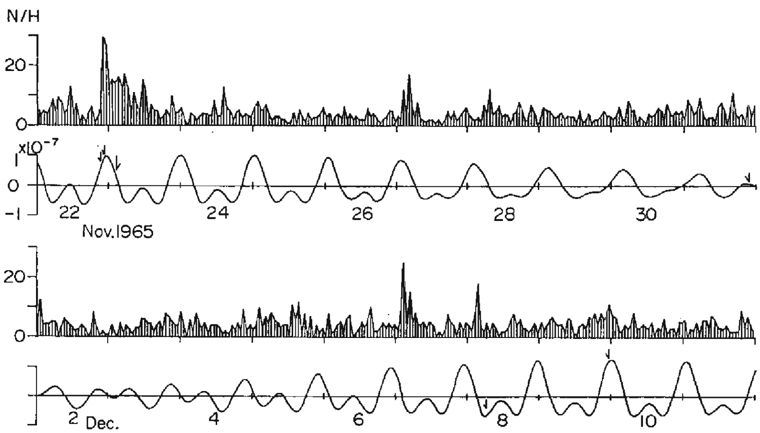

Fig. 4. The relation between the variation of hourly numbers of felt earthquakes and the dilatational strains. Five large events are shown by arrows.

number of larger earthquakes began to increase. Their hypocenters and magnitudes were calculated and reported in the Bulletin of JMA. Eleven larger events occurred from November 2 to 23, 1965 as shown in **Fig. 3.** Eight of them occurred in the period when the dilatation curve was above the zero line in the figure.

Fig. 4 shows the relation between the hourly number of felt events and dilatational strains from November 22 to December 11, 1965. The number of the events increased rapidly in this period. There are some conspicuous peaks of the variation of the hourly number of events. Large peaks occurred on November 22, 27 and 28, and on December 7 and 8. They began around peaks of the dilatational strains. Comparatively large events are also shown by arrows in the figure. They also occurred around the peak of dilatational strains.

3.3 From the end of April to the beginning of May, 1966

This period was just after the start of the second stage of the swarm. It was also just after the peak of the activity of the Matsushiro earthquake swarm over the whole period. From **Fig. 2,** it is found that water discharge was going to increase rapidly and the rate of crustal movements changed in this period. Large events are compared with dilatational strains in **Fig. 5** from April 27 to May 6, 1966. A tendency for the occurrence of earthquakes around the peaks of dilatational strains can be found from April 27 to May 5.

3.4 The end of July, 1966

This period was the initial one of the third stage of the swarm. It corresponded to the period when the epicentral area of the swarm began to extend into the surrounding region. The result is shown in **Fig. 6.** A tendency for the occurrence of earthquakes around the peaks of dilatational strains can be found from July 22 to August 1 in the figure.

In other periods from August, 1965 to the end of 1966 excluding periods shown in **Figs. 1** and **3** to **6,** no clear correlation between earthquakes and peaks of the dilatation can be found by simple observation of time sequences. **Figs. 7** and **8** show some examples of these cases. **Fig. 7** shows the high activity during the period when earthquakes were occurring frequently in the period around the peak of the Matsushiro swarm activity. **Fig. 8** shows the diminished activity at the end of 1966

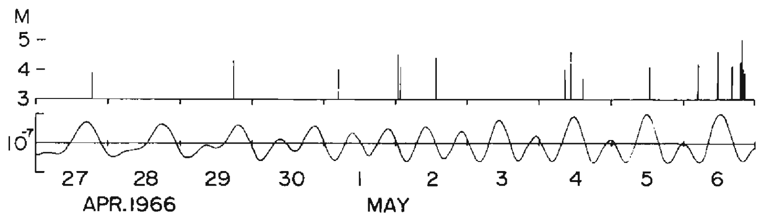

Fig. 5. Comparatively large events and dilatational strains just after the start of the second stage of the Matsushiro swarm.

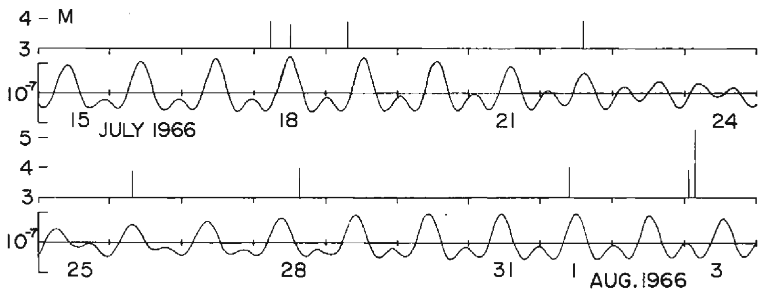

Fig. 6. Comparatively large events and dilatational strains in the beginning of the third stage.

