ON PECULIAR MODE OF SECULAR GROUND-TILTING CONNECTED WITH A SEQUENCE OF EARTHQUAKES IN SOME RESTRICTED AREAS

BY

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1. Introduction

Marked upheaval and subsidence of the ground connected with great destructive earthquakes were frequently reported from old times, and, in recent times, these crustal deformations were precisely measured by geodetic surveys of levelling and triangulation in the epicentral region by comparison of data obtained in both surveys before and after the earthquake-occurrence. This method of geodetic survey of frequent operations in a short period on wide area was found practically difficult for reason of large expense and number of operator. Moreover, this geodetic survey could not tell us the process and mode of crustal deformation in progress shortly before and after an earthquake-occurrence because its data were only related with the values at two end points of time during a comparatively long period. As a substitute or supplement for this geodetic survey, a continuous observation of crustal deformation with the tiltmeter and the extensometer (or the strainmeter) at many points in the seismically active area, was recently adopted and gave some promising results for study on phenomena forerunning earthquakes.

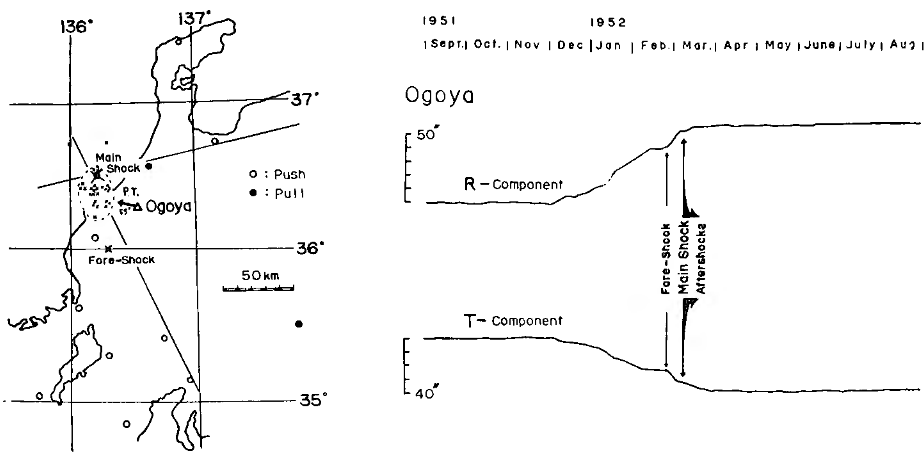
At present more than 25 stations for continuous observation of crustal deformation are in operation in Japan, almost all of their observation rooms being deeply situated in the underground of firm rock (from several meters to several hundreds meters deep under the ground surface). During a period of the recent 25 years' observations, several examples of anomalous crustal deformation which preceded destructive earthquake have been obtained. In these cases their analysis and argument are generally restricted in the point that anomalous crustal deformation observed at some observation stations in the epicentral region being treated in connection only with individual earthquakes. From this method of treatment we have obtained some knowledge on the appearance time of anomalous crustal deformation which precedes an earthquake-occurrence. Namely they appear in several hours before an earthquake in some cases, several days in other cases, and several months in another case. And, there were a few examples in which two or, in a special case, three kinds of periods of appearance above mentioned being combinedly observed. This method of treatment for individual earthquakes is considered to be one of the promising ways to advancement and completion of study on earthquake-prediction, but, in the present state, it is very dangerous to draw any conclusive rule in a hurry from such a small number of examples as obtained in our past observation. Hereafter we must endeavour for a rapid and large increase of number of observation stations and obtaining a sufficiently large number of good examples possible to find an useful law on anomalous crustal deformation preceding destructive earthquakes.

In this paper the data obtained at some observation stations were treated and discussed on a different standpoint from that of the past treatment above mentioned. Namely the observed data on secular tilting motion of the ground (shortly expressed as the ground-tilting) at an observation station were analysed and discussed in reference to a *series* of earthquakes which occurred in sequence in a certain restricted area, instead of treatment on individual earthquakes. On the other hand, an attempt was also made to find any common character, if existing, among the modes of anomalous secular ground-tilting observed at some areas.

