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EARTHQUAKE PREDICTION

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SUMMARY

Earthquake prediction research programmes in a number of countries are reviewed together with achievements in various disciplines involved in earthquake prediction research, i.e., geodetic work, tide gauge observation, continuous observation of crustal movement, seismic activity and seismological method, seismic wave velocity, geotectonic work, geomagnetic and geoelectric work and laboratory work and its application in the field.

Present-day development of earthquake prediction research suggests that actual prediction of some class of earthquakes, if not all, may be possible within a period of a few tens of years provided that basic data could steadily be accumulated.

Mention is also made about the difficulties in issuing an actual forewarning of earthquake on the basis of the experience of the 1965–1966 Matsushiro earthquakes during which a few long-term predictions of moderately destructive earthquakes were officially issued to the public for the first time in history.

INTRODUCTION

Those who are living in non-seismic countries like western Europe would hardly be able to realize the terror of great earthquakes. It is difficult to explain how one feels when one experiences violent quakes of the ground on which one stands. Perhaps even a scientist who is professionally concerned with seismology is terrified when he is attacked by an earthquake of a large intensity.

In addition to such psychological horror, those who live in a seismically active country suffer frequently from actual damages caused by earthquakes. The great Kanto earthquake, that attacked the Tokyo area on September 1, 1923, destroyed the most industrial part of Japan. More than 100,000 lives were lost; mostly by fire starting soon after the shock. The population of Tokyo at that time was much smaller than it is now. What would happen if such a big shock attacks again the world's largest city having a population over 10,000,000? Although most of the modern buildings are supposed to be of anti-earthquake structure, supply of electricity, gas and water would immediately be suspended. Floods of traffic would prevent the activity of fire-brigades. It is quite certain that Japan's capital would lose its function completely. One can hardly imagine how tragic it would be if Tokyo were involved in a first-class earthquake. Yet, there is no guarantee that such a fatal event will not take place in the near future.

The situation is much the same for large cities in other parts of the world such as the western United States, South America, Turkey, Yugoslavia and so on. It has been estimated that the destruction would amount to $4,500,000,000 if the 1906 San Francisco earthquake were to repeat (PRESS, 1968).

Modern technology has now achieved an approximate way of forecasting weather. People can now be informed well before a typhoon is approaching, so that they can prepare themselves well beforehand even though it is hard to destroy or stop the typhoon itself. Would it be possible to forecast an earthquake in a similar way as we do in the case of a typhoon? To such a question, earth scientists were reluctantly forced to answer "No" until about 10 years ago. But the situation has dramatically changed in recent years. The answer would now be "Yes, it would be possible in some cases provided we have a well-arranged network of observing geophysical elements". Actually, Japanese seismologists succeeded to some extent in long-range forecast of the 1965–1966 Matsushiro earthquakes (HAGIWARA and RIKITAKE, 1967).

DEVELOPMENT OF PROGRAMMES FOR EARTHQUAKE PREDICTION RESEARCH

The blue-print of earthquake prediction research

At the beginning of Japan's new civilization in the late 19th century, many eminent scholars were invited from then advanced countries. Some of them who were shocked by frequent earthquakes in Japan were interested in earthquake phenomena. They, together with Japanese scientists, formed the world's first seismological society. In this way, scientific researches on earthquake originated in Japan about 90 years ago.

After the Nobi earthquake in 1891, the Imperial Earthquake Investigation Committee was established in order to intensify the studies of earthquakes. Earthquake research in Japan has made a steady progress ever since. The 1923 Kanto earthquake encouraged the Japanese Government to strengthen the research in a more modernized way. The Earthquake Research Institute was then founded in the Tokyo Imperial University (now the University of Tokyo). Together with the activities at a number of seismological institutes attached to national universities and the Central Meteorological Observatory (now the Japan Meteorological Agency), the Earthquake Research Institute conducted intensive research related to earthquake over a period of 40 years.

All through the work since the beginning of earthquake research in Japan, especially through the 40-year study after the Kanto earthquake, Japanese seismologists began to realize vaguely a possible way to approach earthquake prediction. A research group for earthquake prediction was eventually formed by active seismologists in 1961. Problems directly related to earthquake prediction were discussed by them at many meetings. A report named *Prediction of earthquakes—progress to date and plans for further development* (TSUBOI et al., 1962) was in due course published as the summarized view of Japanese seismologists about the earthquake prediction problem. The now-famous report has been colloquially called by the Japanese seismologists the "blue-print of earthquake prediction programme" and became the mile-stone of earthquake prediction research in Japan in the following years.

The "blue-print" describes what the Japanese seismologists believe the best in achieving prediction of earthquakes. It was emphasized that the urgent thing was to concentrate on obtaining basic data for possible prediction rather than to hurry for actual forecasting. The proposed work was divided into a number of disciplines, i.e., geodetic work, continuous observation of crustal deformation, seismic activity, seismic wave velocity, active fault and geomagnetic–geoelectric work. A forecast of expected development in each discipline was given in detail in the blue-print. Even the anticipated outcome of the proposal was mentioned. It would perhaps be of interest for the readers to quote a few paragraphs from the last chapter of the blue-print.

"It is proposed, with regard to investigations by geodetic methods, that the time interval for nation-wide repeated surveys be 5 years for levelling and 10 years for triangulation. Hence, it would be some 10 years or so before the program really got under way. For certain special areas, a considerable amount of information should be obtained within 5 years. But when we realise that during the initial years of the project much work in instrumentation and education of personnel will be demanded, 5 years should reasonably be allocated for the preparatory stage.

Tide-gauge stations would be completed in 2 years, but data covering several years would be necessary to be really useful.

Continuous observation of crustal deformation: six base stations would be established under a 3-year project, and personnel trained in these stations. Then, such trained personnel would construct the proposed 100 stations under an 8-year scheme. If things work out as planned, completion of stations would be accomplished in 11 years.

Observation of microearthquakes: twenty branch stations and their subsidiary stations would be established under a 10-year project.

Observation of ultra-microearthquakes: a small network of stations in six special areas would be carried out under a 6-year project.

Determination of seismic wave velocity by means of explosion seismology:

regular operation would be continued with explosions at six places under a 6-year project.

Investigation of active faults would be completed in 2 years.

Investigation of geomagnetism and earth currents: several fixed stations in special areas would be completed in 3 years.

Provided that the project is promoted as planned above, an amount of useful information would be obtained in 5 years and after 10 years the amount of data should be fairly adequate for earthquake prediction.

In other words, it will take at least 10 years before the survey and observation under the present proposal really get under way. After that, the stage for processing data would start. At present, statistics show that earthquakes with magnitude $M > 6$ occur about five times every year in and near Japan. Among these, one is usually destructive. If we aim at predicting earthquakes with magnitude $M > 6$, it seems highly probable that we would be able to find some significant correlation between earthquake occurrence and observed phenomena merely by accumulating data for several years."

Nothing was mentioned about the expenses necessary for putting the "blue-print" into practice. Very roughly speaking, however, it was estimated that a sum of the order of 10,000,000,000 yen ($27,800,000) should be defrayed within 10 year's time in order to carry out the proposals. Although Japan's economic situation has much improved in recent years, the payment of such a large sum of money by the government seemed to be too difficult. Consequently, no financial arrangement for the proposal has been materialized until 1965.

Five-year plan for earthquake prediction research in Japan

Quite unexpectedly on June 16, 1964, a destructive earthquake attacked the Niigata area, the most industrialized city on the Japan Sea coast. As the earthquake was the first one to hit an economically important portion of Japan in the last 10 years, the public opinion longing for the forecasting of earthquakes was strengthened. The government decided to launch the programme of earthquake prediction research with its financial support. It was fortunate that a well-arranged programme was in existence at this time.

A subcommittee for earthquake prediction research had been set up in the Geodetic Council, Ministry of Education, which is responsible for administrative coordination of geodetic and geophysical observation in Japan, since 1963. Although the first-year programme was hurriedly made up by the subcommittee, a more comprehensive programme for a 5-year period was studied and put forward by a newly-established Subcommittee for Earthquake Prediction, associated with the National Committee for Geodesy and Geophysics, Science Council of Japan, March, 1965. The 5-year plan thus proposed has actually been under way since the 1965 fiscal year. The plan of course bases largely on the "spirit of the blue-print", although some modification was needed in order to meet the limited amount of the governmental budget.

The 5-year plan originally included the following categories: geodetic work, observation of tide gauges, continuous observation of crustal deformation, seismic activity, geomagnetic work, tectonics and laboratory work (RIKITAKE, 1966). It was aimed at concentrating on obtaining basic data for possible prediction rather than actual forecasting. At this stage, only seismologists were concerned with the plan, naturally.

Nation-wide interest in earthquake prediction was suddenly raised after the occurrence of the Matsushiro earthquake in 1965. The swarm activity centering Matsushiro Town, Nagano Prefecture, was one time so high that more than 600 earthquakes were felt a day with occasional destructive shocks of magnitude (M) 5 or so on the Gutenberg–Richter scale. It then became an urgent matter for the local people to know whether or not a bigger earthquake was to attack them. The mayor said to press-men: "What we badly need is a science of the earthquake". Under these circumstances, Japanese seismologists were forced to do whatever they could although the prediction research had just been started. It may be said that the Matsushiro operation made some success in foreseeing the growth and decay of the seismic activity and a sort of long-range forecast of earthquake occurrence was officially issued to the public for the first time in history. We will come back to the topic later.

The Matsushiro experience suggested possible improvements of the predic-

TABLE I

BUDGET FOR THE JAPANESE 5-YEAR PLAN IN UNITS OF 1,000 YEN[1]

Discipline	*1965*	*1966*	*1967*	*1968*	*1969*	*Total for 5 years*
Geodetic observation and tide-gauge station	50,476	72,441	91,050	257,638	248,864	720,469
Continuous observation of crustal deformation	30,871	38,754	37,542	154,410	169,061	430,638
Seismic activity	73,827	115,556	96,756	436,331	369,949	1,092,419
Seismic wave velocity		1,235	1,260	14,000	14,000	30,495
Active fault and folding	from other sources					
Geomagnetism and earth currents	19,580	48,175	16,355	85,546	158,248	327,904
Data-processing centre			10,562	273,860	139,380	423,802
Field patrols			43,909	186,249	71,624	301,782
Total	174,754	276,161	297,434	1,408,034	1,171,126	3,327,509

[1] 1,000 yen is equivalent to \$ 2.78.

tion research planning. Importance of quick data processing as well as field patrols which can be sent to the area of emergency at any time was recognized.

These points were subsequently taken up in a revised plan. In Table I is summarized the financial state of the 5-year plan. The amount as approved by the government is given for 1965–1967, while the figures for the remaining 2 years are the amount as proposed by the subcommittee.

Every effort has been made toward constructing new observatories for microearthquakes, crustal deformation and the like throughout the first half of the 5-year plan. The most important item for the second phase of prediction research following the 5-year plan would be possible development of new measuring techniques and data processing based on up-to-date technology.