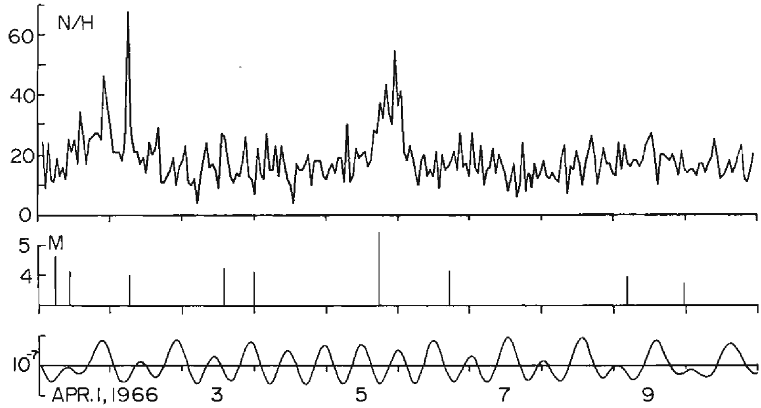

Fig. 7. Sample graphs from the most active period of the Matsushiro swarm. No correlation between earthquakes and the dilatational strains was found.

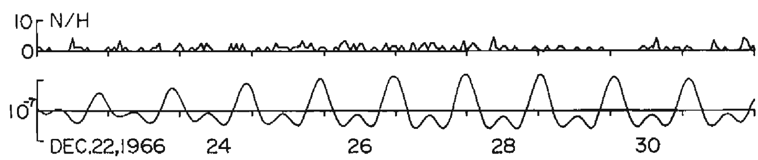

Fig. 8. Sample graphs from the period when the activity was going to decay at the end of 1966. No correlation between earthquakes and dilatational strains was found.

which was the end of the third stage of the swarm. Thereafter, the activity was in decay.

4. Patterns of Seismic Activities in Small Groups of Events Concentrated in the Time Axis

Events in the Matsushiro earthquake swarm did not occur constantly throughout its entire duration. Many burst type activities concentrated in time were found.

There are four typical activity patterns: One is the isolated large event type (A-type). The second type is where a large main shock occurs suddenly followed by many smaller aftershocks (B-type). The third is the swarm type which is composed of many shocks including a few large shocks (C-type). The C-type corresponds to the type with foreshocks, main shock and aftershocks. The last is the swarm type with many small but no conspicuously large shock (D-type).

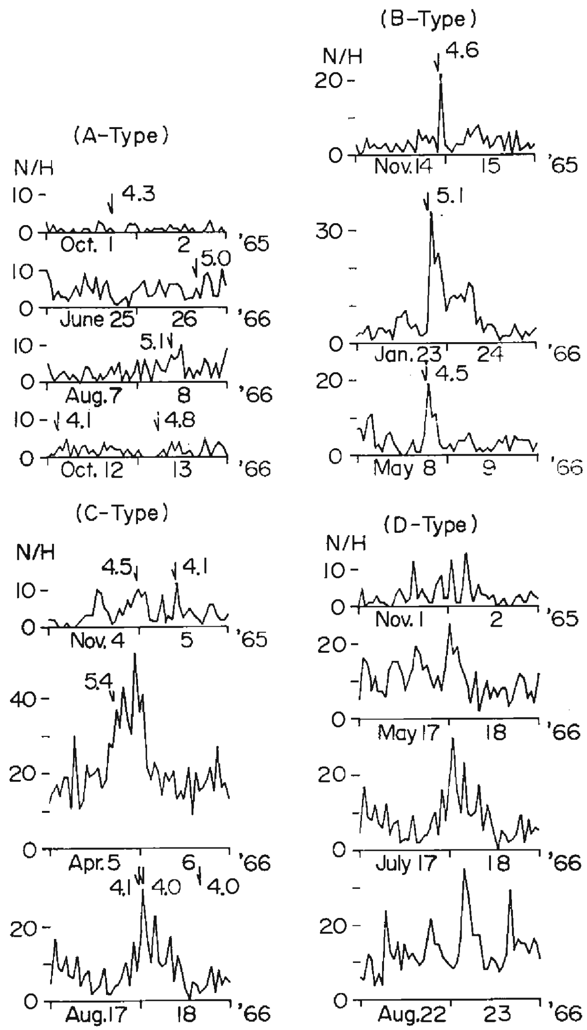

Fig. 9. Four types of patterns of the small group seismic activities. Larger shocks indicated by arrows are compared with the hourly variation of the number of shocks. A-type means the isolated large event. B-type means the main shock with many aftershocks. C-type means the swarm activity with a few large shocks. D-type is the swarm with no conspicuously large shocks.

