PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Earthquake Fault Studies in Japan

K. Kasahara

Phil. Trans. R. Soc. Lond. A 1973 **274**, 287-296
doi: 10.1098/rsta.1973.0055

Phil. Trans. R. Soc. Lond. A. **274**, 287–296 (1973) [287]
Printed in Great Britain

Earthquake fault studies in Japan

By K. Kasahara
Earthquake Research Institute, University of Tokyo, Japan

The paper reviews the current status of earthquake fault studies in Japan, taking the work on the off-Honshu tectonics as an example. Within the Japanese tectonic provinces, the belt along the Pacific coast of central and western Honshu is of special interest from the viewpoints of earthquake prediction as well as of global tectonics.

Observations in this field are being made most extensively in the south Kanto district as represented by a complex monitoring system surrounding the Sagami Bay. Complemental use of geophysical instruments with geodetic surveys is successful. The basic mode of strain accumulation thus observed seems consistent with the Sagami trough fault model as proposed by Kanamori and Ando in 1971 to explain the focal processes of the great Kanto earthquake of 1923. Comparison of tiltmeter records at the adjacent stations Aburatsubo and Nokogiriyama suggests crustal strains migrating at an extremely low velocity (20 km/year, apparently), from east to west (Yamada 1972).

Nakamura and Kanamori have shown that correlation of the activities of this fault with those of the Oshima volcano and seismicity in the Kii Peninsula, as seen in old records, provides notable evidence for the mechanism of stress transmission in a tectonic unit.

Introduction

Within the various tectonic provinces in Japan, the one which extends parallel to the Pacific coast of Honshu, from Kanto to Kinki and Shikoku, is of primary interest. Some 10 earthquakes of 8th magnitude have occurred in this particular area in the past six centuries. This amounts to between one half and two-thirds of the number of the big earthquakes which occurred in the same period in the whole Japanese area. High seismic activity in this province, which is adjacent to the vital part of the mainland, is especially hazardous as proved distinctly by the 1923 and 1946 earthquakes. It is natural, therefore, that scientific and social concern has been focused on this area in relation to earthquake prediction.

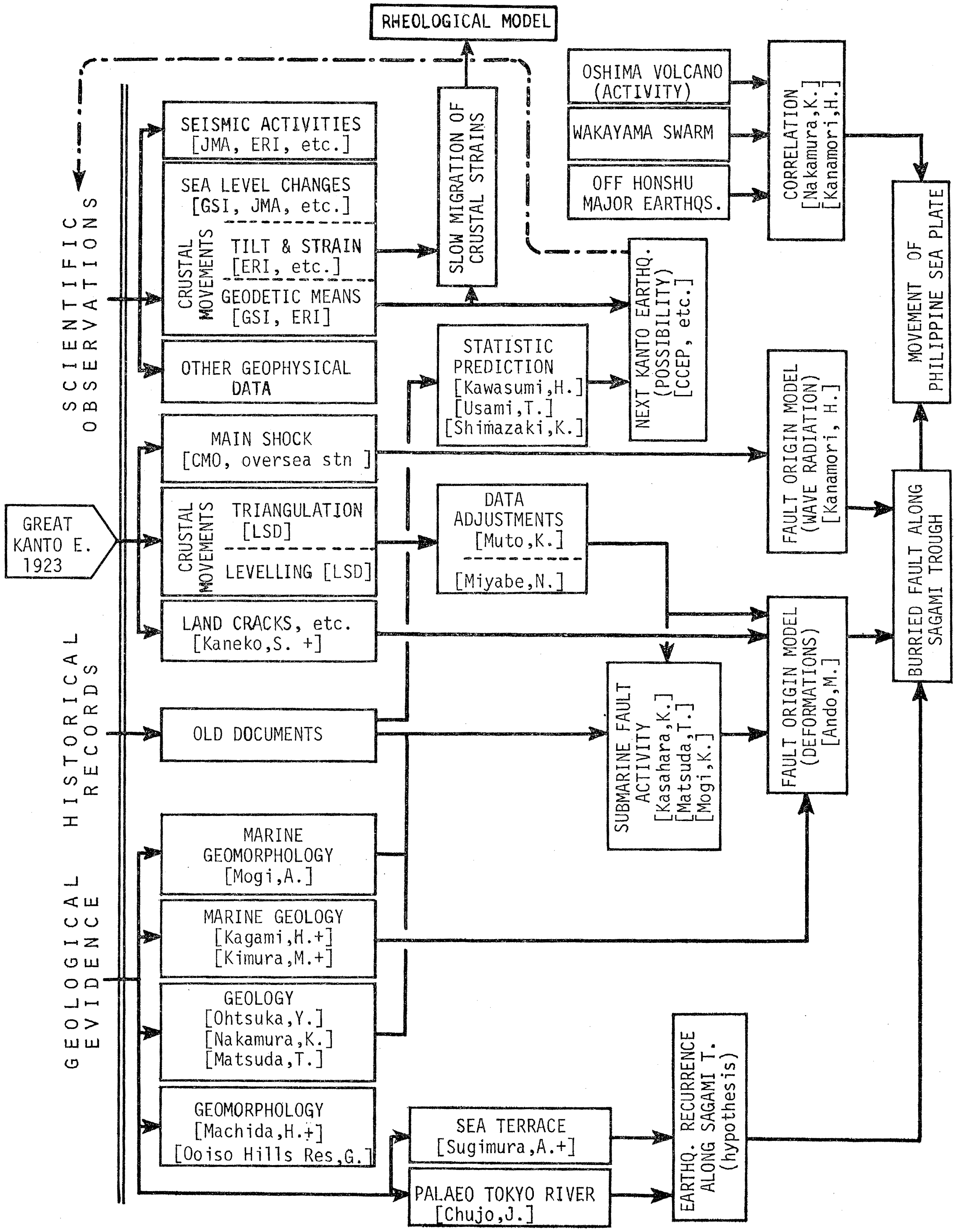
From the tectonic point of view, the present area lies on the boundary of the continental block to the Pacific plate, or more precisely, the Philippine Sea plate. It is doubtless one of the critical areas in the western Pacific to be studied for further development of the global tectonic theory.

