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Japanese Program on Earthquake Prediction

A prediction program now under way in Japan succeeds in long-range forecast of the Matsushiro earthquakes.

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Forecasting earthquakes is one of the goals of seismologists in Japan, which has long suffered from destructive earthquakes. The great Kanto earthquake that attacked the Tokyo area in 1923, for example, killed more than 100,000 people. No nationwide effort toward earthquake prediction had been made, however, until a group of seismologists proposed a project for research on earthquake prediction based on modern earth sciences.

The Earthquake Research Institute, founded in the Tokyo Imperial University (now the University of Tokyo) soon after the Kanto earthquake, conducted intensive research related to earthquakes. Seismological institutes at a number of universities as well as the Japan Meteorological Agency also made important contributions to clarification of phenomena relevant to earthquakes. The 40-year study of earthquakes enables Japanese seismologists to plan possible methods of earthquake prediction. A program for research on earthquake prediction (*1*) was sponsored by the Japanese government after 1965, and a 5-year plan for this research (*2*) is now under way with financial support from the government of Japan. The program concentrates on obtaining basic data for possible prediction rather than actual forecasting, and will probably be followed by another program strengthened by the results of the present one.

The Matsushiro earthquake swarm that started in August 1965 provided an excellent opportunity for testing the feasibility of various methods in the program. The still-continuing swarm activity was so high at one time that more than 600 earthquakes per day were felt. Moderately destructive shocks of magnitude 5 on the Richter scale frequently attacked the northeastern part of Nagano prefecture in the central part of Japan. Various instruments were set up over the earthquake area (approximately 20 by 50 kilometers) by the Earthquake Research Institute. As a result of observation for 1½ years, a number of outstanding findings, which hopefully suggest the possibility of forecasting earthquakes, were brought out. We believe that the present program of prediction research is headed in the right direction, for the most part, although the Matsushiro operation also suggested minor points which should be improved.

The Prediction Program

In 1964, a Subcommittee for Earthquake Prediction, associated with the National Committee for Geodesy and Geophysics, Science Council of Japan, prepared the 5-year plan for research on earthquake prediction. This plan was primarily based on the "blueprint" (*1*).

Through the intensive studies of earthquake phenomena over the 40-year period, Japanese seismologists noticed that certain effects were sometimes observed prior to an earthquake. They reported on anomalous land deformations, foreshocks, and local geomagnetic changes that were apt to precede earthquakes of some magnitude. Due to the fact that these reports were fragmentary, it has been difficult for seismologists to arrive at definite conclusions.

In view of the dramatic improvement in measuring techniques in recent years, the study of phenomena prior to earthquakes is certainly worthwhile. Therefore, Japanese seismologists proposed a new program calling for well-organized observation, well-informed researchers, and most up-to-date techniques. Although it was not easy to meet all these requirements with limited financial conditions, the 5-year plan was launched in 1965.

The plan includes the following categories: geodetic work, observation of tide gauges, continuous observation of crustal deformation, seismic activity, geomagnetic work, tectonics, and laboratory work. In addition to these, data-processing centers may be established, and a few field patrols may be formed.

Geodetic work. A somewhat dense network of triangulation stations covers the Japanese Islands. The Geographical Survey Institute, Ministry of Construction, is responsible for conducting the triangulation survey. Whenever a great earthquake occurs, the Geographical Survey Institute surveys the earthquake area to recover the correct positions of triangulation stations. Thus, it is clear that a land deformation of the order of 10^{-4} in the maximum strain always takes place in association with great earthquakes of a magnitude of about 7.

So far, we have not identified a crustal deformation prior to an earthquake by means of the triangulation method. But most seismologists feel that, if we repeat triangulation surveys over a seismically active area with

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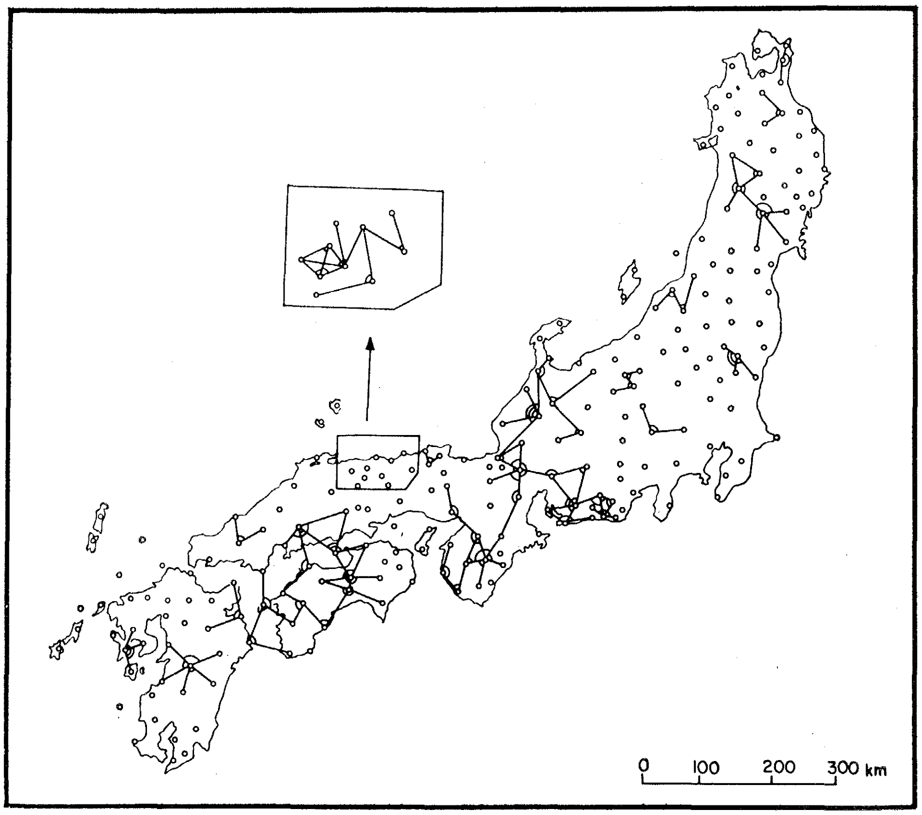