In the following sections several examples of earthquakes were treated from two standpoints, one, a discussion on secular anomalous ground-tilting refering to a series of earthquakes in a small restricted area, and the other finding out of any common character among anomalous ground-tiltings connected with several earthquakes in various areas.

2. Case of a Series of Daishōji-Oki Earthquakes

The main shock of Daishōji-Oki Earthquake occurred on March 7, 1952. Its magnitude and focal depth were 6.8 and 20 km respectively, and the positions of epicenter and the observation station of Ogoya concerned (40 km from the epicenter of main shock) are shown in Fig. 1(a). As clearly seen in Fig. 1(b), anomalous ground-tilting appeared in December, 1951 and continued its downward tilting in nearly the direction of epicenter in a fairly rapid rate. This particular motion abated suddenly after the occurrence of main shock and quite ended in 15 days after it, the period of which coincided with termination of the aftershocks. As also seen in the Figure, there remained a permanent set of ground-tilting in the present case, and it is very interesting that its direction pointed to the center of area of the aftershocks. A local earthquake occurred on February 25, 1952 at 35 km distance from Ogoya and its epicenter was on the extention of a long axis of elliptical area of aftershocks as shown in Fig. 1(a). This earthquake of magni-



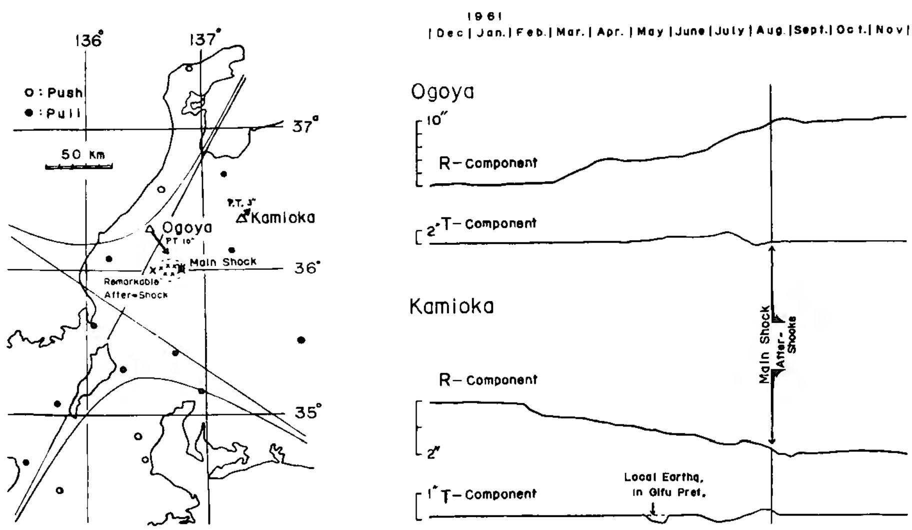
(a) (b)

Fig. 1(a) Push-pull distribution of initial motion of main shock and the position of epicenter of aftershocks in case of the Daishōji-Oki Earthquake.
Arrow indicates the vector of permanent tilting. (*P.T.*).
(b) Ground-tilting at Ogoya in radial (R) and transversal (T) components to the epicenter of the Daishōji-Oki Earthquake.
The upward change in R- and T- component shows the ground-tilting downward to the epicenter and to the right.

tude of 4.5 is considered to a fore-shock of the Daishōji-Oki Earthquake judging from the curve of ground-tilting shown in Fig. 1(b). From these data the relation between the pattern of a series of earthquakes in a certain restricted area (20×40 km^2 in the present case) and its corresponding mode of ground-tilting in the epicentral region could fairly in detail be studied.