Re-investigation of the great Kanto earthquake

The great Kanto earthquake of 1923, which is known to be one of the most hazardous quakes ever to have occurred, was also a remarkable event in the history of Japanese seismology. Following this revealing event, systems of observation and research have been strengthened significantly.

Progress in research of the 1923 earthquake and its tectonic background may be schematically shown in figure 1, which is a modified reproduction of a flow-chart by M. Ando (unpublished). Items on the left are the observational data, in general, whereas the hypothetical ones are arranged from the centre to the right in their logical order. Authors' names are given in brackets, but full references will be omitted unless necessary for further discussion.

In spite of the accumulated data, however, a picture of the source was not drawn clearly for this earthquake until recently. There are many reasons for this, but the concealment of the



CCEP	Coordinating Committee for Earthquake Prediction	GSI	Geographical Survey Institute
CMO	Central Meteorological Observatory (now JMA)	JMA	Japan Meteorological Agency
ERI	Earthquake Research Institute	LSD	Land Survey Department (now GSI)
		NRCDP	National Research Center for Disaster Prevention

FIGURE 1. Studies on the off-Honshu tectonics with special reference to the great Kanto earthquake of 1923 (revised copy of a chart by M. Ando (personal communication)). The bottom list represents abbreviations of the principal organizations.

fault under the sea seems the main one. Kanamori (1971) and Ando (1971) have revived research into the Kanto earthquake on a modern theoretical basis. Their work appeared timely for prediction research, because the possibility of another Kanto earthquake has been a matter of great concern for many years. Following the statistical prediction by H. Kawasumi, the Geographical Survey Institute (G.S.I.) has discovered anomalous ground uplift accumulating at a high rate in the Boso Peninsula. Taking all these data into consideration, the Coordinating Committee for Earthquake Prediction has decided to organize concentrated observations in the south Kanto district as shown in the flow chart (figure 1).