Prediction programmes in the U.S.A.

The afore-mentioned "blue-print" seems to have stimulated much interest in earthquake prediction research among overseas seismologists. As a matter of course, a U.S.–Japan conference on problems related to earthquake prediction research was held in Tokyo under the auspices of the U.S.–Japan Scientific Cooperation Plan in March, 1964. Immediately after the conference, a great earthquake took place in Alaska. It seems that the earthquake accelerated the effort toward prediction research in the U.S.A. A group of scientists accordingly presented a report of a 10-year programme of research (PRESS et al., 1965). The programme consists of the following five parts; i.e., microseismicity arrays, development and installation of other cluster instruments (tiltmeters, strainmeters,

TABLE II

ESTIMATED COST FOR THE AMERICAN PLAN IN CALIFORNIA-NEVADA REGION
(After PRESS et al., 1965)

Discipline	*10-year total*
Microseismicity arrays	$ 3,000,000
Development and installation of other cluster instruments (tiltmeters, strainmeters, magnetometers, gravimeters, meteorological instruments)	3,050,000
Development and installation of special survey devices (laser strain seismograph, optical surveying devices, etc.)	9,050,000
Development and installation of supercluster instruments (including drilling)	7,800,000
Installation of telemetry	5,000,000
Operation and management of instrument system	2,500,000
Total	$ 30,400,000

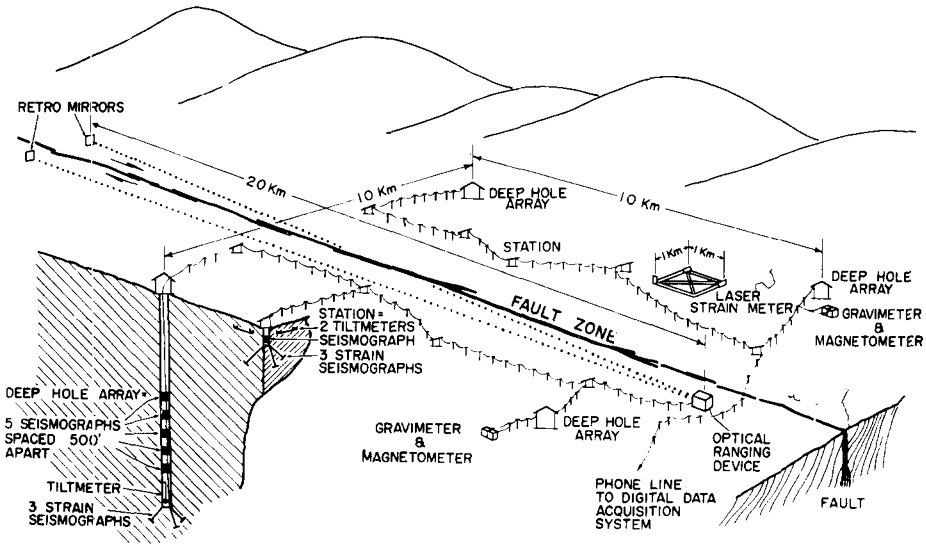

Fig.1. A hypothetical super-cluster. (After PRESS et al., 1965.)

magnetometers, gravimeters, meteorological instruments), development and installation of special survey devices (laser strain seismograph, optical surveying devices, etc.), development and installation of super-cluster instruments (including drilling), and installation of telemetry. In Table II are given the estimated expenses for completing the proposed plan in the California–Nevada region. The 10-year totals of the whole project amount to \$137,000,000. The U.S. plan is about one order of magnitude larger than the Japanese plan in its financial scale.

Much stress is put on geophysical observation along the seismic belts in California–Nevada and Alaska–Aleutian areas. Observatories which provide multidisciplinary functions will be set up from place to place along a seismic belt. They are called the clusters or super-clusters. Fig.1 indicates the idea about how a super-cluster will be equipped with seismometers, strainmeters and so on. It is hoped that premonitory events would be detected with adequate sensitivity.

The programme has not yet been implemented. But it has doubtless given rise to an increasing interest in the earthquake prediction research in the U.S.A.

A symposium on earthquake prediction was held by the Environmental Science Services Administration (E.S.S.A.) at Rockville, Maryland, in February, 1966. Possible contributions from the E.S.S.A. to earthquake prediction were discussed there (ENVIRONMENTAL SCIENCE SERVICES ADMINISTRATION, 1966). In June of the same year, the second U.S.–Japan conference on problems related to earthquake prediction research was held in New York with a field excursion to the Nevada–California seismic area. During the excursion, the American as well as Japanese seismologists found newly-developed echelon-like cracks on the ground at Parkfield, California, which is situated on top of the San Andreas fault. An earthquake of $M = 5.4$ actually occurred right there accompanying a fault about 30 km in length after 10 days.

Prediction programmes in the U.S.S.R.

Attention has also been drawn to earthquake prediction research in the U.S.S.R. although nothing official has been released about the programme. It is surmised, however, that some systematic observations with a special intention of earthquake prediction have been in progress in central Asia and Kamchatka for a few years. Two targets, Talgar and Garm districts, have been chosen in central Asia. The project leader there is I. L. Nersesov, while the Kamchatka project is led by S. A. Fedotov. Nothing certain has been disclosed about the financial scale of the projects. But it is said that 80% and 15% of the total budget are respectively spent for the central Asia and the Kamchatka projects. The remaining 5% is devoted to laboratory work (T. Hagiwara, personal communication, 1967).

In addition to the above programmes, geodetic and geotectonic work has been conducted in various parts of the U.S.S.R. What is written in this section is mostly based on information from unofficial sources, and the writer would be pleased if someone would correct or add something new to the present statement.

Working Group on Earthquake Prediction (W.G.E.P.)

In view of the rapidly-increasing interest in the earthquake prediction, it was very timely that an international symposium on earthquake prediction was held during the 14th General Assembly of the International Union of Geodesy and Geophysics (I.U.G.G.). The symposium (Convenor: T. Hagiwara) was held at the Swiss Federal Institute of Technology in Zurich on October 2, 1967.

Following the general talks on earthquake prediction programmes in a number of countries, highlights of earthquake prediction research in various branches of seismology and geophysics were reviewed. The papers have been jointly published in a special issue of *Tectonophysics* (Rikitake, 1968b).

After the symposium, members of a working group on earthquake prediction were nominated. The working group, that is attached to the International Association of Seismology and Physics of the Earth's Interior (I.A.S.P.E.I.), will be responsible for the international coordination of researches relevant to earthquake prediction. The working group was initially started with thirteen members representing various countries, the International Association of Geodesy (I.A.G.), the International Association of Geomagnetism and Aeronomy (I.A.G.A.), the International Association of Volcanology and Chemistry of the Earth's Interior (I.A.V.C.E.I.) and the Upper Mantle Committee (U.M.C.). T. Hagiwara was appointed chairman with T. Rikitake as secretary.

International research project on earthquake prediction in northern Anatolia

It has been well known that many first-class earthquakes take place from time to time along a mountain range running from east to west in northern Anatolia. The 1939 Ercincan earthquake ($M = 8$), for instance, killed 40,000 people and was associated with a fault of 300 km in length. Like the San Andreas fault, the Anatolian fault is an active one.

At its Zurich Assembly in 1967, the I.U.G.G. adopted a resolution in which it was strongly recommended to conduct an intensive investigation with international cooperation aiming at possible prediction of earthquakes in northern Anatolia. It is hoped that the Turkish Government will set up a modern seismometric network covering the areas of active fault. A working group should also be formed in the European Seismological Commission and the working group should present a report on research programmes of the Anatolian area to the next general assembly of the Commission. This program is also supported by UNESCO.

Although the writer does not know in detail what the working group is now planning, it is highly interesting and important that an international effort is going to be focussed on investigating the Anatolian activity. It appears that an Anatolian earthquake is apt to occur at a point which has not been subjected to a fault movement in recent years. One might choose such places as the candidates of the next activity. If observation tools are set up there well beforehand, the probability of catching premonitory effects would certainly be high.

GEODETIC WORK

Land deformations accompanied by a large-scale earthquake have often been reported in historical records. After the development of geodetic techniques, numerous examples of such land deformation have come to our knowledge even in the cases of relatively minor earthquakes. It is quite natural, therefore, to suppose that, if we repeat triangulation or levelling surveys over a seismically active area within a reasonably short interval of time, pre-seismic land deformations that would be smaller probably by one order of magnitude than the ones associated with the whole course of an earthquake might be detected.

Levelling surveys

Levelling surveys are less laborious than triangulation surveys, so that many an example of land deformation have so far been brought out on occasions of earthquakes. Even a number of examples that might indicate premonitory deformations have been reported. Since the first survey in 1898, a number of levelling surveys have been carried out along a levelling route passing through Niigata City on the Japan Sea coast in Japan. In order to check the ground subsidence which was said to be caused by the withdrawal of natural gas from the plain area, levelling surveys have been repeated with an unusually short time-interval since 1958. Upheavals as had been noticed at the bench marks in the northern portion of the route seem to have been increased to approximately five times the normal around 1955. The rate started to decrease after 1959, and a tendency toward subsidence was observed. A survey after the Niigata earthquake ($M = 7.3$) on June 16, 1964 made it clear that these bench marks considerably subsided as can be seen in Fig.2. Should the sudden change in the rate of anomalous land deformation be a premonitory effect, an earthquake warning should be provided by repeating levelling surveys every 5 years (TSUBOKAWA et al., 1964).

MESCHERIKOV (1968) presented an example of similar kind in relation to the 1966 Tashkent earthquake in the U.S.S.R. Fig.3 shows the changes in height at four stations in the Tashkent area. Stations A and B, located near the epicentre, have experienced an upheaval since 1900. The sign of movement changed around 1964 and a subsidence followed. During the period of seismic activity, an upheaval started again with an enormous rate that was 10–20 times larger than the previous one. Changes in height at stations C and D, which are distant from the epicentral area, are varied. But, like at stations A and B, a premonitory effect seems to have started about 25 years prior to the earthquake, at stations C and D also.