3. Case of a Series of Kitamino Earthquakes

The main shock of Kitamino Earthquake occurred on August 19, 1961. Its magnitude and focal depth were 7.2 and 40 km respectively, and the positions of epicenters of the main shock and its aftershocks are shown in Fig. 2(a). Positions of the observation stations concerned of Ogoya (40 km distant from the epicenter of main shock) and Kamioka (60 km distant from the epicenter of main shock) are also described in Fig. 2(a), with distribution of first motion in the seismic waves of the main shock (crack-type). As seen in Fig. 2(b), anomalous ground-tilting in the direction of the epicenter appeared on March at Ogoya, and on February at Kamioka, and also, in the orthogonal direction to the epicenter, anomalous ground-tilting was observed since the beginning of May at Ogoya. In such a way anomalous ground-tilting clearly appeared nearly 6 months before the Earthquake at both stations of Ogoya and Kamioka, in the direction of the epicenter,



(a) (b)

Fig. 2(a) Push-pull distribution of initial motion of main shock and the position of epicenter of aftershocks in case of the Kitamino Earthquake.
Arrows indicate the vector of permanent tilting.
(b) Ground-tilting at Ogoya and Kamioka in radial (R) and transversal (T) components to the epicenter of the Kitamino Earthquake.

and since 2 months before the Earthquake the peculiar mode of ground-tilting was also observed at both stations. Also in the present case the forerunning tilt and the permanent tilt pointed to the center of aftershock area and the epicenter respectively, as observed in case of Daishōji-Oki Earthquake.

4. Case of the Ōdaigahara Earthquake

The magnitude and focal depth of Ōdaigahara Earthquake on December 26, 1960 were 6.0 and 60 km respectively. The position of the epicenter, the push-pull distribution of first motion, and the orientation of observation stations concerned are shown in Fig. 3. In this case the push-pull distribution of initial motion should be explained by a cone-type rather than a quadrant-type. The azimuth of the cone-axis was identical with that of Yoshino Earthquake on July 18, 1952 which occurred near the epicenter of Ōdaigahara Earthquake. As seen in Fig. 3, the observation stations of Kishyū, Yura and Shionomisaki were in the push-zone, Akibasan and Ōura in the pull-zone, and Kamigamo near the nodal line respectively. In Fig. 4, secular ground-tiltings observed at these stations are represented in two components of radial (in the direction of the epicenter) and transversal (orthogonal to radial direction) directions. As clearly seen in the Figure, the

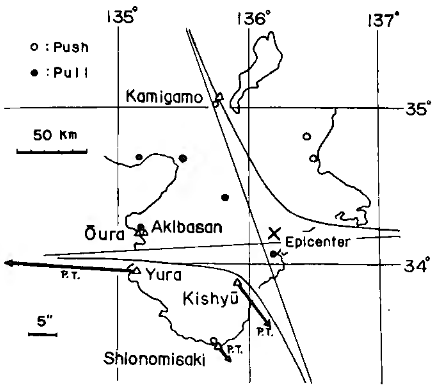


Fig. 3 Push-pull distribution of initial motion of the Ōdaigahara Earthquake.
Arrows indicate the vector of unrecovering tilting at each observatory.