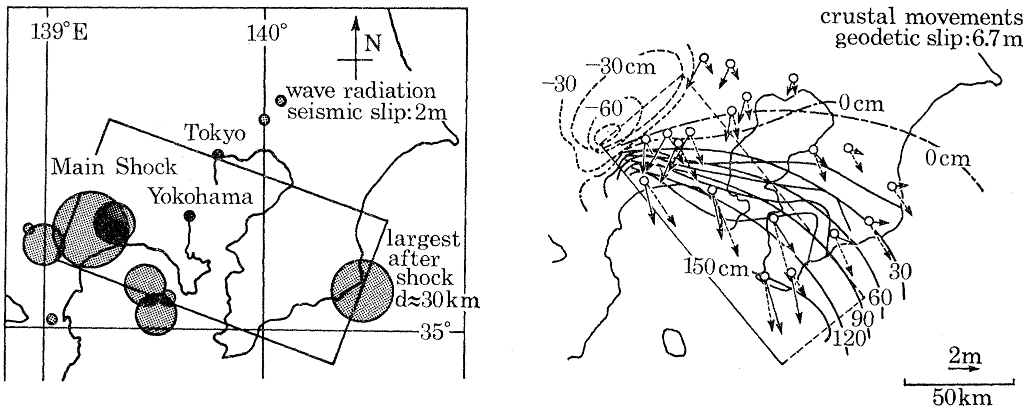


Figure 2. Fault-origin models of the great Kanto earthquake as derived (upper) from seismological observations (H. Kanamori 1971), and (lower) from geodetic surveys (M. Ando 1971). Horizontal movements: ← (theory), ←- - (observed). Vertical movements: — (theory), — (observed).

Figure 2 represents the two fault-origin models as proposed by Kanamori and Ando, respectively. There are several quantitative discrepancies between them, naturally reflecting the different data and techniques used. Still, they are consistent, basically, in showing that a submarine reverse faulting was the seismic source. More precisely, this fault was accompanied by a right-lateral strike-slip component and appeared in a plane dipping landward with the NW–SE strike.

A geophysical monitor system in the south Kanto district

The foregoing discussion attracts attention to the tectonics along the Sagami Trough. Systematic distribution of historical earthquakes there and geological and geomorphological evidence for the past seismic deformations are also notable. Thus recurrence of fault activity along the trough has been hypothesized (figure 1). Taking all these sorts of information into account, we may design a complex observation system in order to monitor the crustal processes leading up to the next major earthquake (Kasahara 1970).

Figure 3 illustrates the monitor system thus constructed. It includes stations and network by various groups. For the simplicity's sake, however, the J.M.A.'s routine seismographic stations and the G.S.I.'s levelling routes are not drawn in spite of their importance.

Repeated trilateration by G.S.I. (1972), as shown in figure 4, is one of the principal components. Development of a laser geodimeter was a notable contribution to the present system without which long-range monitoring across the trough was almost impossible. Numerals attached to the respective base-lines represent their extension (+) or contraction (−) in centimetres as

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

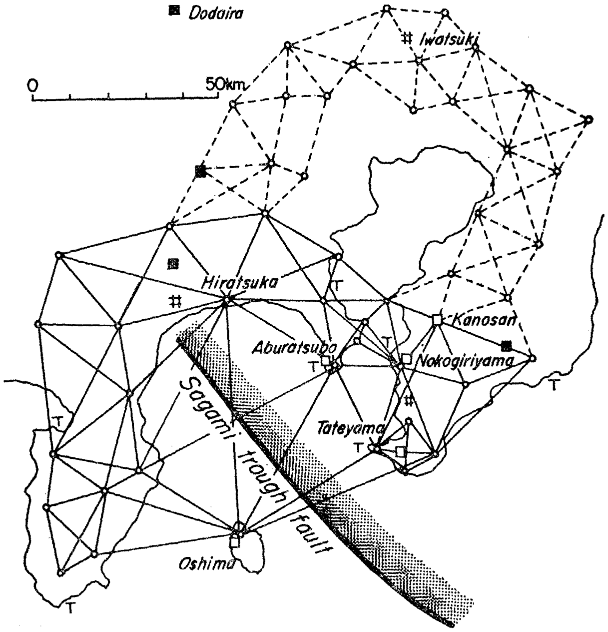


Figure 3. A geophysical monitoring system in the south Kanto district. ○—○, geodimeter survey; ○- - - -○, geodimeter survey (planned); ■, station (seismic); □, station (crustal movement, geomagnetic); T, tide-guage; #, bore-hole station.