Fig. 1. First-order triangulation stations. The angles which indicated changes between 2.5 and 3.0 seconds of arc during the two surveys are also shown. [After Harada]

a reasonably short time interval, some deformation that would be smaller probably by one order of magnitude than the one associated with the whole course of an earthquake, might be expected to occur before an earthquake. Harada (*3*), who analyzed the existing data of the first-order triangulations in Japan, found, without exception, very conspicuous changes in the angle (larger than 3 seconds of arc) made by two straight lines, each connecting a triangulation station to the two neighboring stations in areas that experienced major earthquakes between the first and second surveys. The first survey was made between 1883 and 1909, while the second was made between 1948 and 1963. His analysis also indicated that most moderately large changes in the angle (between 2.5 and 3.0 seconds of arc) are also likely to be associated with earthquake areas. But there are a few examples of moderately large changes which seem to have nothing to do with earthquake occurrences. Some of the triangulation stations close to the Matsushiro area indicated some changes although no major earthquakes attacked that area during the period concerned (Fig. 1). Nothing is known about the cause of the anomalous change in the central part of Kyushu.

The prediction program emphasizes the speedy repetition of triangulation surveys. The 330 first-order stations will be reoccupied every 10 years. In addition to these surveys, the program also stresses the use of a geodimeter which measures a distance of 20 kilometers with a precision of one part in 10^5. Rhombic base lines with a distance of about 10 kilometers will be set up over a number of seismically active areas, and changes in lengths will be checked from time to time.

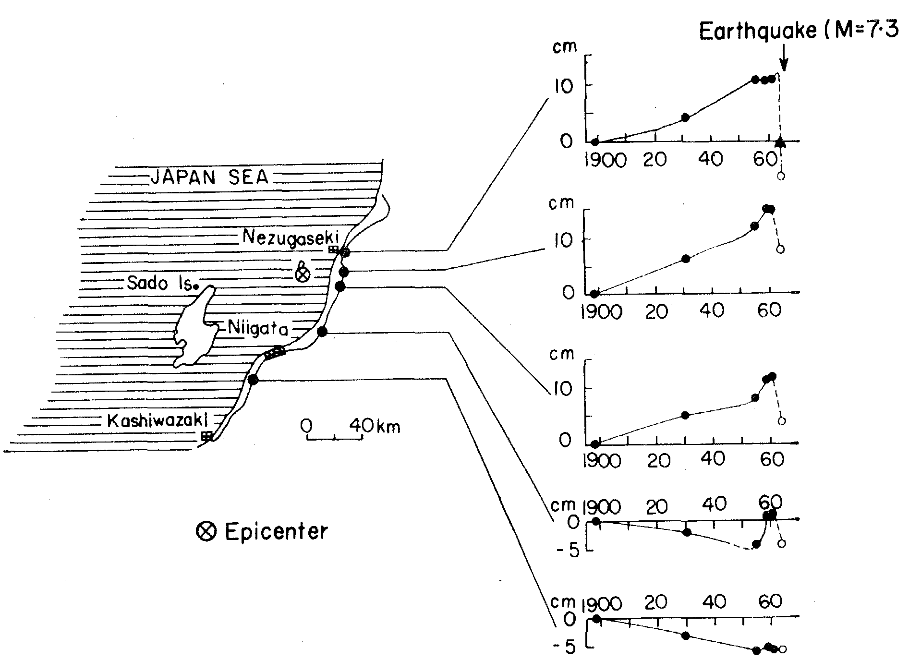


Fig. 2. ●, Anomalous changes in height at leveling bench marks before the 1964 Niigata earthquake. ▲, Land subsidence at the time of the earthquake as estimated on the basis of the Nezugaseki tide gauge. ○, Changes as found by the leveling survey after the earthquake. Tide-gauge stations are located at Nezugaseki and Kashiwazaki. [After Tsubokawa *et al.*]

Leveling is a little less laborious than triangulation. Japanese investigators have compiled much information on leveling in regard to the crustal deformation at times of earthquakes. A clear-cut land deformation which may be regarded as a warning sign of earthquake was found on the occasion of the Niigata Earthquake (magnitude of 7.3) on 16 June 1964 (*4*). Since the first survey in 1898, a number of leveling surveys have been conducted along a leveling route (approximately 200 km) passing through Niigata City (Fig. 2). To check the ground subsidence possibly caused by the withdrawal of natural gas, the Geographical Survey Institute has frequently repeated the leveling surveys since 1958. The speed of upheaval was accelerated approximately five times at the bench marks (Fig. 2) to the north of Niigata City about 1955. The speed then decreased after 1959, and a tendency toward subsidence was observed. A survey after the earthquake demonstrated a large subsidence of the land at all the bench

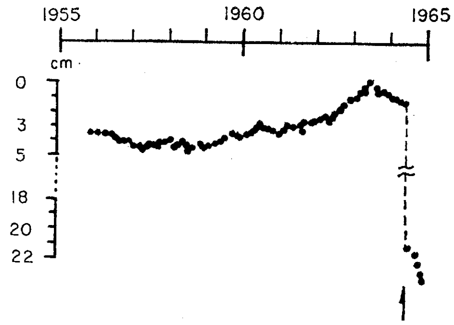


Fig. 3. Changes in the monthly mean sea level at Nezugaseki relative to Kashiwazaki. [After Tsubokawa *et al.*]