Summarizing many levelling results in Japan, Yugoslavia, Hungary, Alaska and the U.S.S.R., Mescherikov has concluded that three phases of crustal movements can be distinguished in seismic regions. They are: (*1*) slow movement revealed during the cycle between the bursts of seismic activity (α-phase); (*2*) pre-

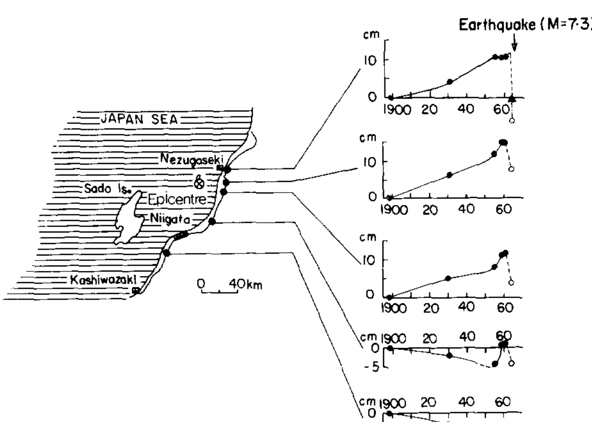

Fig.2. Anomalous changes in height at levelling bench marks before the 1964 Niigata earthquake (solid circles). The hollow circles indicate the heights as found by a levelling survey soon after the earthquake. The land subsidence at the time of the earthquake as estimated on the basis of the Nezugaseki tide gauge is marked by a solid triangle. (After TSUBOKAWA et al., 1964.)

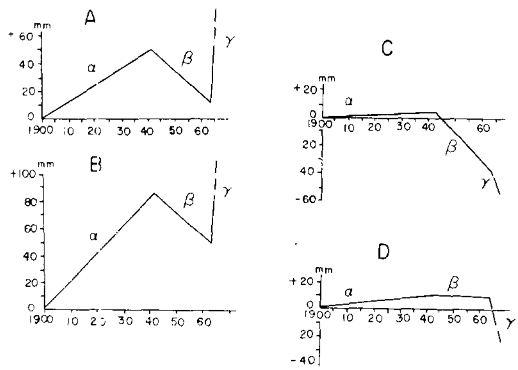

Fig.3. Three phases of crustal deformation as revealed by changes in heights. A, B in the epicentral area of the 1966 Tashkent earthquake; C, D at other non-epicentral stations. (After MESCHERIKOV, 1968.)

seismic crustal movement of coming earthquake (β-phase) and (3) movement caused by the earthquake (γ-phase). In Fig.3 are also noted these phases.

Mescherikov's classification seems to be received favourably by geodetists who are specifically concerned with crustal movement accompanied by earthquakes. Although the nature of the β-phase has not been clarified yet, detection of its start would have an important bearing on earthquake prediction. It has been empirically noticed that the larger the magnitude of an earthquake is, the longer is the period of the β-phase. Mescherikov pointed out that the β-phase of the Alaska earthquake ($M = 8$) had started not less than 40 years before the earthquake. I. Tsubokawa (personal communication, 1968) noticed that pre-seismic land deformation of an earthquake having a magnitude as small as 5 would become noticeable only a few months prior to the earthquake.

Repetition of levelling surveys is thus regarded as one of the most powerful means for indicating a probable seismic event in the future. The Japanese programme of earthquake prediction research requests to reestablish the first-order bench marks along the 20,000-km routes covering Japan every 5 years.

Triangulations and geodimeter work

A dense network of triangulation stations covers the Japan Islands. Whenever a large-scale earthquake occurs, a resurvey over the earthquake area is conducted in order to recover the correct positions of triangulation stations. It has been established by the resurveys hitherto conducted that a land deformation of the order of 10^{-4} in maximum strain is always associated with an earthquake having a magnitude 7 or larger.

As the labour and expense for triangulation survey are tremendous, it has not been practicable to repeat triangulation surveys with a time-interval comparable to levelling surveys. Although no advance land deformation prior to an earthquake has so far been discovered by repetition of triangulation surveys, it seems to be the general feeling of geodetists and seismologists that, if we repeat triangulation surveys over a seismically active area with a reasonably short time-interval, some premonitory effect should be observed before an earthquake. The Japanese programme stresses speedy repetition of triangulation surveys, i.e., it is recommended that the 330 first-order stations should be reoccupied every 10 years.

Recent development of the geodimeter, which measures a distance of some 20 km with a precision of one part in 100,000, enables us to repeat surveys equivalent to triangulation with a much shorter time-interval. According to the Japanese programme, rhombic base lines with lengths of about 10 km will be set up over a number of seismically active areas, and changes in lengths will be checked from time to time. Usefulness of geodimeter observation has been proved at the time of the 1965–1966 Matsushiro earthquakes. An enormous extension of land amounting to 116 cm in 3 km was reported during a 13 month's period. The increasing rate of ground length was found to be closely correlated with the seismic activity (KASAHARA and OKADA, 1966; KASAHARA et al., 1966, 1967).

Geodimeter observation is also intensively conducted by the California Department of Water Resources over the San Andreas fault zone (HOFMANN, 1967). Movement along the San Andreas fault is maximum near Hollister at 4.1 cm/year. It diminishes southward to zero near Los Angeles. Prior to the 1964 Corralitos earthquake ($M = 5.2$), a reversal of the fault movement was found. There are several examples of this sort preceding small earthquakes. More frequent repetition of measurements with a time-interval smaller than 1 year will be required in order to use the geodimeter work as one of the prediction techniques.

TIDE GAUGE OBSERVATION

There are a few historical records of rapid changes in sea level which clearly indicated the occurrence of anomalous land deformations prior to an earthquake. At the time of the 1872 Hamada earthquake ($M = 7.1$) that occurred on the Japan Sea coast in the western Honshu Island of Japan, for example, a considerable retreat of the sea water was reported before the main shock. Detonations and small-tremors had been felt there to several days before the main shock. The seismic activity having gradually increased, the retreat of the sea was observed at about 20 min before the main shock. It was reported that local inhabitants could walk on the exposed sea floor to an island 140 m off the coast and that they could pick up living shells there. A tsunami then attacked the area some time after the earthquake. According to the report by the staffs of the Hamada Weather Station, there is no doubt that the sea level lowered as much as 2 m or more at some places in the earthquake area. It is thus evident that a conspicuous land upheaval relative to the sea level took place prior to the earthquake.

Changes in sea level are nowadays recorded with tide gauges. Curiously enough, no changes clear as the one accompanied by the Hamada earthquake have ever been reported by tide gauge observation in recent years. Height of sea level is influenced by various environmental elements such as atmospheric pressure, water temperature and so on. In addition to these noises, we also have tides of large amplitude. Although the periodic tidal effect can approximately be eliminated by taking averages over a long period, say monthly or yearly means, the former noises are of serious obstacle in discussing a change in the height of sea level within a range of several centimeters. A conventional way of making the signal-to-noise ratio large in this case is to make differences in the observed height of sea level between neighbouring tide gauge stations.

We had two tide gauge stations in the vicinity of the epicentre of the 1964 Niigata earthquake (Fig.2). Fig.4 indicates the difference in the tidal record between the two stations Nezugaseki and Kashiwazaki (TSUBOKAWA et al., 1964). A land upheaval of a few centimeters can be seen in the figure since 1958, such an upheaval being compatible with the results of levelling work. In the middle of 1963, the land began to subside, and the main shock took place about 1 year later. The sea level indicates a sudden jump at the time of the earthquake as can be clearly seen in the figure. Nothing definite can be concluded from the changes shown in Fig.4 because we have no guarantee that the noises are completely eliminated by the difference technique. But the change of sign in the gradient that happened about 1 year before the shock might be a forerunning indication of the seismic event.

According to the Japanese programme, 92 tide gauge stations will be set up at intervals of approximately 100 km along the coast line of the Japan Islands. All the tidal records will be rapidly processed at a centre established in the Geographical Survey Institute. It is hopefully expected that anomalous land upheaval or subsidence, if any, could always be detected in this way.

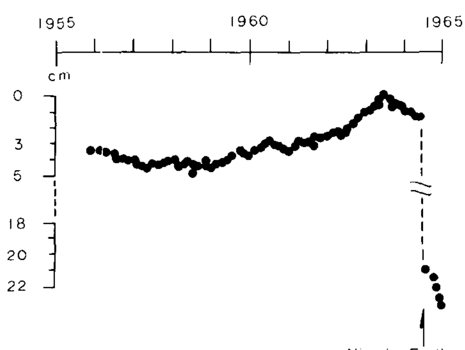

Fig.4. Changes in the monthly mean sea level at Nezugaseki relative to Kashiwazaki. (After TSUBOKAWA et al., 1964.)

CONTINUOUS OBSERVATION OF CRUSTAL MOVEMENT

No short-term change in crustal movement can be detected by geodetic methods which are essentially intermittent. For the purpose of watching crustal movement constantly, tiltmeters and extensometers have been and will be widely used. These instruments being highly sensitive to temperature change and other

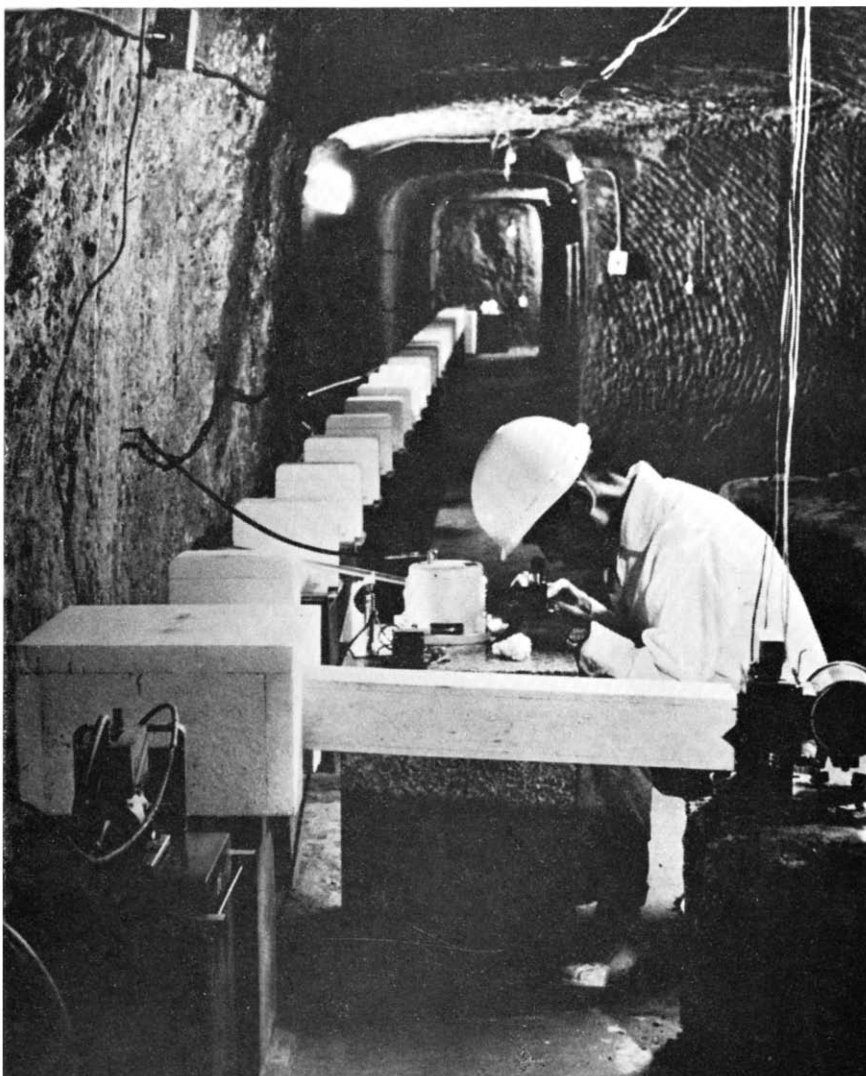

Fig.5. Interior of the Nokogiriyama Observatory for crustal deformation. An observer is measuring the height of water surface of a 25 m water-tube tiltmeter. A 25 m silica-tube extensometer with recording systems can also been seen in the picture.

environmental conditions of observation, it is required to set them up in an underground vault in order to attain a high signal-to-noise ratio.