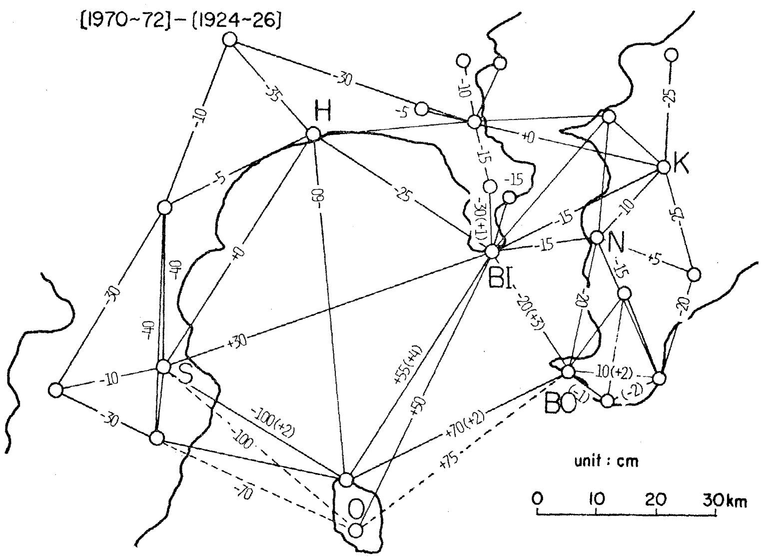


Figure 4. Secular changes in the base-line lengths during 50 years after the 1923 earthquake (unit: cm). Parenthesized data represent the very recent changes (1971–2). Principal stations: (BI) Bishamon, (BO) Bodaisan, (H) Hiratsuka, (K) Kanosan, (N) Nokogiriyama. (After G.S.I. 1972.)

derived from the recent work in comparison with previous work (1924–6). The resultant accuracy of comparison might not be so high as the present surveying specifications due to errors in the old triangulations. Yet, we can learn much from it about the strain events which accumulated in fifty years after the 1923 earthquakes. Several points may be made: (1) as a whole, this area is subject to areal contraction; (2) areal contraction predominates most in the western part of the district, including the Izu and Tanzawa areas; (3) strain pattern in the Boso Peninsula is predominated with shearing as indicated by a north–south contraction and an E–W extension of similar magnitude, and; (4) strain over the Sagami Bay is also large shearing, reaching 2×10^{-5}, approximately. However, the principal axes are in the directions of NW–SE (contraction) and NE–SW (extension), being rotated counterclockwise from those of the Boso area.

Tiltmeters and strainmeters in the monitor system

Complementary use of geophysical instruments, such as tiltmeters and strainmeters, with geodetic surveys is another principle in the present system. The idea is to alleviate the disadvantage that geodetic measurements have of being discontinuous in time. Use of geophysical instruments is, however, often subject to an essential question whether a small-size instrument like this responds to large-scale tectonics satisfactorily.

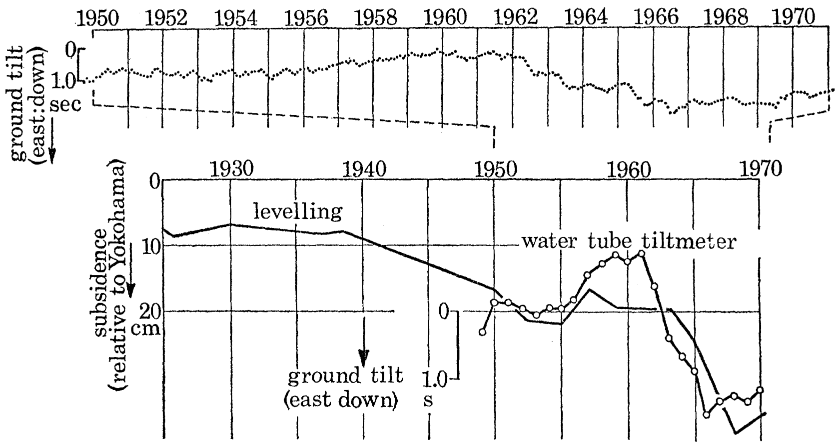


Figure 5. Twenty-year readings on a water-tube tiltmeter (Aburatsubo) as compared with secular tilting of the Miura peninsula since 1925.

Long-term observations at the Aburatsubo and Nokogiriyama Observatories seem to answer this last question affirmatively (Aburatsubo Crustal Movements Observatory and Nokogiriyama Crustal Movements Observatory (1969, 1971, 1972)). Strainmeters at Nokogiriyama have been recording, since their installation in 1960, north–south contraction and east–west extension continuously, which are accumulating at a common rate about 1.2×10^{-6}/year. Although the rate is two or three times as high as shown by the geodimeter survey, the present mode of accumulation is basically consistent with the large-scale data.