Fig. 9 shows examples of each temporal pattern classified into four types. The variation of the hourly number of events and large shocks among them shown by arrows were used for the classification.

Mogi (1963)[17] clarified the relation between the patterns of seismic activities and the homogeneity of the crust. He showed that swarm type activities occur in an inhomogeneous crust such as, for example, one where there are many Quaternary volcanoes. Sudden occurrences of large events with aftershocks are observed in the region where homogeneity is high.

Applying the results by Mogi (1963)[17] on the relation between the patterns of activities and the homogeneity of the crust, we can suppose the variation of the conditions of rocks in which earthquakes occurred. Many burst type occurrences of small groups of events in the Matsushiro swarm are the most suitable for such an application.

Fig. 10 shows the temporal distribution of four types clusters. Concentrations of A- or B- type would correspond to those earthquakes occurring in less fractured areas. If many C- and D-type events occur, it would mean that they are taking place in highly fractured areas.

A symbol "T" plotted in **Fig. 10** indicates that the correlation between earthquakes and the peaks of dilatational strains have been found around it. Many A- or B-type activities continued after the time when "T" is plotted. It means that the correlation between earthquakes and the tidal dilatation occurred when earthquakes began to occur in the less fractured areas. It corresponds to the stage when the hypocentral distribution was going to extend into the wider area in each stage of the activity mentioned by Hagiwara *et al.* (1968)[5].

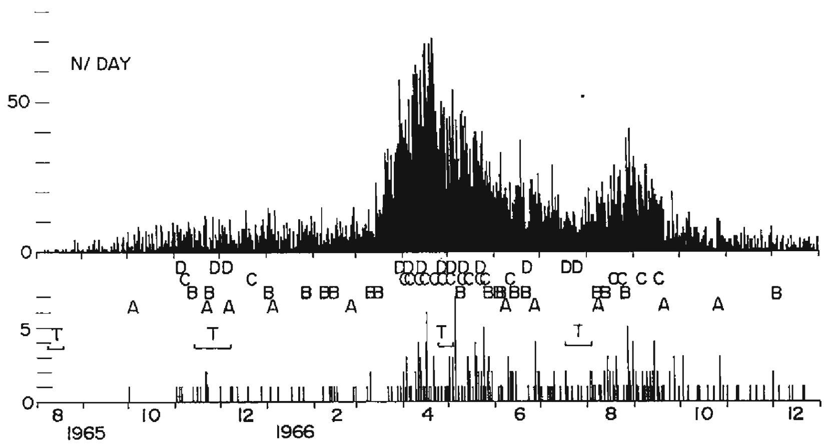

Fig. 10. Temporal distribution of the four types of clusters of earthquakes. A, B, C and D are plotted at the time when A-, B-, C- and D-type activities occurred. T indicates that correlation between shocks and dilatational strains was found there. These periods are also indicated by thick bars in Fig. 2 to compare with the variations of other phenomena.

5. Discussions and Concluding Remarks

Klein (1976)[15] concluded that no correlation was found between the seismicity of the Matsushiro swarm and semidiurnal earth tides applying his method to 6678 events from October, 1965 to December, 1966. He treated all events statistically. In our case the whole series of earthquakes were compared with dilatational strains in the time domain. Four periods in which there were correlations between earthquake occurrences and the dilatational strains were found.

The correlation of earthquakes to the expansive peaks of the dilatational strains suggests that the triggering mechanisms are significantly related to the decrease of confining pressures and the strength of rocks in the hypocentral region.

Pressure axes of major shocks of the Matsushiro swarm were oriented in the east-west direction and their focal mechanisms were of the strike-slip fault type (Ichikawa, 1967)[11]. However, each group of shocks corresponded better to the peak of dilatational strains than to that of differential strains (f) in **Fig. 1,** which corresponded to the variation of shear stresses that cause earthquakes with the focal mechanism as mentioned above.