The experience over many years of observation has led Japanese seismologists to an idea about how to construct an observatory for continuous observation of crustal deformation. A standard observatory is equipped with two sets of water-tube tiltmeters and horizontal pendulum tiltmeters and three sets of silica-tube or invar-wire extensometers. Fig.5 is a photograph showing the interior of one of the standard observatories in Japan. It is usually required to set up tiltmeters and extensometers in underground galleries of a few tens of meters in length which are at least as deep as 30 m from the entrance of the fault. In a modern observatory of this kind, some additional instruments such as laser strainmeters and the like are also installed. Remote recordings and digitalization of records are now becoming popular. The Japanese 5-year plan includes the construction of nineteen observatories all over Japan.

Tiltmeters

It has been known that a horizontal pendulum type tiltmeter is very sensitive to local disturbances. Tilting observed by it represents only that of the tripod on which the tiltmeter is mounted. A large drift, which probably has nothing to do with the general ground tilt, is sometimes observed. Most seismologists therefore believe that a horizontal pendulum tiltmeter may be used only for observing a sudden change.

A water-tube tiltmeter, by which the heights of water surface at two reservoirs about 30–40 m apart are compared, is thought to indicate ground tilt averaged over its length. Ground tilt as observed by a set of water-tube tiltmeters approximately coincides with that revealed by a repetition of levelling surveys along a route running nearby the observatory. It is the general agreement between seismologists that even a slow ground tilt may be reliably detected if it is observed by a set of water-tube tiltmeters.

Present-day advancement of electronics seems to call the revival of the horizontal pendulum tiltmeter. There is a possibility of detecting true ground tilt by making use of an array of tiltmeters of this kind. Even simple pendulum or inverted pendulum could be used as a tiltmeter that can possibly be installed in a deep bore-hole. These instruments are now at their developing stage.

Soon after the outbreak of the Matsushiro earthquakes, two components of water-tube tiltmeters 40 m in length were installed in a vault of the Matsushiro Seismological Observatory operated by the Japan Meteorological Agency. Remarkably large changes in the inclination of the ground were brought to light by the tiltmeters as can be seen in Fig.6 in which we can also see that these changes are strongly correlated with the growth and decay of seismic activity. The tiltmeter observation during the Matsushiro events thus provided a powerful tool for a long-term estimate of seismic activity (HAGIWARA et al., 1966; HAGIWARA and RIKITAKE, 1967).

Fig.7 illustrates an example of anomalous tilt of the ground as detected by the water-tube tiltmeter when the Matsushiro activity was extremely high. A number of tilting events of this sort were observed shortly before earthquakes of magnitude 5 or so. Very roughly speaking, these precursory tilts took place approximately in a direction connecting the epicentre to the observation point although we also observed exceptional directions in some cases. Focal depths of the earthquakes accompanying such anomalous ground tilt were shallower than 5 km. The magni-

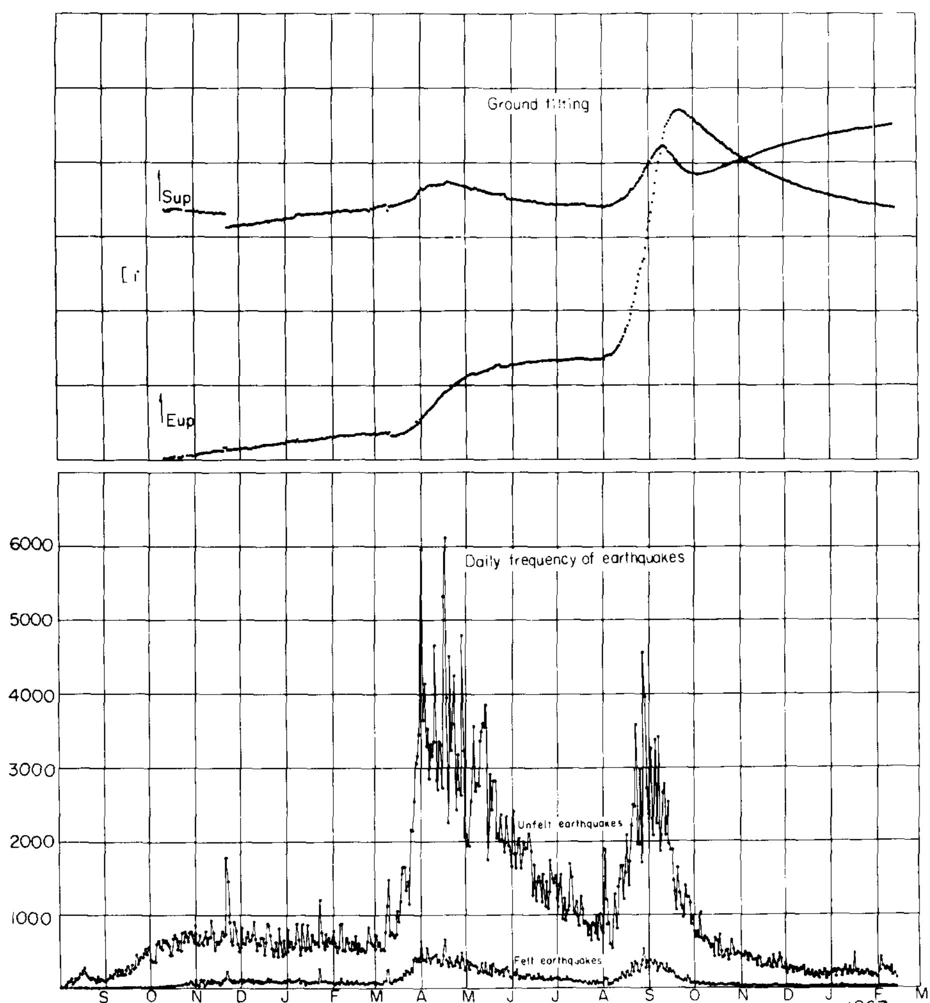

Fig.6. Changes in ground tilting and daily number of unfelt and felt earthquakes during the Matsushiro earthquakes. (After HAGIWARA and RIKITAKE, 1967.)

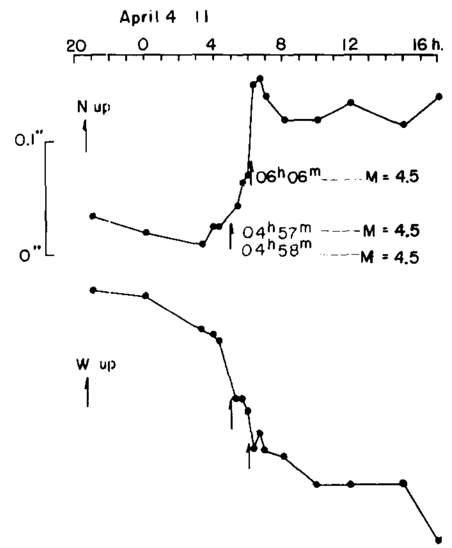

Fig.7. A change in the ground tilting prior to a series of earthquakes. A sharp change in the direction of tilting, started at about 3 a.m., was followed by three strong shocks all occurring northeast of the observation point within a hypocentral distance less than 10 km. (After HAGIWARA and RIKITAKE, 1967.)

tude of precursors seems to be the largest when the distance between the observation point and the epicentres are several kilometers. It would be physically acceptable that very near earthquakes probably accompany fairly uniform upheaval or subsidence of the ground around the observation point, so that no large tilts would be observed when an earthquake occurs immediately beneath the tiltmeter.

A few more reports of precursory effects as detected either by water-tube or horizontal pendulum tiltmeters have been put forward on other occasions of seismic event in Japan. According to SAVARENSKY (1968), tiltmeter observation is also carried out at many stations in the U.S.S.R. The observation at the Dushanbe Station in Tajikistan revealed the so-called S-type disturbances a few days prior to earthquakes having epicentral distances less than 100 km though some of the earthquakes were not accompanied by such forerunners.

In the light of the above examples, tiltmeter observation might be one of the most promising tools of detecting forerunners of seismic event. However, more data should be accumulated in order to achieve a practicable forwarning by tiltmeter observation because no general character of the forerunning effect has been firmly established yet.

Extensometers

In contrast to tiltmeter observation, very few forerunning effects have been reported by extensometer observation. This is probably because the history of extensometer observation is not long enough. We see no reason why some effects should not be detected by extensometers. Silica-tube extensometers are widely used in Japan as well as in the U.S.S.R.

Detectability of pre-seismic deformation

The over-all sensitivity of observing crustal deformation by the instruments such as used in Japanese observatories are estimated to be 10^{-1}–10^{-2} seconds of arc for inclination and 10^{-7}–10^{-8} in linear strain when a usual noise-level is assumed. When we take the frequency of occurrence of earthquakes which give rise to a pre-seismic crustal deformation of the cited order into account, the proposed coverage of an observatory net over Japan would result in possible detection of premonitory effect once or twice a year. Supposing that observation by the network is maintained over 10 years, we would hope to have a sufficient set of data in analyzing forerunners (K. Kasahara, personal communication, 1968).

SEISMIC ACTIVITY AND SEISMOLOGICAL METHOD

Investigation of seismicity is certainly the most basic part of earthquake prediction research. Considerable effort has recently been made toward establishing seismometric networks in many countries. Even in a country like Japan, which is covered by a dense network for seismic observation, however, it is not possible to accurately locate all earthquakes of $M \geqq 3$. Further completion of observation network is therefore urgently needed in order to see the over-all seismicity in Japan.

Recent advancement of seismometry enables us to observe microearthquakes ($3 > M \geqq 1$) and ultra-microearthquakes ($1 > M$). Observation of very small earthquakes has raised many important points. What is the relationship in space and time between large and small earthquakes? How are microearthquakes correlated with geologic and geotectonic structure? Would it be possible to make use of microearthquakes for inferring possible occurrence of a much larger earthquake? These points have an important bearing on earthquake prediction research.