More clearcut evidence is seen on tiltmeters records at the two stations, as will be discussed in this and following sections. The upper picture of figure 5 illustrates the 20-year readings on a water-tube tiltmeter (east–west component) at Aburatsubo. This station is particularly suitable for comparison because precise levelling has been repeated very frequently along the Miura Peninsula, which has the station at its southern extremity. Solid lines in the lower picture refer to the G.S.I.'s data and illustrate the episode of Aburatsubo's vertical movement relative to Yokohama, or the base of the peninsula. As is well known, the peninsula tends to tilt down southward in an aseismic period. The general trend of the levelling curve seems to reflect this motion. The subsidence is rather smooth and uniform for the first thirty years. Then the curve is more irregular with large undulations since 1963. The curve connecting small circles is a reproduction of the upper curve, with its time axis adjusted for better comparison. Good agreement of the two curves proves the satisfactory response of the tiltmeter to regional movements. It is rather surprising to see this agreement when we compare the size of the instrument (10 m) to that of the peninsula (20 km). It must be remarked, however, that the present conclusion holds only for the mode of movements. The direction and the amplitude of the ground tilts, as derived from the tiltmeters, do not necessarily agree with the geodetic data. These sorts of disagreement are likely to arise from to geological heterogeneities or block structures in the peninsula.

Migrating crustal strains

Successful results from the foregoing discussion encourage us to carry out further investigation, namely, comparison of tiltmeter readings at a pair of adjacent stations. Again, Aburatsubo is a suitable station for this purpose. It has the Nokogiriyama station about 20 km east of it, which has been operating on a similar instrumental basis since 1960.

Figure 6 compares the ground tilting at the two stations taking loci of their tilting vectors, where the annual variations contaminating the original data have been removed by filtering (Yamada 1972). As discussed previously, the ground tends to tilt SE or SEE secularly at Aburatsubo. At Nokogiriyama, on the other hand, the ground tends to tilt down to NE secularly. Therefore, the coordinates of the Nokogiriyama vector have been transformed so that its curve may appear close to the Aburatsubo curve in the diagram.

Several irregular events which appear in pairs on the two curves may be noticed. Symbols A, B, C, etc. are assigned to them, for reference. Perhaps the events A and E are the most remarkable among them for they indicate quick reversal of the tilting mode. Several other pairs (B, C, D) are also recognizable, although they do not appear so sharp in the figure.

As Yamada noticed, all these events appear at Nokogiriyama approximately 1 year before Aburatsubo. This phase relation may be seen more definitely in figure 7, where the episodes at each station are schematized as a cyclic repetition of the two primary stages, positive and negative. The positive stage denotes the ground tilt accentuating the secular movement, which is SE-down at Aburatsubo and NE-down at Nokogiriyama, respectively.

It is now clear that the irregular events are migrating from Nokogiriyama to Aburatsubo. The direction of migration is unknown from the two stations, but we tentatively suppose it to be from SE to NW, by reference to the G.S.I.'s data (1972*b*) on the ground uplift patterns in two recent successive periods, 1965–9 and 1969–71. They do not resolve details of the episodes so well; yet we notice, in the figure, the centre of uplift travelling northwestward across the Boso Peninsula.

The migration velocity is about 20 km/year, apparently (see broken lines in figure 7), but further analysis of the velocity is a problem for the future. Little is known, at present, about the origin of these irregularities. They might have originated from a locality not far from the peninsula, but a more interesting picture may be imagined by extending the broken lines in figure 7 farther to the east where they meet a locality 200 to 250 km away Aburatsubo in the 1950s, where and when the Boso-oki earthquake ($M = 8.3$) occurred. The writer would like to mention it only as one of the possibilities and leave it for further research.