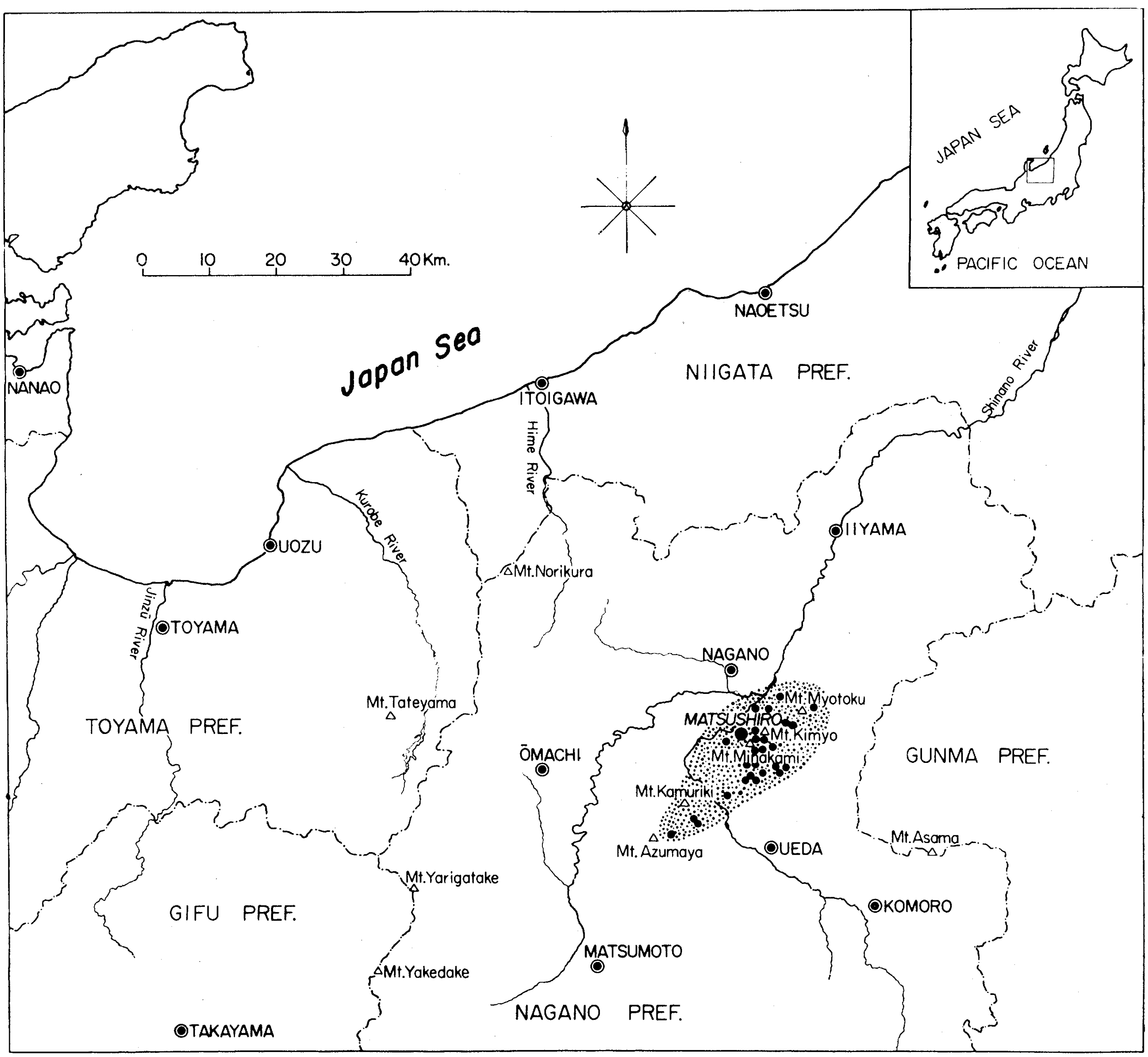
Fig. 4 (below). Matsushiro seismic area. The areas in which felt earthquakes took place are shown; black circles indicate epicenters of earthquakes having magnitudes larger than 4.7.

marks. If such acceleration and deceleration of the land deformation take place prior to the earthquake, repetition of leveling surveys every 5 years should reveal an anomalous land deformation.

Hence, Japanese seismologists unanimously agree that leveling survey should be drastically intensified. The prediction program is intended to reestablish the first-order bench marks along the 20,000-kilometer leveling routes, covering Japan every 5 years.

Tide-gauge observation. In the Japanese literature, we find a number of reports on change in the sea level prior to earthquakes. One of the most marked examples is the Ajikazawa earthquake that took place in the northern part of Japan in 1792. The earthquake occurred at about 2 p.m. The local inhabitants who noticed an extraordinary retreat of the sea in the morning were so afraid of tsunamis that they ran up into the mountains where they felt a strong shock in the afternoon. The terrified people ran back to the seashore only to be inundated by the tsunamis that arrived there some time later. This incident certainly reveals an anomalous land upheaval that takes place several hours prior to an earthquake.

In spite of these records, we seldom observed with a tide gauge such a premonitory land deformation. At the time of the Niigata earthquake, we had two tide-gauge stations—Nezu-



gaseki and Kashiwazaki—in the vicinity of the earthquake area (Fig. 2). Figure 3 indicates the difference in the tidal record between the two stations. We can clearly observe in the figure a land upheaval at Nezugaseki since 1958; such an upheaval has also been confirmed by the leveling work. In the middle of 1963, the land began to subside, and the main shock took place about 1 year later. A sudden jump in the sea level at the time of the earthquake is also seen in the figure. Although there was no conspicuous change in the sea level just before the earthquake, the long-term change that started 1 year before might be some indication of the event.