Strain release and microearthquakes

ALLEN et al. (1965) constructed a strain-release map of southern California during the 1934–1963 period. The strain release has been dominated by a few large earthquakes that occurred on or near major faults. The low strain-release area, about 100 km northwest of Los Angeles, is identified as the portion of the San Andreas fault where the 1857 Fort Tejon earthquake, which shook a widespread area comparable to that of the 1906 San Francisco earthquake, took place. A microseismicity study (BRUNE and ALLEN, 1967) also indicates a very low activity along the fault segment associated with the 1857 earthquake. The microearthquake activity south of Los Angeles shows a marked identity to the strain-release pattern mentioned above. It is suggested that, in the area of higher microearthquake activity, the accumulating tectonic strain may be released by many smaller earthquakes because of structural weakness, and the earthquake area of the great 1857 earthquake may be characterized by a high structural strength possibly due to some locking mechanism.

AKI (1968), who examined strain release not only in California but also in Japan, emphasizes the following two points:

(*1*) The regional pattern of microearthquake activity is grossly similar to the seismicity pattern of larger earthquakes.

(*2*) The response of the crust to regional tectonic stress differs from place to place even in the same general tectonic area, resulting in a complex pattern of strain concentration and microearthquake activity.

ASADA (1957) was the first to point out that the Gutenberg-Richter relation:

$$\log N = a - bM$$

holds for earthquakes of M from less than zero up to 5 or thereabouts, where N is the number of earthquakes having a magnitude M. a and b are constants. The fact suggests that microearthquake observation over a certain area may well represent the over-all seismicity there. According to the Japanese programme, emphasis has been made to the construction of nineteen microearthquake observatories, which have a number of satellite stations, and also to the establishment of several field parties equipped with ultra-microearthquake seismographs. The parties will conduct field observations over seismically important areas. It is thus hoped to eventually bring out the whole features of microearthquake and ultra-microearthquake activities all over Japan. If some change in the activity pattern should be observed over a particular area, it would certainly be worthwhile intensifying all sorts of observation because something extraordinary might be going on in the earth's crust there.

Classification of earthquake provinces

An important suggestion about possible classification of earthquake areas was made by T. Asada (personal communication, 1967). He pointed out that the following classification of earthquake provinces may be made:

(*A*) Intrinsically non-seismic area.

(*B*) Steadily earthquake-generating area.

(*C*) After-shock area.

(*D*) Post after-shock area.

A is a district where seismic activity has been extremely low (a Japanese example is the interior of the Hokkaido Island). Probability of expecting a large-scale earthquake would be very small in such a district. Asada is of the opinion that there are *A* areas which have a much smaller extension.

In a *B* area, earthquake occurrence is more or less steady (an example is the crust immediately off the Pacific coast of northeastern Japan), so that the largest magnitude of earthquakes originating there has been (and will be) limited. If the frequency of earthquake occurrence is governed by the well-known Omori formula in an area where we had a large earthquake some time in the past, the area may be identified as *C*. In a *C* area, no appreciable strain energy would be accumulated as yet. Area *D* is characterized by the mode of earthquake occurrence which is different from the Omori formula (the southern Kanto area in Japan seems to belong to this category). In such an area, after-shocks accompanied by a great earthquake in the past seem to have been terminated. Since the probability of being attacked by a great earthquake is thought to be high in *D* areas, every effort toward earthquake prediction should be made in such areas.

Asada's working hypothesis is important in the fact that it is useful for choosing targets of concentrating prediction observations. In a country like Japan where we do not identify major faults such as the Anatolian and the San Andreas ones, it would be wise to choose fields for prediction research according to the working hypothesis. It would be urgent to form a chart on which the said classification of earthquake provinces is indicated.

Microearthquake work over the Matsushiro area

The 1965–1966 Matsushiro earthquakes provided an excellent opportunity to conduct microearthquake observation and to test various ideas about the relationship between large earthquakes and small ones although it would be dangerous to generalize the Matsushiro experience for earthquake events of different kind.

Earthquakes of magnitude 5 or thereabouts frequently occurred in the seismic area during the Matsushiro activity. The tripartite and mobile observations of ultra-microearthquakes brought out a fact that very small shocks had been occurring, without exception, in the epicentral area of the main shock a few months earlier. This finding is certainly an important progress in the study of the relationship between small and large earthquakes although the time-interval between the ultra-microearthquake swarm and the main shock has not been worked out. No remarkable increase in the number of small shocks was reported immediately before the main shocks. At any rate, ultra-microearthquake observation played an important role on predicting long-range activity of the Matsushiro earthquakes.

K. Hamada (personal communication, 1968), who carried out an extensive observation of ultra-microearthquake over the Matsushiro area, presented a very interesting result concerning the statistical frequency of time-interval of small-shock occurrences. Fig.8 shows the day-to-day changes in the cumulative frequency versus time-interval relations before and after a moderately large earthquake ($M = 5.1$) that occurred at the northeastern margin of the Matsushiro seismic area on October 26, 1966. The thin straight lines in the figure indicate the cumulative frequency calculated on the condition that microearthquakes were taking place at random with a certain probability. Such a probability is calculated from the observed data. The standard deviations of the theoretical frequency are also shown in the figure with two thin curves. If the occurrence time-interval is random, about 70% of cumulative frequency should be found within the hatched area bounded by the two curves.

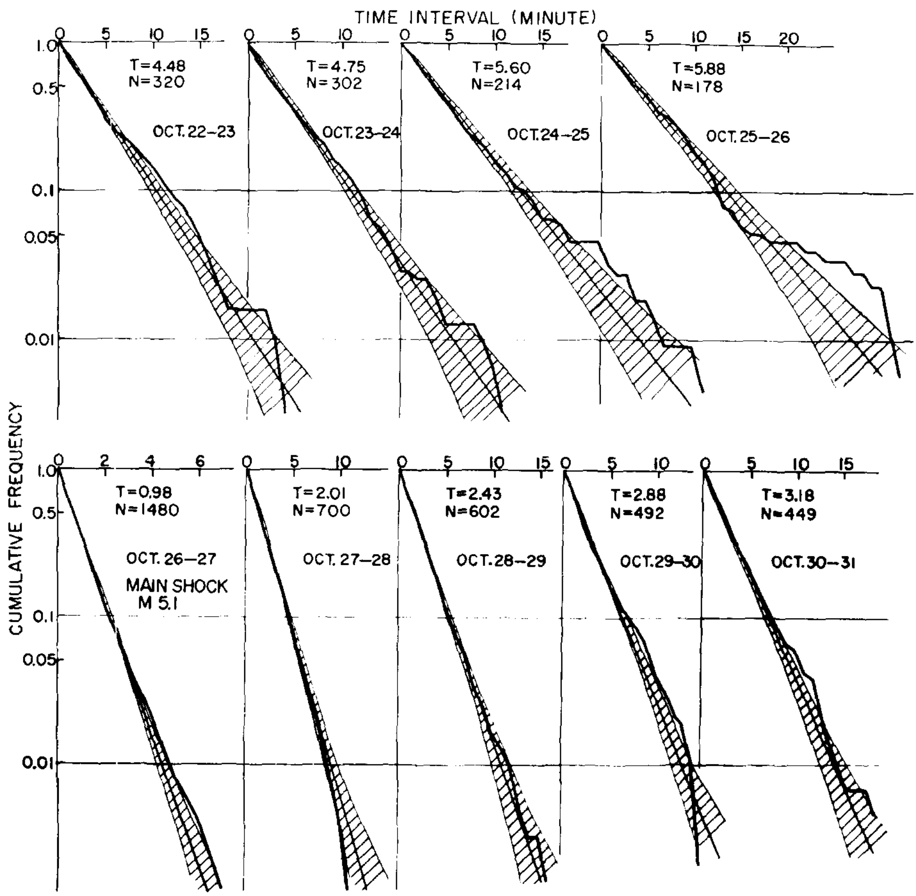

Fig.8. Day-to-day change in the cumulative frequency of time-interval of microearthquakes before and after a moderately large earthquake on October 26, 1966. T and N denote respectively the mean time-interval in minutes and the total number of shocks. (After HAMADA, 1968.)

According to K. Hamada, no marked deviation from random occurrence of microearthquakes has been noticed from October 22–24. But a tendency for occurrence of microearthquakes with time-intervals longer than 20 min became appreciable during the pre-earthquake period of October 25 and 26. After the main shock, microearthquakes tended to occur randomly again. Such systematic changes in the mode of microearthquake occurrence have been noticed a few times in association with moderately large earthquakes ($M = 5$) which took place at marginal areas of the Matsushiro activity. Although it is not clear why we observe such changes in occurrence-mode of microearthquakes, possible application of such a time-interval method to prediction techniques is suggested.

SEISMIC WAVE VELOCITY

When the earth's crust is strongly strained, one might expect changes in physical properties of rocks composing the crust. Much of suppositions of this kind bases on laboratory experiments that will be reviewed later (Fig.16). A few examples that changes in seismic wave velocities are actually observed before and after an earthquake event have been reported.

According to SAVARENSKY (1968), Kondratenko and Nersesov examined travel-time curves of relatively small earthquakes before and after moderately large earthquakes ($M \geqq 5$), originated in a region between Garm and Djirgital in Tadjikistan in southern central Asia during a period from 1958 to 1961. More than 800 shocks were used for the study. A systematic difference in the statistical travel-time curves of the P-wave passing through the epicentral area between those before and after main shocks was found. The P-wave velocity amounts to 5.3 km/sec before strong earthquakes, while it becomes as high as 6.3 km/sec after the shocks, so that a 15% increase in the P-wave velocity is associated with seismic events. Whether or not such a large change in seismic wave velocity is physically acceptable is not known. If it is interpreted in terms of a change in elasticity, some 30% change must be assumed. Since no results of this sort except the above example have been reported in recent years, it would take some time to reach an established conclusion about possible changes in seismic wave velocities prior to a strong earthquake.

A much more accurate measurement of changes in seismic wave velocity, if any, could be achieved by measuring arrival-time of seismic waves from man-made explosions. The first step toward this kind of work was put forward by the Stanford Research Institute. EISLER (1966) made explosion experiments at Salinas in the Gabilan Range, California. Arrival-times of the P-wave were measured at a point 42 km distant from the shot point. Repetition of explosions with 100 kg explosives led to a conclusion that the source function is amazingly constant and also that the error of arrival-time measured is smaller than $\pm$ 1 msec. If we conduct explosion tests of this kind from time to time, it is highly probable to reach a conclusion whether or not seismic wave velocity is subjected to a change. Similar experiments are now undertaken in the Matsushiro area and also in the southern Kanto area in Japan although several years' work would be needed in order to reach a well-established conclusion.

GEOTECTONIC WORK

Occurrence of earthquakes along the Anatolian and San Andreas faults clearly indicates that earthquakes are closely correlated with active faults. Considerable attention has been paid to study the movement of fault and folding in Japan as well as in the U.S.S.R.