Going back to the velocity, the observed value is extremely low – so low that no reasonable explanation seems available for it, at the moment. However, reference to several types of crustal movements is useful in approaching the present puzzle. For example, Mogi (1968) studied migration of earthquakes on global and regional scales and suggested 50 ~ 100 km/year as

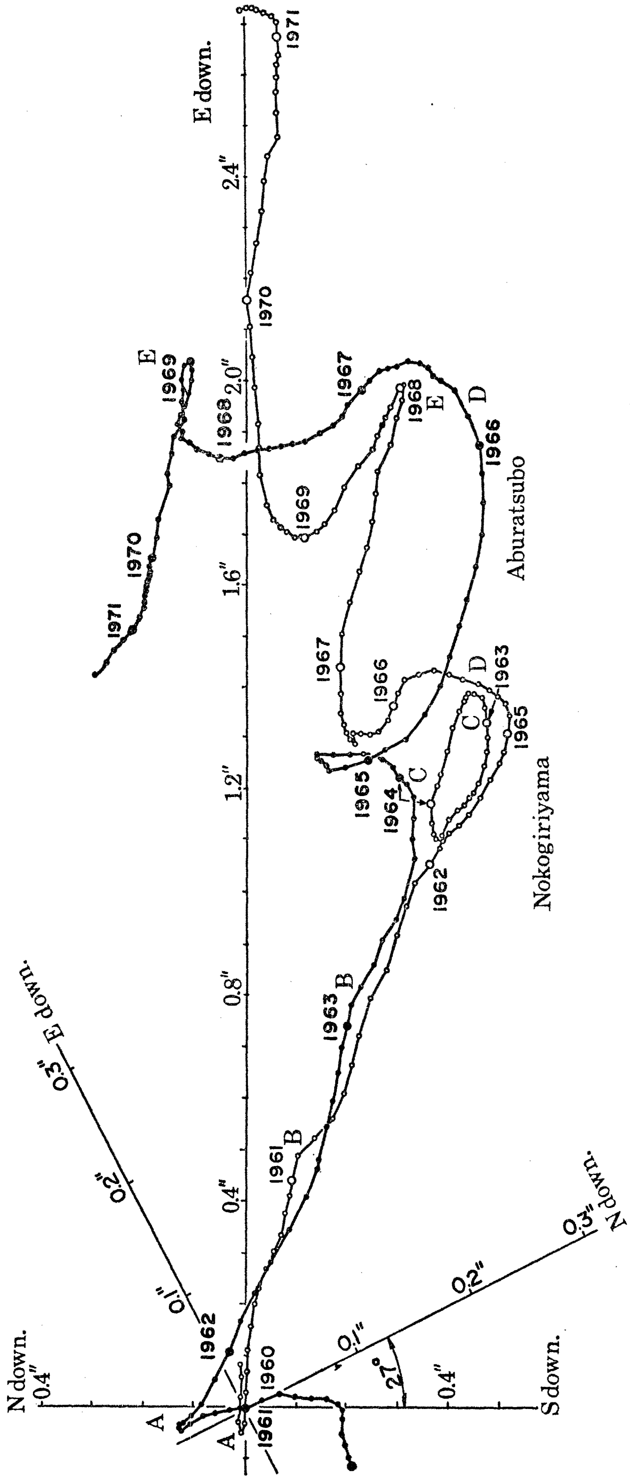


FIGURE 6. Locus of the tilt vector at Aburatsubo as compared with the data at Nokogiriyama. (After Yamada 1972.)

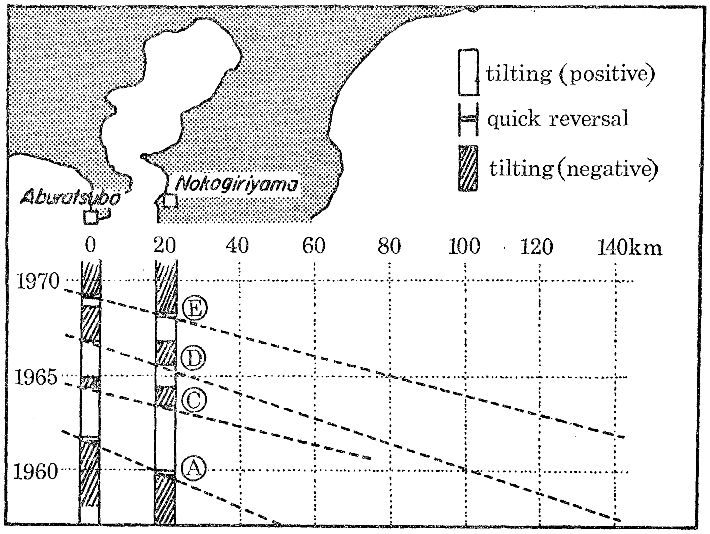


FIGURE 7. Comparison of irregular ground tilting at Aburatsubo and Nokogiriyama, which schematically shows the westward travelling of anomalous events. Symbols attached to the events refer to figure 7. Positive tilting denotes the event accumulating the secular trend, which is SE-down and NE-down in the Aburatsubo and Nokogiriyama areas, respectively.