As part of the prediction program, 92 tide-gauge stations will be set up at intervals of approximately 100 kilometers along the coastlines of the Japanese Islands. The records will be sent to a center in the Geographical Survey Institute where rapid data-processing will be done.

Continuous observation of crustal deformation. Observation by geodetic means is inevitably intermittent, so that a short-term crustal deformation with a duration reckoned in days or hours can hardly be detected. Continuous observation of crustal deformation with

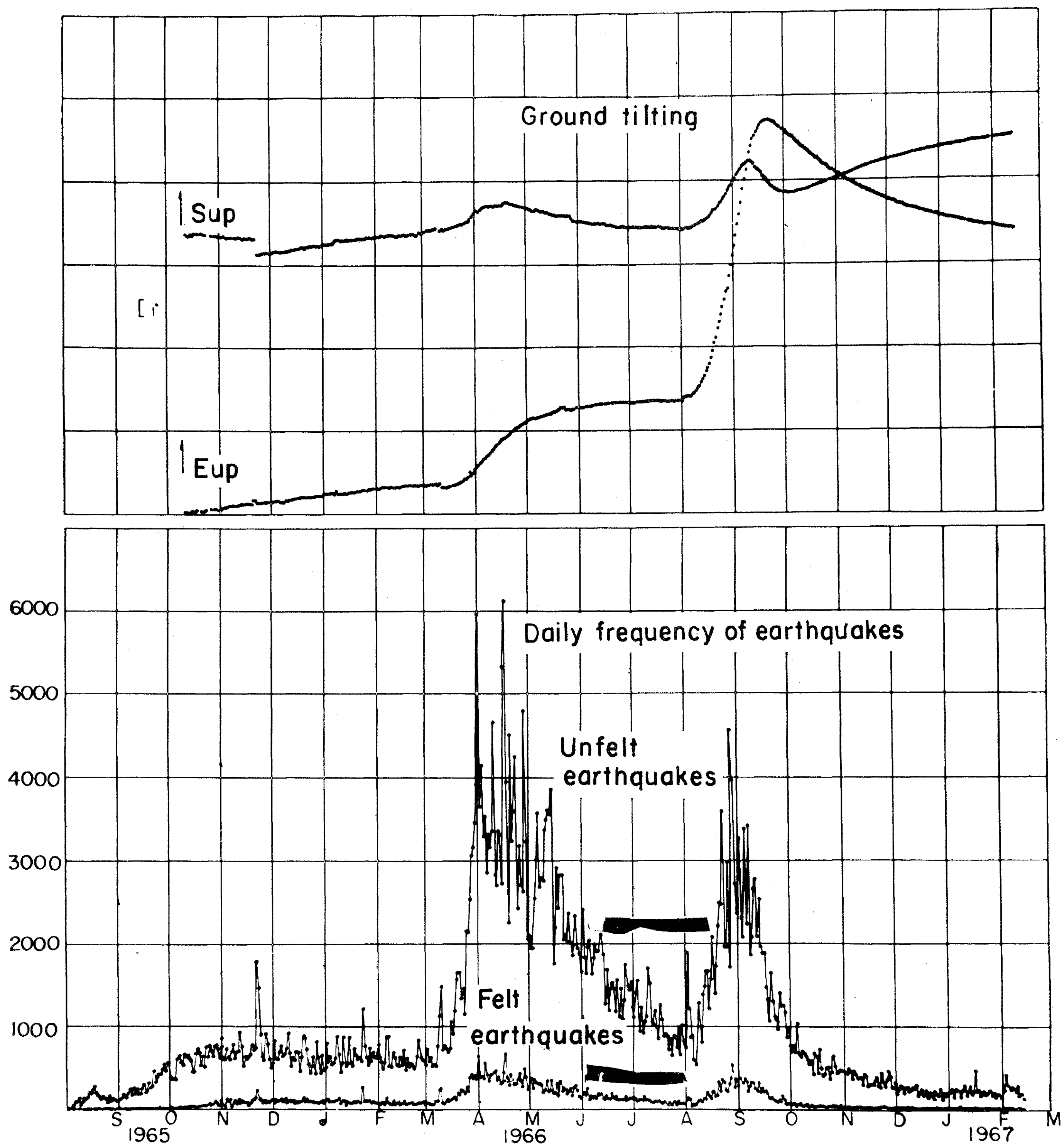


Fig. 5. Changes in ground tilting and daily numbers of unfelt and felt earthquakes during the Matsushiro earthquake swarm.

a tiltmeter, extensometer, or similar instrument is therefore important in supplementing the geodetic work. The tiltmeter observation made by the University of Tokyo and the Kyoto University for 20 years shows that a horizontal-pendulum tiltmeter may record enormously large secular changes in the ground tilting which are not compatible with those deduced from leveling surveys along a route nearby the observation point. Such secular changes tend to lessen when the tiltmeter is placed deep in an underground vault. Therefore, many of the Japanese workers now believe that a horizontal-pendulum tiltmeter is sensitive to the local condition—probably to that of the immediate neighborhood of the tripod on which the tiltmeter is placed. To get rid of such small-scale irregularities, Japanese observatories now use water-tube tiltmeters of a few decameters in length for crustal deformation.

Soon after the outbreak of the Matsushiro earthquake swarm (Fig. 4), the Earthquake Research Institute installed two components of water-tube tiltmeter 40 meters in length in a vault of the Matsushiro Seismological Observatory operated by the Japan Meteorological Agency. We observed surprisingly large changes in the inclination of the ground (Fig. 5). These changes are strongly correlated with seismic activity, so that tiltmeter observation provides a powerful tool for a long-range estimate of seismic activity.