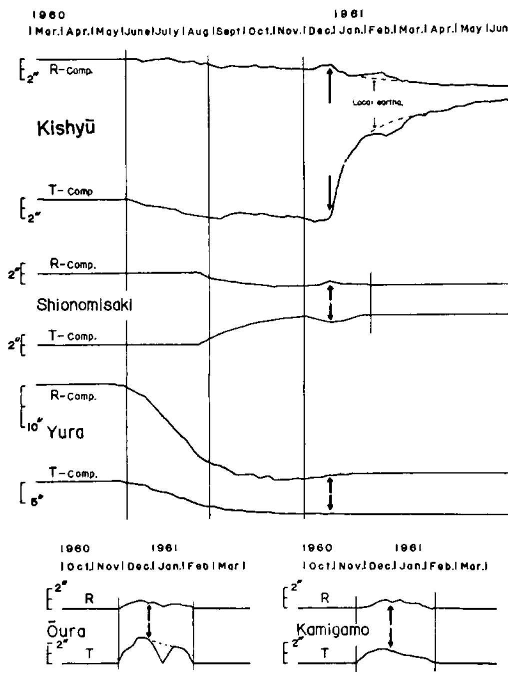


Fig. 4 Ground-tilting at each observation station in radial (R) and transversal (T) components to the epicenter of the Ōdaigahara Earthquake.
Arrows indicate the time of occurrence of the Earthquake.

anomalous ground-tilting observed at these stations may be divided into four stages. Namely, in the first stage (from the beginning of June to the middle of August, 1960), anomalous ground-tiltings were observed at two stations of Kishyū and Yura, both being in the push-zone of first motion. In the second stage (from the middle of August to the end of November, 1960), another mode of anomalous ground-tilting was observed at three stations of Kishyū, Yura and Shionomisaki, all of which were also in push-zone of the first motion. In a period of third stage, from end of November to the time of occurrence of Ōdaigahara Earthquake (December 26, 1960), peculiar modes of ground-tilting were observed at three stations above mentioned (Kishyū, Yura, and Shionomisaki) and moreover at three other stations, Kamigamo, Ōura and Akibasan (close by Ōura), Ōura and Akibasan being in pull-zone of the first motion and Kamigamo being on the nodal line. The fourth stage was one of post-earthquake, its period and mode of recovery being diverse for one station from another. Namely, as clearly seen in Fig. 4, the period of fourth stage observed at Ōura (similarly with Akibasan) (the epicentral distance: $d=90$ km), and Kamigamo ($d=100$ km) was from December 26, 1960 to the beginning of February, 1961. In this case the anomalous ground-tilting was perfectly recovered leaving no permanent set. With respect to Yura (d=95 km) and Shionomisaki (d=90 km) the fourth stage ended on the beginning of February, 1961 as similarly with the case of Ōura and Kamigamo. But, in this case of Yura and Shionomisaki, a considerably large permanent set remained. Kishyū (d=40 km) was the nearest station to the epicenter and considered to be just above the hypocenter because the focal depth was estimated to be 60 km. A period of fourth stage observed at Kishyū was observed as 6 months long after the Earthquake as shown in Fig. 4. In this case the amount of anomalous ground-tilting of post-earthquake (the fourth stage) was extremely large, and especially in transversal component, its direction in permanent set was reversed compared with that of anomalous ground-tilting forerunning the Earthquake.

In summary in case of Ōdaigahara Earthquake, the ground in the south-western area to the epicenter responded early (7 months before) to the Earthquake and, in the north-western area to the epicenter, the anomalous ground-tilting connected with the Earthquake appeared one month before the earthquake-occurrence. The behaviour of ground-tilting in another areas of north-east and south-east quadrants was not observed because lack of observatories in these area. A permanent set of ground-tilting with respect to the Earthquake was observed only at stations in the south-western area. These permanent tilts with respect to the Earthquake observed at three stations were also represented in Fig. 3. The present data observed on the particular azimuthal distribution of mode in anomalous ground-tilting forerunning earthquake and remaining permanent set of ground-tilting with respect to earthquake, will be useful for study on the relation between the generation mechanism of earthquake and its corresponding mode of crustal deformation before and after an earthquake in the epicentral region. This problem will in detail be discussed in another paper of near future publication.