approximate velocities. Gradual development of an aftershock area as sometimes observed must also be mentioned (M. D. Wood, R. V. Allen and S. S. Allen reported migration of local seismic activity along the San Andreas fault, at this discussion meeting). From these sorts of evidence, we learn that the slow migration of crustal strains, as observed in the south Kanto district, might be a general effect which is related to rheological properties of the crust (or mantle).

GREAT EARTHQUAKES, EARTHQUAKE SWARMS, AND VOLCANIC ACTIVITIES IN A TECTONIC PROVINCE

High tectonic activity in the off-Honshu province is represented most vividly by the recurrence of great earthquakes there. Kanamori (1972) and Nakamura (1972) have discovered that the temporal variation of the Wakayama swarm activity and of the Oshima volcanic activity show a remarkable relation to the occurrence of great earthquakes. Figure 8 illustrates the sequence of these events. The bottom picture refers to old documents up to 1600 and shows the year of occurrence of all the shallow earthquake ($M \geqslant 7$) in this province in comparison with the sequence of volcanic activities at Oshima. For future reference, the earthquakes are classified into two groups, eastern and western, with respect to the meridian about 138° E as a border (the broken line represents the 1854 event which occurred around the border 32 h before the one in the western group). It is clear that the three sorts of activities are correlated with each other, with few exceptions. One may discover, in the figure, a systematic phase relation among the three, with the volcanic activity and the eastern earthquakes leading western earthquakes in this order.

The middle picture shows a detailed comparison of the three principal components for the period 1880–1970. They are, volcanic activities, great earthquakes, and the annual number of felt earthquakes at Wakayama, Kii Peninsula. The swarm activity rises up and falls off at the time of respective earthquake. Its response is not similar, however. Roughly, the swarm becomes active in the case of an eastern earthquake (f.i. 1923, 1953), but falls down abruptly following a western earthquake. (A local peak around the 1946 earthquake (top picture) is attributed to aftershocks. The swarm activity seems unaffected by the 1891 earthquakes that occurred in the land.)