In addition to such long-term changes, the observer often caught remarkable changes in the tilting shortly before earthquakes of about magnitude 5 (Fig. 6). Noting that there were frequent earthquakes during the midnight hours, an observer started continuous observations at about 3 a.m. A very sharp change in the direction of tilting was thus caught, while we had a series of three strong earthquakes, all occurring northeast of the observation point within a hypocentral distance less than 10 kilometers. The anomalous tilt change seemed to terminate soon after the last shock. This kind of change in the ground inclination had also been reported in the aftershock observation of the Fukui earthquake in 1948 (*5*).

Silica-tube extensometers are widely used to measure extension and contraction of the ground. A standard vault for continuous observation of crustal deformation includes two components of water-tube and horizontal-pendulum tiltmeters and three sets of extensometers. The 5-year plan proposes to establish 20 observatories similar to the Nokogiriyama Observatory. Because Japanese seismologists believe that an observatory is only able to detect anomalous strains preceding an earthquake within a distance of about 50 kilometers, a drastic increase in the number of observatories will certainly be needed.

Seismic activity and geomagnetic work. The seismometric network of the Japan Meteorological Agency will be completed in the course of the present program which aims at observing all earthquakes of magnitude larger than 3. Observation of microearthquakes (of a magnitude between 3 and 1) and ultramicroearthquakes (less than 1) will be made by those working in the universities. Some 21 microearthquake observatories are planned; each observatory provides eight satellite stations. To have overall information about seismic activity in Japan, we need many more observatories. This will be supplemented by the mobile observation of ultramicroearthquakes.

No clear-cut relations between a large earthquake and micro- or ultramicroearthquakes have so far been established. As rock-breaking experiments (*6*) suggest the occurrence of minor shocks prior to the rupture, so we must seek the same relation for natural earthquakes. Important progress in this respect has actually been made by the Matsushiro operation. Earthquakes of a magnitude of 5 or larger often took place at the margins of the seismic area. The tripartite and patrol observations of ultramicroearthquakes made it clear that very small shocks had been occurring, without exception, in the

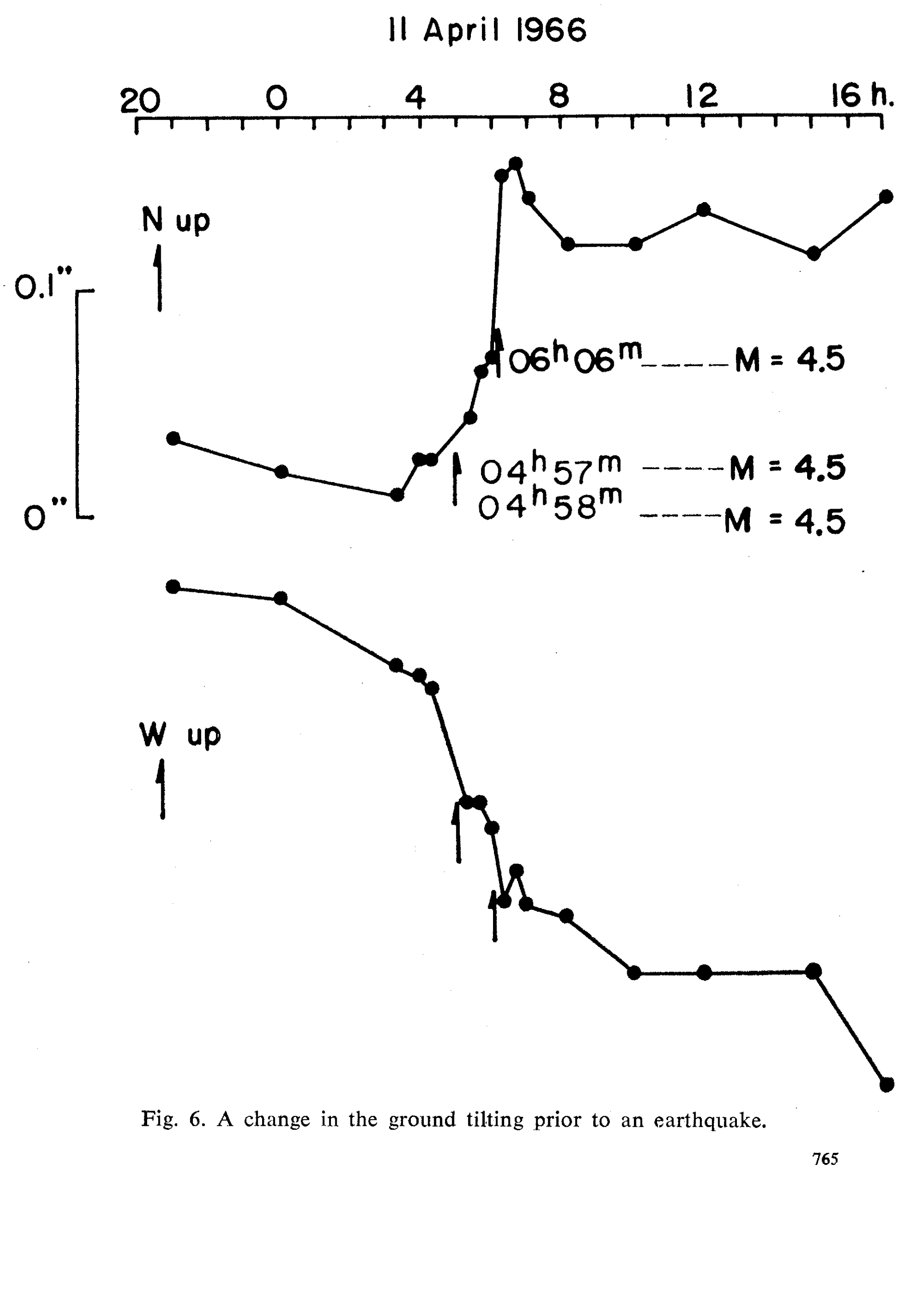


Fig. 6. A change in the ground tilting prior to an earthquake.