Fig.9 shows the geology and the vertical movement in the neighbourhood of the Surkhob fault in the highly seismic Garm area in the U.S.S.R. (MESCHERIKOV, 1968). Precise levelling surveys have been systematically conducted there since 1957. It is surprising that one side of the fault indicated an upheaval with a velocity amounting to 10 mm/year while another side did not show any movement. The transition zone has a width as small as 200 m. According to a geomorphological study there, it is concluded that a movement forming a 55 m river terrace has been taking place over a period of 5,000 years. The agreement between the geomorphological and geodetic data is excellent, so that it is reasonably concluded that the movement has more or less continued over the period cited above.

Geologists and geographers are now working hard on tracing active faults and foldings in Japan. No faults which exhibit present-day creep movement have been found in Japan, so that search is made for faults which show evidence that they were active some time in the Late Quaternary. In contrast to present-day

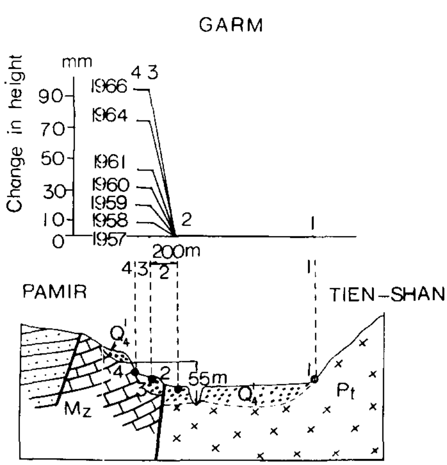

Fig.9. Vertical movement and geology around the Surkhob fault. (After MESCHERIKOV, 1968.)

active faults like the San Andreas, these faults do not seem to be subjected to any measurable movement in recent years, but geomorphological study brought out that considerable movement of these faults must have taken place during the past 10^5–10^6 years. In the central area of Japan, a few faults with evidence that they made creep deformation with a speed amounting to 1–5 m/1,000 year have been found. It is feared that these fault movements might result in large-scale earthquakes some day. Judging from the rate of deformation and the strength of the crust, the average interval of earthquake occurrence would be from several hundred to one thousand years (T. Matsuda, personal communication, 1967). Occasional geodetic and geodimeter surveys are now undertaken over these fault areas.

Japan's peninsulas on the Pacific coast are characterized by a secular seaward dipping (7 mm/year at one of their extremities) and also by a sudden 1–2 m upheaval of their extremities at times of great earthquakes occurring off the coast. Recent geomorphological study made it clear that the rate of upheaval during the past 10^5 years has been approximately the same as it is now. If so, repetition of large-scale earthquakes there with a 100–200 year time-interval as reported in the historical records could be extended to the period at least 10^5 years ago. This in turn suggests possible repetition with the same interval in the future.

Numerous examples of large earthquakes of magnitude 6 or larger that originated from areas where foldings are under way at present have been reported in Japan. Great care should be taken to watch the rate of folding constantly.

Unlike earthquake fields in the U.S.A., Turkey and the like, everything related to earthquake occurrence seems complex in Japan. It would be almost impossible to cover all active faults and foldings with first-class observation networks at the same time even if the prediction programme develops as expected. It is planned therefore that, if something extraordinary is found by some means at a particular site, all sorts of observation will be immediately focussed there.

GEOMAGNETIC AND GEOELECTRIC WORK

Coincidence of geomagnetic as well as geoelectric phenomena and earthquakes has often been reported since the 18th century. In classical literature in Japan, we find a report that all nails and iron pieces being attracted to a huge horse-shoe magnet at an optician's in Edo (new Tokyo) dropped to the ground about two hours prior to a destructive earthquake in 1885. Probably, one of the most complete summary reports on these phenomena in the early days would be the one due to MILNE (1890).

A study with the intention of clarifying the relationship between geomagnetic change and earthquake was first conducted in relation to the 1891 Nobi earthquake (TANAKADATE and NAGAOKA, 1893). Studies of similar sort have further been carried out by many investigators, notably by KATO (1939).

The present writer (RIKITAKE, 1968a) made a survey of these existing data of geomagnetic changes associated with earthquakes. It was then pointed out that the amount of change has been steadily decreasing from some 1,000 to 10 gammas since 1891. Most likely such a marked decrease amounting to two orders of magnitude does not mean that the seismo-magnetic change itself decreases as years advanced. But the development of measuring technique along with that of noise-elimination technique must well be demonstrated by such a decrease. The writer is of the opinion, therefore, that seismo-magnetic effects as reported in classical literature are not reliable.

Modern magnetometers and seismo-magnetic effect

Very accurate observation of any element of the geomagnetic field over a long period of time, say months and years, has been a difficult task until recent years. Only at a well-equipped observatory has it been possible to perform a long-period geomagnetic observation with an accuracy of $\pm$ 1 gamma. However, invention of the proton precession magnetometer and optical pumping magnetometer has drastically changed the situation. Being both based on atomic constants, the absolute values measured with these magnetometers are scarcely affected by environmental conditions of observation and so they are practically free from any drift.

The Japanese programme of earthquake prediction research puts much stress particularly on observation of geomagnetic changes with proton precession magnetometers. Some twenty observatories equipped with the magnetometers specially designed for the programme will be at work all over Japan when the 5-year plan is completed. A proton precession magnetometer is also suitable for field observation because no skill is required for an observer. An array of six proton precession

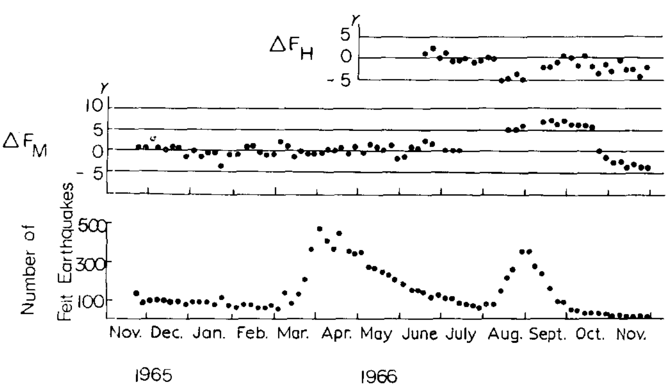

Fig.10. Five-day means of the local anomalous changes in the total geomagnetic intensity values at two stations in the seismic area of the Matsushiro earthquakes. The bottom curve indicates the number of felt earthquakes. (After RIKITAKE, 1968a.)

magnetometers was set up over the Matsushiro earthquake area (approximately 20 by 50 km) in association with the 1965–1966 Matsushiro earthquake. Fig.10 indicates the changes in the total intensity of the geomagnetic field at Matsushiro (F_M) and at another station (F_H) about 6 km north of Matsushiro. ΔF_M and ΔF_H are obtained relative to a standard magnetic observatory about 200 km apart from the seismic area. In association with the seismic activity towards August, 1966, we see an increase of the order of 10 gammas in ΔF_M and decrease of the same order in ΔF_H. Enormous upheaval and extension of land have also been observed at this epoch of activity. If we assume an intensification of the magnetization of the earth's crust, the anomalous change in the geomagnetic field could be physically understood (RIKITAKE et al., 1966a, b, c, 1967a, b). To the writer's knowledge, this is the first and only seismo-magnetic effect as observed by proton precession magnetometers.

An extensive work of detecting seismo-magnetic effects by an array of rubidium magnetometers, a type of optical pumping magnetometer, has been carried out by BREINER (1967) over the San Andreas fault area. An array of five magnetometers was first established with an approximately 30-km interval along the fault from San Francisco due south to Hollister (Array I). A denser array (Array II) over a distance of about 25 km was later formed around Hollister which is famous for occasional fault creeps as observed at a winery. All the signals were telemetered to Stanford University on telephone lines.

During a 1.5 year observation period by Array I, Breiner observed a number of anomalous geomagnetic changes only at Hollister. These changes usually lasted a few minutes and had an amplitude of 1 gamma or smaller. As the geomagnetic fields at each station were recorded relative to the one at the centre of the array and their changes are somewhat different from station to station on magnetically disturbed days, it is possible that some of the anomalous changes were not

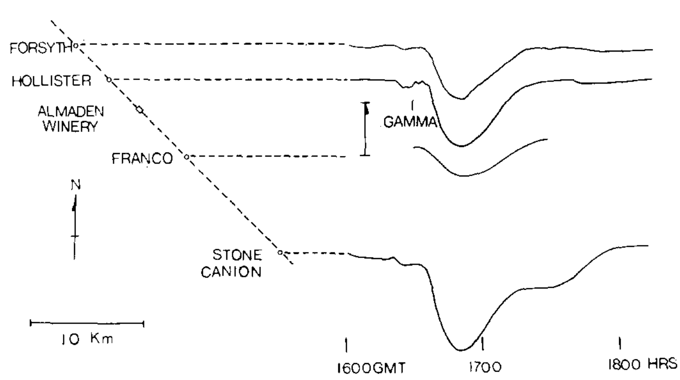

Fig.11. Local magnetic event at stations of Array II on April 18, 1967. (After BREINER, 1967.)

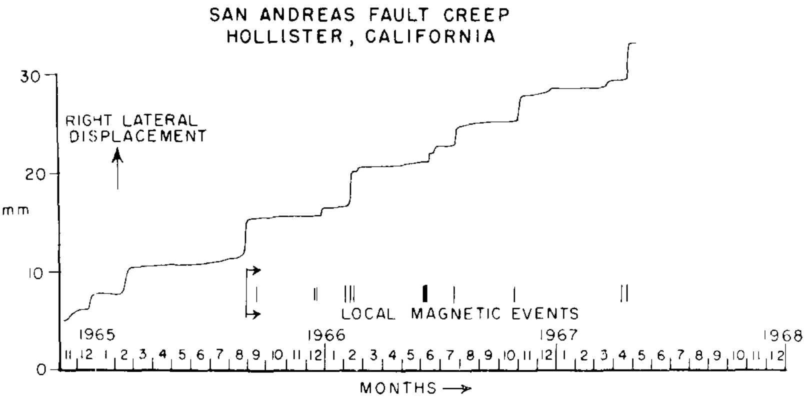

Fig.12. Fault creep at Hollister and magnetic events. (After BREINER, 1967.)

noticed. However, close coincidence of such change and sudden creep displacement, which usually takes place a few days later, has been noticed.

A very interesting local magnetic event was observed on magnetometers of Array II on April 18, 1967 (Fig.11). A large amount of creep was observed on the next day. A series of local earthquakes also occurred from April 20 to 22, the largest magnitude of which was 3.6 occurring in the central part of the array. Fig.12 indicates the occurrences of creep displacements at Almaden Winery together with those of the local magnetic events. We can easily see in the figure the forerunning character of magnetic event.

Geomagnetic noises to seismo-magnetic effect

A local magnetic change can be detected relative to a standard station which is far from the anomalous area. Recent studies have revealed that a simple difference between field values simultaneoulsy observed at two stations at moderate distance is subjected to a serious error which far exceeds the accuracy of measurement by modern magnetometers.