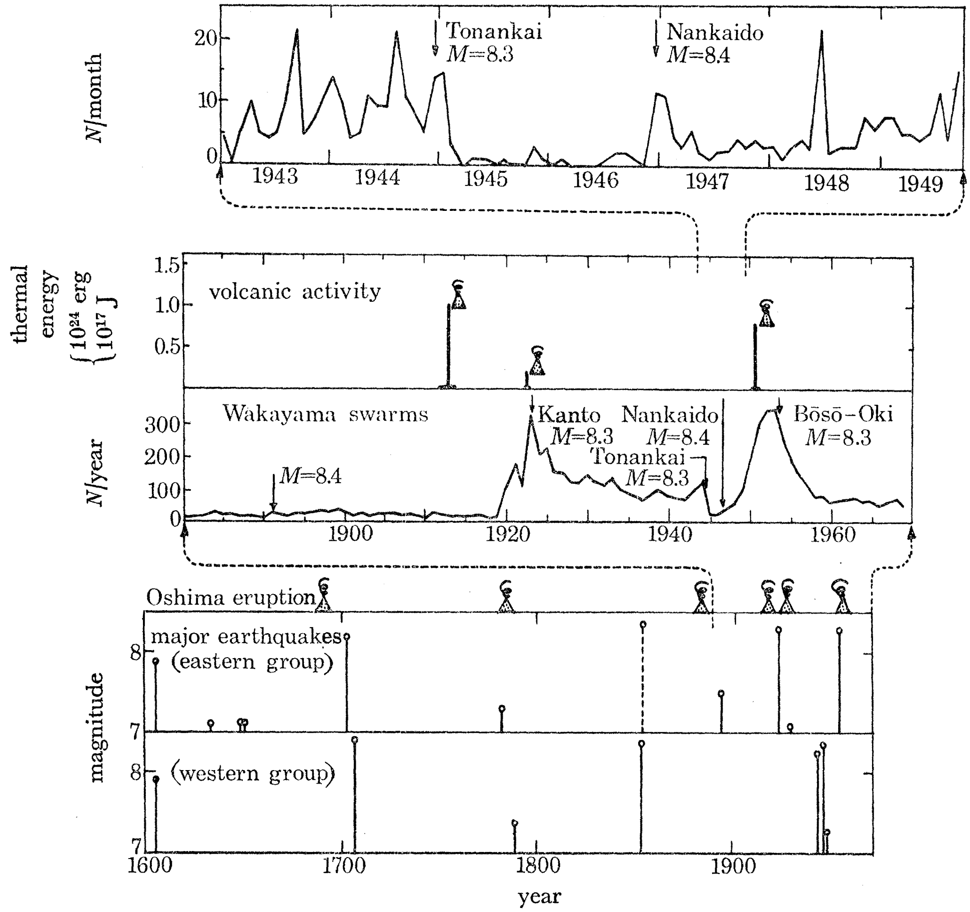


Figure 8. Sequence of major earthquakes (off-Honshu), swarm earthquakes (Wakayama), and volcanic activity (Oshima), showing good correlation with each other. Upper two figures illustrate details. (Compiled from Nakamura (1972) and Kanamori (1972).)

On the basis of such evidence, Kanamori has proposed a model as follows: the swarm activity in the continental block which is opposing the motion of the Philippine Sea plate falls off when a great earthquake occurs at the boundary between this block and the Philippine Sea plate, but rises when a great earthquake occurs at the boundary between the Philippine Sea plate and one of the other continental blocks. Great earthquakes which are not associated with the motion of the Philippine Sea plate do not affect the activity of the earthquake swarm.

Good correlation of volcanic activity and great earthquakes may also be explained from the viewpoint of plate tectonics (Nakamura 1972). The Oshima volcano being located close to the northeastern boundary of the Philippine Sea plate (or the Sagami trough), it is possibly governed by the motion of the plate and the resulting stress change affects there. In other words, the local stress change affects the magma reservior to squeeze magma out of it, as Nakamura hypothesized. Details of its mechanism are still unknown, but we may tentatively compare it to nature's stressmeter, just like the function of the Wakayama swarm in the western part of the plate.

These ideas about the dynamics of the Philippine Sea plate will be particularly useful for earthquake prediction research, as they suggest promising approaches to successful monitoring of stress accumulation.

I wish to express my hearty thanks to my colleagues in the Earthquake Research Institute, particularly to M. Ando, H. Kanamori, K. Nakamura, and J. Yamada, who offered me valuable materials for reviewing. Assistance by Miss R. Kawashima throughout this study is also gratefully acknowledged.

Thanks are also due to the Organizing Committee of the Discussion Meeting and to the Royal Society for offering me an opportunity of reviewing the problem of my interest.

References (Kasahara)

Aburatsubo Crustal Movements Observatory and Nokogiriyama Crustal Movements Observatory 1969 *Rep Coordinating Com. Earthq. Prediction* **1**, 34–38; 1971, **6**, 33–36; 1972, **8**, 27–31. (All in Japanese.)
Ando, M. 1971 *Bull. Earthq. Res. Inst. Tokyo Univ.* **49**, 19–32.
Geographical Survey Institute 1972 16*th Meeting, Coordinating Com. Earthq. Prediction* (17 April 1972).
Geographical Survey Institute 1972*b* *Earthquakes and earthquake prediction*, 1–32 (in Japanese).
Kanamori, H. 1971 *Bull. Earthq. Res. Inst. Tokyo Univ.* **49**, 13–18.
Kanamori, H. 1972 *Tectonophysics* **14**, 1–12.
Kasahara, K. 1970 *Report, Earthq. Prediction Obs. Center, Earthq. Res. Inst.* **1**, 25–31 (in Japanese).
Mogi, K. 1968 Migration of seismic activity, *Bull. Earthq. Res. Inst. Tokyo Univ.* **46**, 53–74.
Nakamura, K. 1972 *Bull. Volcanological Soc. Japan* (in Japanese with English abstract) **16**, 63–71.
Yamada, J. 1972 *J. Geod. Soc. Japan* (to be published).