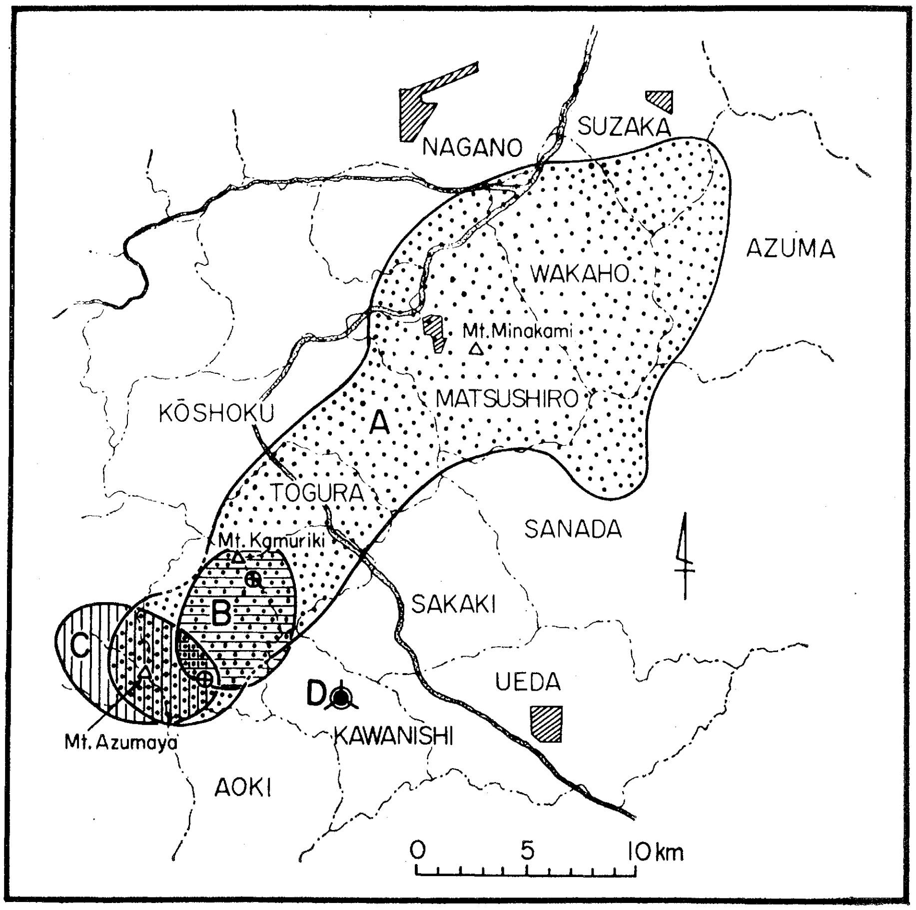


Fig. 7. *A*, Ultramicroearthquake area as observed by a seismic tripartite station from April to December 1966; *B*, epicenter and aftershock area of the earthquake (magnitude 5) on 16 January 1967; *C*, epicenter and aftershock area of the earthquake (magnitude 4.8) on 3 February 1967; *D*, seismic tripartite station.

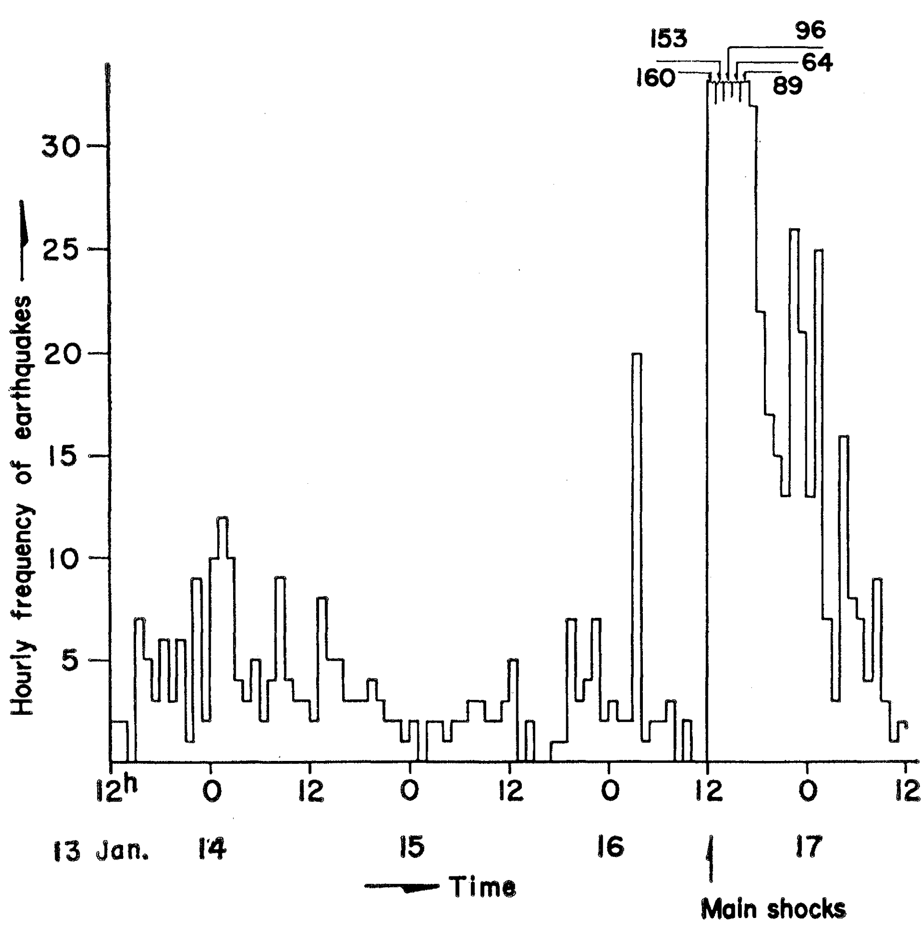
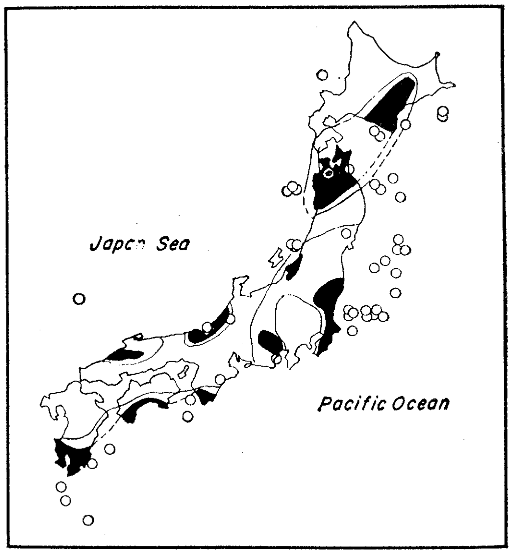