In Fig.13 are shown the standard deviations of statistical distribution during a three-month period of simple difference values in the total geomagnetic intensity between all the available stations in the central part of Japan as plotted against the distances between stations. The observations are made six times at about 1 o'clock local time. It is seen that the standard deviation of comparison is so large on disturbed days that it exceeds 5 gammas for stations some 250 km apart from one another. Even on quiet days, the standard deviation exceeds 2 gammas. If one compares daytime data, the dispersion is even larger.

Such an inequality of the instantaneous level of the geomagnetic field seems likely to be caused mostly by inhomogeneity of electric currents induced in the earth by geomagnetic variations arising outside the earth. A comparison between

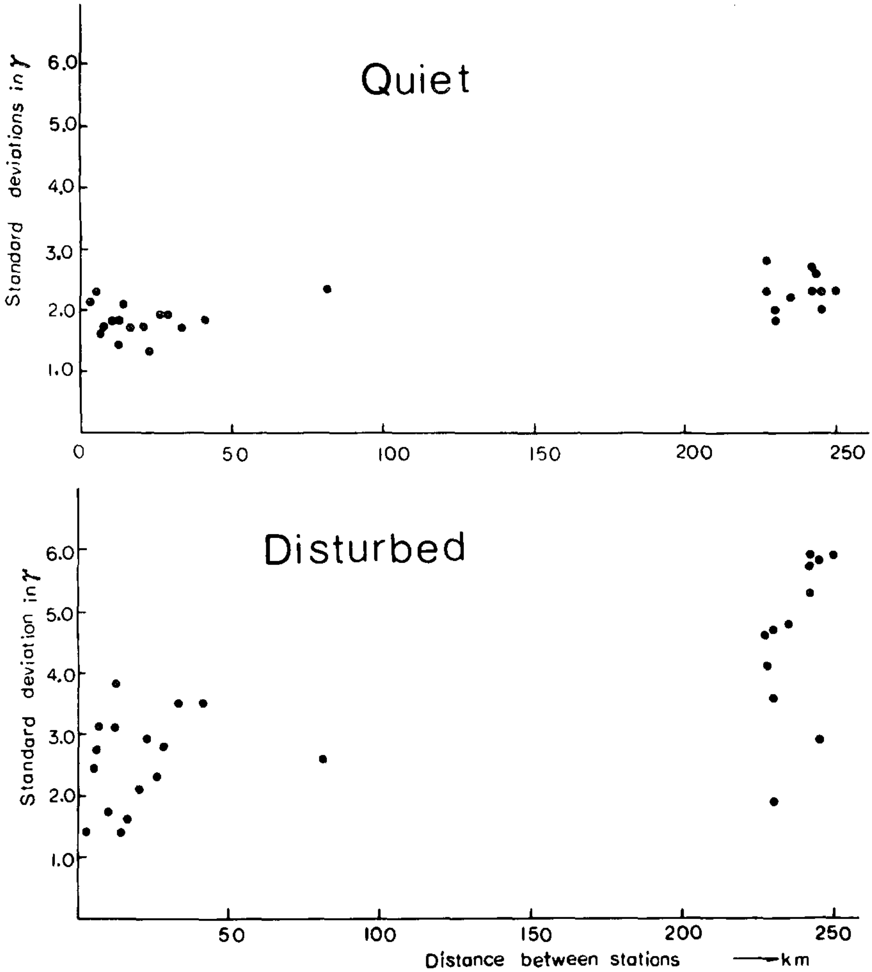

Fig.13. Standard deviation of statistical distribution of difference in the total geomagnetic intensity value between two stations as plotted against the distance between the two stations for magnetically quiet and disturbed days. (RIKITAKE et al., 1968.)

two stations, only 7 km apart, on an island resulted in an astonishingly large dispersion (RIKITAKE et al., 1968).

In the light of such noises of natural origin, the detectability of seismo-magnetic effect is limited. Studies on lessening geomagnetic noises are now intensively under way. It has already been established that techniques of weighted difference and of mixing signals from a number of magnetometers are useful. It is hoped to reach eventually some means by which the signal-to-noise ratio will be improved to a large extent.

Repetition of magnetic surveys

Anomalous secular variations in the geomagnetic field have sometimes been found by repetition of magnetic surveys. Unlike the work in the earlier days, much care is nowadays taken of occupying exactly the same magnetic station and of reducing the observed values to those at a standard observatory. TAZIMA (1966) reported that the over-all accuracy of the Japanese first-order magnetic survey is $\pm$ 4 gammas.

Fig.14 represents an anomalous change observed at a station on Kii Peninsula in central Japan. The anomalous gradient of the change in the horizontal intensity

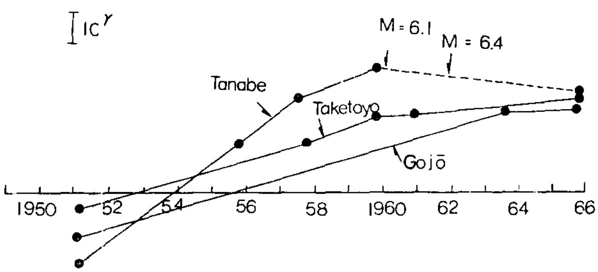

Fig.14. Anomalously large secular variation in the geomagnetic horizontal intensity at Tanabe on Kii Peninsula, Japan. The changes at the neighbouring stations, a few tens of kilometers distant from Tanabe, are also shown. Occurrences of the two earthquakes in the vicinity of Tanabe are indicated together with their magnitude. (After TAZIMA, 1966.)

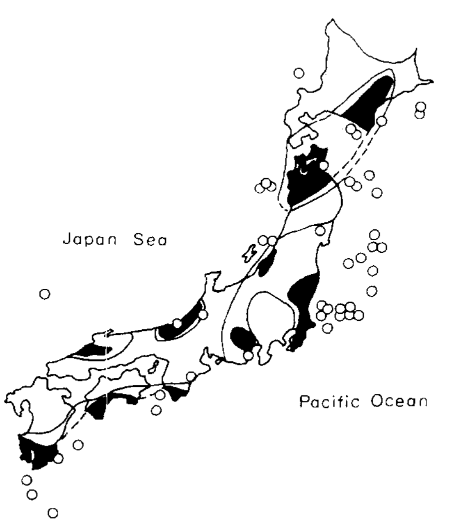

Fig.15. Areas in which we observed anomalous secular changes in the geomagnetic field from 1955 to 1960. Earthquakes of magnitude 6 or larger are indicated with small circles. (After TAZIMA, 1966.)

seems to vanish after two successive earthquakes. The areas over which such anomalous secular changes were observed during the 1955–1960 period are indicated in Fig.15. Except the anomaly in the western part of Honshu Island, most of the anomalous areas seem to be closely correlated with major earthquakes.

Possibility of detecting premonitory magnetic effect

Present-day advancement of geomagnetic measurement makes it possible to observe a local change of 1 gamma although the over-all accuracy of detection would be a few gammas because of geomagnetic noises. Theoretical studies on seismo-magnetic effect (STACEY, 1963, 1964; YUKUTAKE and TACHINAKA, 1967) indicate that a local change of the order of 10 gammas could well be expected to occur in association with an earthquake of moderate magnitude. It is hopefully expected to detect a local magnetic change, probably amounting to a few gammas or so, which precedes an earthquake of magnitude 6 or larger, by an extensive use of modern magnetometers.

Earth currents and earthquake occurrence

Most of the changes in earth currents are caused by rapid geomagnetic variations of ionospheric origin. However, numerous earth-current events have also been reported in association with earthquake occurrences since the last century. Reports on these events are fragmentary, so to speak. No general rule as to what type of earth-current change takes place in association with what kind of earthquakes has been known. Earth-current observation over a long period of time is in general a difficult one to carry out because of the instability of contact potential at the electrodes. Although possibility of detecting a premonitory effect by earth-current observation cannot be ruled out, it would take some time until we arrive at a clear-cut conclusion about the relationship between earth currents and earthquake.

LABORATORY WORK AND ITS APPLICATION IN FIELDS

Much of earthquake prediction research programmes has been planned mostly on the basis of observational experiences over a long period of time without entering into physical mechanism of earthquake occurrence. Very little has been known about theories which explain how crustal deformation, microearthquake, change in the geomagnetic field and so forth are correlated with an earthquake occurrence. Solid advancement in earthquake prediction research can be expected only when we firmly establish the physical basis of various items involved in the programmes. In this connection, it is very important to promote study on "laboratory earthquake" for which we may perform very detailed investigations. In other words, studies on microfracturing, changes in rock properties under stress and the like should be highly encouraged in order to provide theoretical background of earthquake prediction research.

Microfracture

Probably MOGI (1962) was the first who paid attention to the importance of microfracturing of brittle substance under stress. One of the conclusions reached by his experiments is that numerous shocks associated with microfracture production take place prior to the main shock accompanied by breaking of the specimen under experiment of heterogeneous material. It is also made clear that, if the specimen is highly homogeneous, no premonitory shocks are observed and also that no conspicuous main shock occurs when the specimen is extremely heterogeneous.

BRACE (1968) reported on further extension of Mogi's pioneering work to experiments under high confining pressures. An enormous increase in microfracturing occurrences is found above 95 % of the fracture stress as shown for a granite

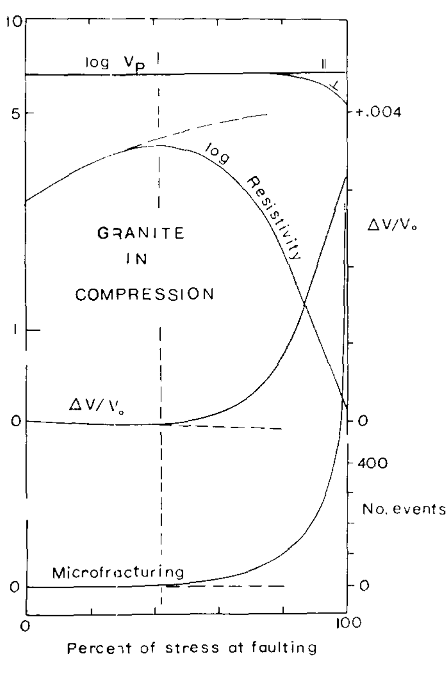

Fig.16. Changes in properties of granite with compressive stress. Data are for westerly granite under several kilobars confining pressure. Microfracturing data from SCHOLZ (1967). (After BRACE, 1968.)