Imoto *et al.* (1983)[12] analysed the relation between earthquakes of the Izu-Hanto-Toho-Oki earthquake swarm in January, 1983, and tidal phenomena, and they showed that earthquakes occurred at low tides from January 18 to 24. They compared the time of occurrence of earthquakes with temporal variations in horizontal shear stress on the vertical plane whose strike is in the N10°W direction, but no clear correlation was found between these shocks and the peaks of the shear stress. The initiation of each burst type activity correlated better with the peak of dilatational strains than with that of shear stress. The phase lag of ocean tides is about 6 hours in this region.

Four periods of the Matsushiro swarm earthquake activities correlated with peaks of the dilatation, and the example described above shows a similar tendency. Nevertheless, we must be prudent in insisting on the correlation of earthquakes with the peak of dilatational strains because there have been many results showing somewhat different kinds of correlations.

Mogi (1983)[18] discussed very interesting phenomena based on his acute observations made at the peak of seismic activity related to the Izu-Hanto-Toho-Oki earthquake in 1983. Quite the same patterns of swarm activity occurred once a day for three days just before the main shock. The pattern was that short-term activity started at the time of low tides, followed by a comparatively long (about 6 hours) swarm activity which commenced at a certain level of the rising tide, then low level activity occurred at the same level of the following ebbing period. These phenomena mean that each group of activity appears closely related to the tidal phases but it does not occur at the same phase.

Yamashina (1976)[24] calculated the change of differential strains related to the earthquake generating stresses in the southwest Okayama and compared his results with times of events reported by Kayano (1973)[13]. His result indicated that there was a good correlation between the occurrences of shocks and the peaks of the differential strains.

We can conclude that the correlations between earthquakes and earth tides really exist under certain conditions, but they appear with various kinds of features. In any case, triggering of earthquakes by earth tides seems to occur under the critical state of stress with respect to the strength of rocks. The synchronized occurrences of shocks with tidal phases over several days can be observed.

In the case of the Matsushiro swarm, the critical conditions seem to have appeared in the four periods. It seems that dilatational strains caused the weakening of rocks which were at a critical state in the Matsushiro region. The dilatation became a trigger for the bgeinnings of small fractures, which could in turn trigger larger activities in new stages.

A large amount of water was discharged after the second stage of the Matsushiro swarm. This was closely related to the swarm activity as shown in **Fig. 2.** The relation between pore pressures and the occurrence of fractures has been studied by many seismologists since Hubbert and Rubey (1959)[10]. The strength of rocks under shear stress depends on the effective pressure which is the difference between the confining pressure and the pore pressure. If the confining pressure becomes low by dilatational strains the strength of rocks decrease. It thus appears that some correlations between earthquakes and dilatational strains have been detected in the case of the Matsushiro swarm.

It is important to find out the synchronized occurrences of shocks with tidal strains. The best way for such analyses is to compare the time sequences of shocks with the tidal strain changes in the time domain. If such synchronization is detected among these two factors, there is a possibility that the stress in the relevant region might be in the critical state.

For earthquake prediction research, especially for the short-term prediction or the prediction of imminent occurrence, the triggering mechanisms would play an important role in estimating the time of occurrences of earthquakes.

Various kinds of short-term precursors of earthquakes also may occur under the critical state of the stress field and rocks, so there is a possibility that these precursors other than foreshocks could occur in relation to variations in earth tides. Guo *et al.* (1983)[3] and Guo *et al.* (1984)[4] presented the modulation model for earthquake prediction. They successfully interpreted the time intervals from the sudden or impulsive precursory phenomena to the main shocks.

It is significant for the further study of triggering mechanisms of earthquakes to survey quantitatively the correlations among various kinds of phenomena at each stage of earthquake activities.

We would like to express our thanks to Prof. Takeshi Mikumo and Prof. Torao Tanaka for their advice and comments. We also thank Mrs. Emi Fujii and Miss Izumi Senoo for preparing the manuscript.

Computations were made on the FACOM M340R of the Data Processing Center of the Disaster Prevention Research Institute, Kyoto University.