Fig. 8. The hourly frequency of earthquakes (magnitude larger than —1) immediately before and after the earthquakes at 12:32 on 16 January 1967. Only the earthquakes of which the times between the primary and secondary waves at the tripartite station ranged from 0.7 to 1.6 seconds were counted. This indicates the activity approximately in the aftershock area of the main shocks.

epicentral area of the main shock a few months earlier. Although the time interval between the ultramicroearthquake swarm and the main shock has not yet been worked out, the fact that a larger shock is always accompanied by many small shocks is of great importance. It was also reported that the ultramicroearthquake activity indicated no increase or seemed to decrease to some extent immediately before the main shock. A tripartite observation made it clear that very small shocks had been taking place in an area (Fig. 7) since the middle of 1966. Strong earthquakes actually occurred at the southwestern margin of the seismic area on 16 January (magnitude 5) and 3 February 1967 (magnitude 4.8). Figure 8 indicates the hourly frequency of earthquakes occurring in the neighborhood of the epicenter of the shocks on 16 January immediately before and after the main shocks. We did not observe an appreciably marked change in the microearthquake activity just before the main shocks.

Close examination of the existing geomagnetic data proves that a seismomagnetic effect would amount to 10 gammas or thereabouts, a value as small as 1/5000 of the earth's magnetic field itself. Recent development of measuring techniques based on proton precession and optical pumping magnetometers enables us, however, to detect changes in the geomagnetic field with an accuracy of 1 gamma or less. The prediction program puts much stress on studying anomalous geomagnetic secular variation by arrays of proton precession magnetometers. Some 20 magnetic observatories will be set up for this purpose.

The repetition of the first-order mag-



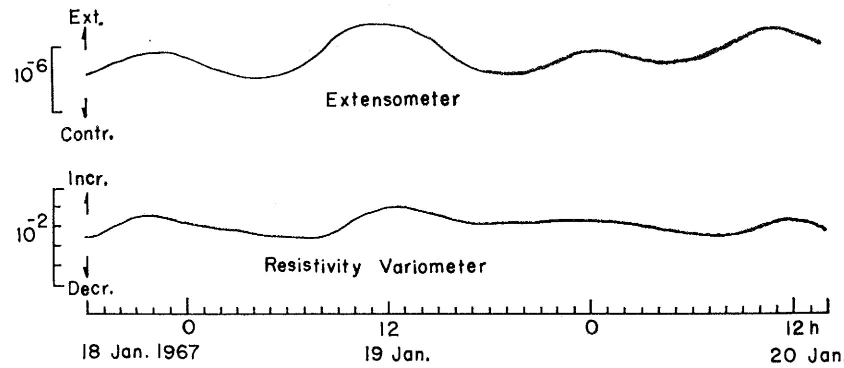


Fig. 9 (left). Areas in which we observed anomalous secular changes in the geomagnetic field from 1955 to 1966. Earthquakes of a magnitude of 6 or larger are indicated with small circles. [After Tajima] Fig. 10 (above). Rate of change in earth resistivity caused by tidal loading as recorded at the Aburatsubo Geophysical Observatory. The record of an extensometer in the same direction is also shown.

netic survey brought to light a number of areas over which the secular variation was anomalous. The maximum anomaly amounts to 5 gammas per year relative to the standard magnetic observatory. The anomalous areas for the period from 1955 to 1960 (Fig. 9) seem to be closely correlated with major earthquakes in and around the areas during the period. The only exception is the anomaly in the western part of Honshu Island. The program proposes to reoccupy 91 first-order and about 1000 second-order magnetic stations within a time interval of 5 years.

Tectonics and laboratory work. Geologists and geographers are encouraged to study the nature and distributions of prehistoric faults and folding. Such work is useful for choosing the most suitable areas for detailed observations of crustal deformation. In contrast to a progressive creep as observed at Hollister on the San Andreas Fault, no creep over a period of years has been observed in Japan.