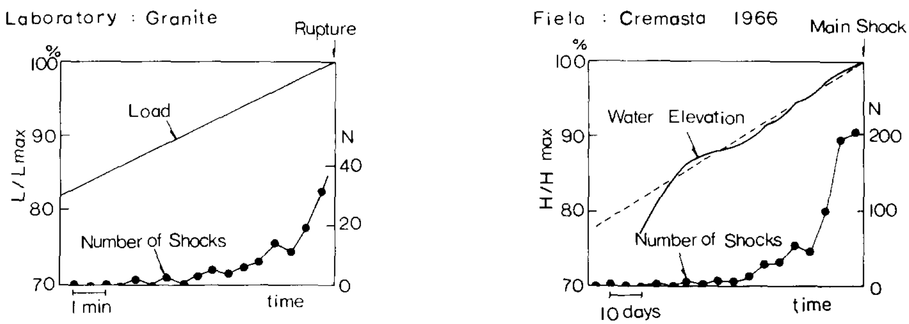

Fig.17. Similarity between the Cremasta Dam earthquake and a rock breaking test on granite. (After MOGI, 1968.)

specimen in Fig.16. SCHOLZ (1967), who measured first arrivals of the S-waves while a granite sample was compressed, found that microfracturing events cluster around a surface close to the eventual fault plane.

It has recently been found that fractured rock can support high stress (BYERLEE, 1967) and so frictional sliding is suggested to be a cause of earthquakes. A clear difference between brittle fracture and frictional sliding has emerged, both in terms of the frequency–magnitude relation and in the way in which activity varies with stress just before fracture or sliding. According to BRACE (1968), it would seem that earthquakes due to frictional stick-slip might be very difficult to predict from the pattern of microfracturing. On the other hand, earthquakes due to brittle fractures might be preceded by: (*1*) acceleration of microseismic activity and (*2*) clustering of small shocks.

K. Mogi (personal communication, 1968) reported on extremely close similarity between foreshocks experienced by a laboratory experiment and those associated with the water-loading of a Greek dam which finally resulted in an earthquake of $M = 6.3$ on February 5, 1966 (Fig.17). Although we do not know whether or not the law of similitude holds exactly between the experiment and the actual event, usefulness of measuring precursory shocks for earthquake prediction is well demonstrated at least in this example.

Piezomagnetic effect

KALASHNIKOV (1954) showed that magnetic susceptibility of rocks decreases with compressive stress. Possibility of making use of the effect for earthquake prediction has been argued notably by STACEY (1963, 1964). NAGATA and KINOSHITA (1967) reported on an enhancement of the effect when a sample is under a hydrostatic pressure.

The effect of uniaxial compression on remanent magnetization is varied and poorly understood. But recent experiments on Japanese rocks(H. Kinoshita and M. Ohnaka, personal communication, 1967) brought out a decrease rate of magnetization in the direction of compression of the order of 10^{-4}/bar. We may well expect that changes of the cited order would be given rise to when the effects on both susceptibility and remanent magnetism are taken into account.

Theories based on such a piezomagnetic effect (STACEY, 1963, 1964; YUKUTAKE and TACHINAKA, 1967) suggest changes in the geomagnetic field of the order of 10 gammas provided a stress of 100 bar or there abouts is assumed. Seismo-magnetic effect is important in the fact that it reflects stress state in the earth's crust. If a homogeneous crust is largely strained, a relatively large seismo-magnetic effect could be expected although very few microearthquakes would be produced prior to rupture (MOGI, 1962).

Electric resistivity

BRACE and ORANGE (1966) measured electric resistivity of saturated rocks under high pressures. For a range of low pressure an increase in resistivity with increasing pressure is found. The reason of such an increase would be the closure of crack pores. An enormous decrease then follows when the compressional stress exceeds a certain value. This seems to be accompanied by newly-produced micro-fractures (Fig.16). The result would seem to suggest a new technique of earthquake prediction. If resistivity deep in the epicentral area could be constantly measured, an enormous decrease in it should be detected before the main rupture. It would not be easy, however, to conduct such an observation in a field because of the need of great electric power and man-made and natural noises to the observation.

YAMAZAKI (1965, 1966, 1967) found that electric resistivity of a porous rock of particular kind is very sensitive to stress. The rate of change in the earth resistivity is larger than that of the earth deformation by a factor of about 1,000. An interpretation of conduction mechanism for such rocks has been presented by RIKITAKE and YAMAZAKI (1967). Yamazaki made an unusually sensitive resistivity variometer; changes in the resistivity caused by tidal loading have been observed at one of the near-coast observatories in Japan (Fig.18). The variometer could be

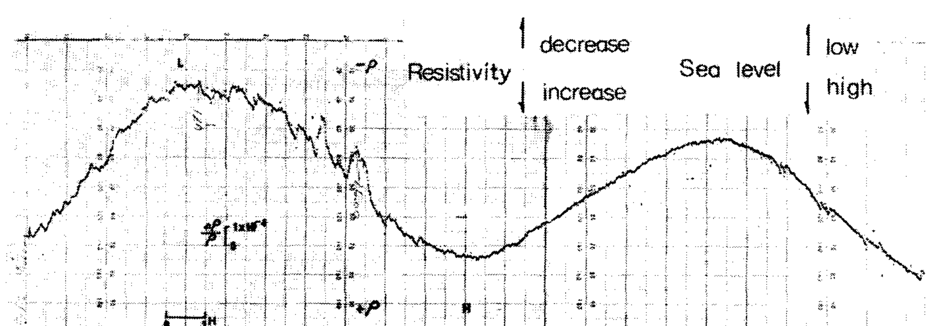

Fig.18. Changes in the electric resistivity caused by tidal loading as recorded at Aburatsubo observatory.

applied to observing resistivity changes caused by extremely small earth strains, so that its possible application as one of the tools of earthquake prediction has been suggested.

Absolute stress and strain

No attempts of measuring stresses within the earth's crust have ever been reported in earthquake prediction research. Measurement of absolute stresses has especially been difficult. Since rupture of rocks is largely governed by absolute value of stress, it is an urgent matter to develop a method of measuring absolute stress and strain in actual fields. Some techniques for the similar purpose exist in mining engineering. If we can measure such quantities at the bottom of deep boreholes from time to time, we might get some clue for possible occurrences of great earthquake.

Perturbation study in fields

Most of the observations planned in earthquake prediction research are of passive character because they are concerned only with naturally occurring changes. One of the biggest topics in recent-year seismology is the 1962–1965 Denver earthquakes (EVANS, 1966) which were caused by fluid injection into a deep waste disposal well at the Rocky Mountain Arsenal. Such an event may suggest that we would be able to give a perturbation to the earth's crust in some way or other and then to see the reaction arising from underground.

It is sometimes said that water-loading of a dam may lead to occurrence of a local earthquake. This may be an example of reaction of the earth's crust to a man-made disturbance. Although no concrete idea about how such a test can be performed at the moment exists, the writer feels that something of such active tests should be undertaken in the framework of earthquake prediction research.

THE MATSUSHIRO OPERATION AND ITS SIGNIFICANCE

The 1965–1966 swarm earthquakes that occurred around the Matsushiro area in central Japan were certainly an epoch-making event in the history of Japanese seismology. About March 1966 when the swarm activity became so violent that local people felt an earthquake approximately every two minutes (Fig.6 and Fig.10), a committee consisting of specialists from the Earthquake Research Institute, the Japan Meteorological Agency, the Geographical Survey Institute and other governmental institutions was formed to investigate the Matsushiro situation and, wherever possible, to inform the local people of up-to-date status of seismic activity. The committee analyzed all the available data and, whenever it was concluded that occurrence of a moderately large earthquake was highly probable, warnings were issued to the public by the Japan Meteorological Agency. These warnings indicated the dangerous period (usually a range of a few months), a rough idea about location and possible maximum magnitude. Earthquake warnings were thus sent out to the public officially by a governmental agency for the first time in history.

The scientific basis for warnings was provided by repetition of levelling surveys, microearthquake and ultra-microearthquake observations, tiltmeter observation, geodimeter survey and geomagnetic observation. It must have been difficult to get at such geophysical data of various kinds if the observation network had not been well established before the violent activities. Although nothing very definite could be concluded about the physical process in the earth's crust, it was possible to surmise the state of activity to some extent. The violent activities in April and August 1966 were thus successfully foretold. Japanese seismologists are now convinced that the earthquake prediction programme planned by them is running in the right direction as long as earthquake events like the Matsushiro earthquakes are concerned because much of the observations over the Matsushiro area was guided by the prediction programme.

Possible improvement of the programme was also suggested by the Matsushiro operation. The lack of a communication network prevented the rapid processing of observed data, so that determination of earthquake origins was sometimes delayed considerably. The lack of field-patrol parties that can be sent to an emergency area at any time caused difficulties in collecting immediate information about activities in some parts of the seismic area. The shortage of spare seismographs forced us to remove instruments from permanent observatories in other parts of Japan. These points were subsequently taken up in the revised edition of earthquake prediction programme.

It is the general feeling of Japanese seismologists that a sort of headquarter for earthquake prediction would be needed in the future. During the Matsushiro operation, each specialist was busy in conducting his own work. Accordingly, no one officialy engaged with the work of summarizing observed data. A commander, so to speak, who is responsible for watching the general development of seismic activity, should be appointed in the future earthquake prediction programme.

It would be important to know the reaction of local inhabitants to the forewarning of an earthquake. A psychological study should be made on the best timing and style of warning to be issued to the public although this would probably be outside the task of seismologists.

A forewarning of earthquake occurrence is certainly helpful for local governments because they can prepare themselves for coming disasters well beforehand. In the case of the Matsushiro events, local governments worked hard to prevent possible earthquake damage by repairing school buildings, strengthening fire-brigades, and so forth. But those who are engaged in the sightseeing and hotel business were not really pleased with the warnings because of expected shortage of tourists. Great care must be taken to find an adequate way of issuing a warning in the future. It is also of importance to train people so as to properly behave in case of an earthquake warning.

ANTICIPATED PROGRESS IN THE FUTURE

It is difficult to say when a more specific earthquake forecast will be accomplished. The most important thing at the present stage of investigation is certainly to accumulate basic data. In order to obtain such data, it is obvious that intensive observations should be carried out over the active fault zone such as the Anatolian and the San Andreas faults. In a country like Japan, where no major faults which are moving at present have been found, choice of targets of earthquake prediction research could be made on the basis of geotectonic work along with Asada's classification of earthquake provinces.

We feel that if a programme like the Japanese one is completed and if observation as planned by the programme could be performed over a reasonably long period of time, say 10 years or so, considerable knowledge about precursory effects of earthquake occurrence would be obtained. At this point, it should be emphasized that introduction of new techniques to earthquake prediction research is most important. Use of laser strainmeter, long-range tiltmeter, deep-hole tiltmeter and seismometer, resistivity variometer and the like is now rapidly developing. There is no doubt that some of these new techniques would eventually make important contributions to earthquake prediction research along with the existing methods as stressed in the earthquake prediction research programme in a number of countries.

Earthquake prediction, which has long been a dream of seismologists, would hopefully be achieved in the near future, probably within a few tens of years, at least for some class of earthquakes, if not all, by strengthening researches now under way in various countries. One might say that such a view is too optimistic, but it would be one of the duties of seismologists to proceed to the final goal of earthquake prediction by making every effort.

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