References

1) Gao, X., Z. Yin, W. Wang, L. Huang, and J. Li, Triggering of earthquakes by the tidal stress tensor, Acta Seismologica Sinica, Vol. 3, pp. 264–275, 1981 (in Chinese).
2) Gao, X., and W. Wang, Relations between earthquake series and solid earth tides, Acta Seismologica Simica, Vol. 5, pp. 323–334, 1983 (in Chinese).
3) Guo, Z. and B. Qin, On the general modulation model for impending earthquake prediction, Northwestern Seismol. Jour., Vol. 5, pp. 91–98, 1983.
4) Guo, Z. and B. Qin, Discussion on the short-term and impending earthquake prediction by the modulation model, Northwestern Seismol. Jour., Vol. 6, pp. 90–98, 1984.
5) Hagiwara, T. and T. Iwata, Summary of the seismographic observation of Matsushiro swarm earthquakes, Bull. Earthq. Res. Inst., Vol. 46, pp. 485–515, 1968.
6) Hamada, N. and S. Kashiwabara, Some problems related to crustal movement observations at Matsushiro, Quarterly Jour. Seiem., Vol. 45, pp. 49–82, 1981 (in Japanese).
7) Harrison, J.C., New computer programs for the calculation of earth tides, Coop. Inst. Res. Environmental Sci., pp. 1–30, 1971.
8) Heaton, T.H., Tidal triggering of earthquakes, Geophys. Jour. Roy. Astr. Soc., Vol. 43, pp. 307–326, 1975.
9) Heaton, T.H., Tidal triggering of earthquakes, Bull. Seism. Soc. Amer., Vol. 72, pp. 2181–2200, 1982.
10) Hubbert, M.K. and W.W. Rubey, Mechanics of fluid-filled porous solids and its application to overthrust faulting, Bull. Geol. Soc. Amer., Vol. 70, pp. 115–166, 1959.
11) Ichikawa, M., Statistical study of the focal mechanism of Matsushiro earthquake swarm, Zishin II, Vol. 20, pp. 116–127, 1967 (in Japanese).
12) Imoto, M. and S. Shimada, The relation between the seismic activity of the Izu-Hanto-Toho-Oki earthquake swarm - on the activity on January, 1983 - , Abstr. Seism. Soc. Japan 1983, No. 2, B40, 1983 (in Japanese).
13) Kayano, I., Microearthquake activity in Hiroshima and Shimane Prefectures and surrounding areas, western Japan, Zishin II, Vol. 26, pp. 178–203, 1973 (in Japanese).
14) Kilston, S. and L. Knopoff, Lunar-solar periodicities of large earthquakes in southern California, Nature, Vol. 304, pp. 21–25, 1983.
15) Klein, F.W., Earthquake swarms and the semidiurnal solid earth tide, Geophys. Jour. Royal Astr. Soc., Vol. 45, pp. 245–295, 1976.
16) McNutt, S. R. and R.J. Beavan, Volcanic earthquakes at Parlof Volcano correlated with the solid earth tide, Nature, Vol. 294, pp. 615–618, 1981.
17) Mogi, K., Some discussions on aftershocks, foreshocks and earthquake swarms --the fracture of a semi-infinite body caused by an inner stress origin and its relation to the earthquake phenomena (third paper), Bull. Earthq. Res. Inst., Vol. 41, pp. 615–658, 1963.
18) Mogi, K., Relations between the 1980 Izu-Toho-Oki earthquake (M6.7) and earthquake swarms-Its relation to the ocean tide, Abstr. Seism. Soc. Japan, 1983, No. 1, A22, 1983 (in Japanese).
19) Nasu, N., F. Kishinouye, and T. Kodaira, Recent seismic activities in the Izu Peninsula (Part 1), Bull. Earthq. Res. Inst., Vol. 9, pp. 22–35, 1931.
20) Ohtake, M., On an earthquake activity that occurred near Kamikochi, Bull. Earthq. Res. Inst., Vol. 48, pp. 65–71, 1970 (in Japanese).
21) Ohtake, M., Ten years since the Matsushiro earthquake swarm, Kagaku, Vol. 46, pp. 306–313, 1976 (in Japanese).
22) Oike, K. and K. Matsumura, Triggers of the occurrence of earthquakes, the Earth Monthly, Vol. 7, pp. 15–19, 1985 (in Japanese).
23) Tanaka, T., Earth tides and earthquakes, Earthquake prediction II, Center for Academic Publications Japan, Tokyo, pp. 287–307, 1985 (in Japanese).
24) Yamashina, K., Microearthquake activity related to the change of earthquake generating stress, Abstr. Seism. Soc. Japan 1976, No. 1, p. 77, 1976 (in Japanese).