Many of the items of the prediction program are planned on the basis of experiences over a long period of time, so that physical mechanisms through which those observable phenomena are correlated with an earthquake occurrence are by no means clear. To achieve further progress in the prediction research, however, it is very important to look into the theoretical background of phenomena occurring prior to earthquakes. Currently, study on rock rupture provides a working hypothesis for the relation between the foreshocks and the main shock. Field studies of ultramicroearthquakes have been made according to the theoretical suggestion. That kind of experiment should be extended to rock samples under rather high confining pressures and also, if possible, under high temperatures. We must simulate the physical conditions within the crust to apply experimental results to actual problems. The 5-year plan recommends the establishment of a few professorships to conduct such basic research.

Nagata and Kinoshita (*7*) have been working on piezomagnetic effect of minerals and rocks. Their experiment revealed reasonably large decreases in the magnetic susceptibility as well as the remanent magnetization accompanied by uniaxial compression; this has an important bearing on the seismomagnetic effect. As emphasized by Press and Brace (*8*), changes in the physical properties of rocks when they are subjected to a mechanical stress should be thoroughly examined. Such studies might eventually lead us to some new techniques applicable to earthquake prediction.

The electric conductivity of rocks of particular kind is very sensitive to mechanical stress (*9*). Recently, the change in the earth conductivity caused by tidal loading was recorded (Fig. 10). The rate of change in the earth resistivity is larger than that of the earth deformation by a factor of about 1000. Even changes in the resistivity in phase with the seiche of the adjacent bay have been observed. As the amplitude of the seiche amounts to only 10 cm or a little less, the associated strain would be of the order of 10^{-7}. We hope that this kind of electric method can be applied to finding an extremely small earth strain.

Use of laser interferometers, long-range tiltmeters, deep-hole tiltmeters, and seismographs is now in a developmental stage in Japan. Although these new techniques are not directly financed by the present program, it is of utmost importance to encourage research on them.

Data-processing centers and field patrols. It is certain that an enormous amount of data will be obtained in the course of the progress of the present program. In the Matsushiro operation, the data were too numerous to be processed by the existing facility. The most urgent need for the program is to establish a few data-processing centers equipped with high-speed computers and other modern apparatus. Research on how to process data of various kinds most efficiently must also be done rapidly.

Observation by a patrol system was originally proposed only for the ultramicroearthquake observation. But the Matsushiro experience revealed that it is also important to have observation parties for other disciplines which can be sent to an emergency area without delay; otherwise it is necessary to remove instruments from existing observatories to carry out the field observation. The prediction program is therefore being revised to include field patrols for geodetic, seismometric, and geomagnetic work.

For the first time in history, warnings of earthquake occurrence were issued frequently during the Matsushiro earthquake swarm. About March 1966 when the swarm activity became violent, the Subcommittee for Earthquake Prediction Research attached to the Geodetic Council, Ministry of Education, which is responsible for administrative coordination of geodetic and geophysical observation in Japan, recommended that a committee be formed to investigate the Matsushiro situation and, wherever possible, to inform the local residents of developments. Accordingly, specialists from the Earthquake Research Institute, the Japan Meteorological Agency, the Geographical Survey Institute, and other governmental institutions met approximately once a month and discussed in detail the observed data. Whenever they thought that the probability of earthquakes of some magnitude was great, warnings along with the analyzed information were issued to the public by the Japan Meteorological Agency. These warnings differed from exact predictions of time, place, and magnitude. They mentioned only the dangerous period (usually a range of a few months), a rough idea about location, and possible maximum magnitude. The situation was much the same as long-range weather forecasting.

The basis for warnings was provided, for the most part, by repetition of leveling surveys, microearthquake and ultramicroearthquake observation, and observation by water-tube tiltmeters. Results of geodimeter observation, geomagnetic observation, and others sometimes play an important role in determining conditions in the crust. It would have been difficult to supply information to the public, as we did in the case of the Matsushiro earthquakes, if the observation network had not been well established before the violent activities. To some extent, it was possible to predict even though nothing certain was known about the underground process. The violent activities in April and August 1966 (Fig. 5) were successfully foretold.

Naturally, local inhabitants are anxious to know the status of the seismic activity. However, care must be taken not to cause undue fear or to be overly optimistic, because these people have actually become conditioned to earthquakes. The Matsushiro experience revealed the problems of forecasting a destructive earthquake even if a more specific means of prediction is achieved.

Reaction to the warnings was varied. Local governments worked hard to prevent possible earthquake damage by repairing school buildings, strengthening fire brigades, and so forth. This was also the case for the national and private railways. Operators of hotels and inns foresaw business problems due to lack of tourists. Further aspects of the Matsushiro earthquakes are given in other reports (*10*).

Research on earthquake prediction has revealed that ultramicroearthquake activities resulted in occurrences of earthquakes of which the magnitude is larger than 5. This makes feasible a long-range forecast. But we do not yet know why ultramicroearthquake activity tended to decrease slightly just before the main shocks. Very quick repetitions of leveling survey also brought to light anomalous land deformation of long and short wavelengths. Quite contrary to common belief, upheaval and subsidence can reach a detectable extent within a period of 1 month. A few examples of such a high rate of deformation were found at the marginal area of the swarm activity. Yet, we have not had earthquakes there in most cases. The latest survey shows that an extensive area surrounding the seismic one was subjected to an extraordinary upheaval, the maximum reaching 8 cm per 6 months. In view of the fact that no such frequent repetitions of the levelings have been performed thus far, it would take some time to evaluate the geophysical significance of the land deformation observed.

Long-term as well as short-term changes as observed by the water-tube tiltmeter encourage future work of this sort. The usefulness of geodimeter, proton precession magnetometer, and other instruments was first confirmed in an actual seismic field. All the experiences throughout the Matsushiro earthquake observation indicate that the Japanese program of earthquake prediction is advancing in a direction that will hopefully lead us to our goal.

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