5. Case of a Series of Yoshino Earthquakes

In this case a series of earthquakes originated in the district of Yoshino in the middle part of Kii Peninsula was treated. Their specifications were as follows:

No.	Date	Epicenter °N	Epicenter °E	Depth km	Magnitude
1*	July 18, 1952	34.5	135.8	70	7.0
2	Aug. 9	34.5	135.8	65	5.0
3	Sept. 1, 1953	34.0	135.7	70	6.5
4	Apr. 21, 1954	34.3	135.9	60	5.0
5	May 10	34.0	135.5	65	4.5

* The so-called Yoshino Earthquake

6	May	22,	1955	34.2	135.5	75	5.0
7	Oct.	31		34.3	135.7	60	1.5
8	Nov.	19,	1956	34.3	135.8	75	5.0

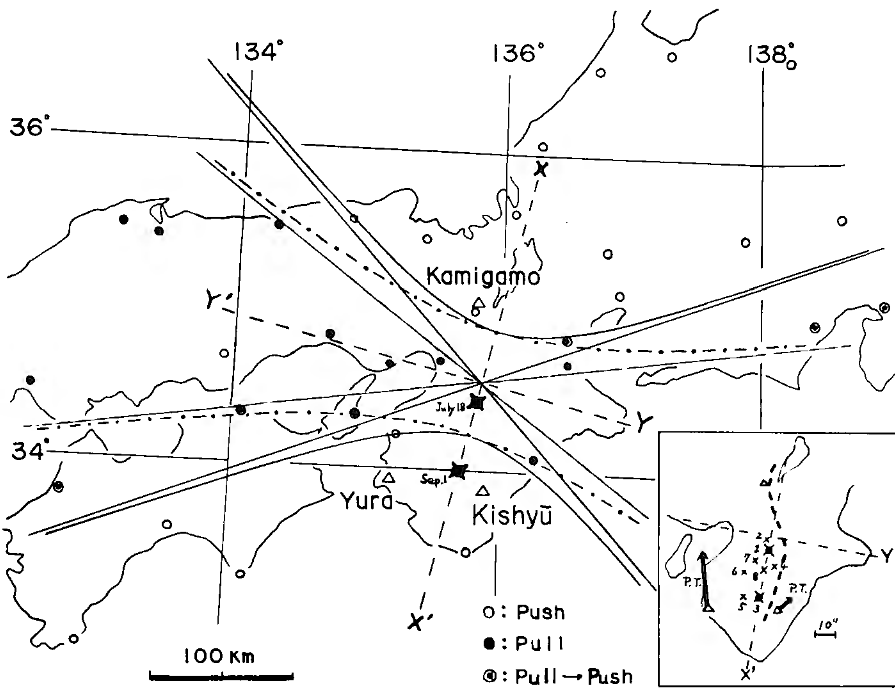


Fig. 5 Push-pull distribution of initial motions in the Yoshino and the Sept. 1-Earthquake.

○ : push, ● : pull, same sense on both Earthquakes

◉ : pull in the Yoshino Earthquake and push in the Sept. 1-Earthquake

Solid line : nodal line in the Yoshino Earthquake

Chain line : nodal line in the Sept. 1-Earthquake

Brocked line : two common axes of nodal hyperbolas

Figure on lower right shows distribution of epicenters of Yoshino Earthquakes having focal depth of 60–80 km. Thick brocken line in this figure illustrates the anticline-axis. Arrows indicate the vector of anomalous tilting during a period from the time of occurrence of the Yoshino Earthquake till that of the Sept. 1-Earthquake.

The positions of their epicenters and the observation stations concerned of Kishyū, Yura and Kamigamo are represented in Fig. 5. In this section two large earthquakes on July 18, 1952 (No. 1) and September 1, 1953 (No. 3) were in detail treated, their push-pull distributions of first motion being also shown in Fig. 5. Same treatment as those in the preceding sections was applied to the present data. Namely, the secular ground-tilting observed at Yura and Kishyū was, as shown in Fig. 6, resolved into two components of radial and transversal directions to the respective epicenters of the Earthquakes on July 18, 1952 (No. 1) and September 1, 1953 (No. 3). Concerning the case of the Earthquake on July 18, 1952 a rapid

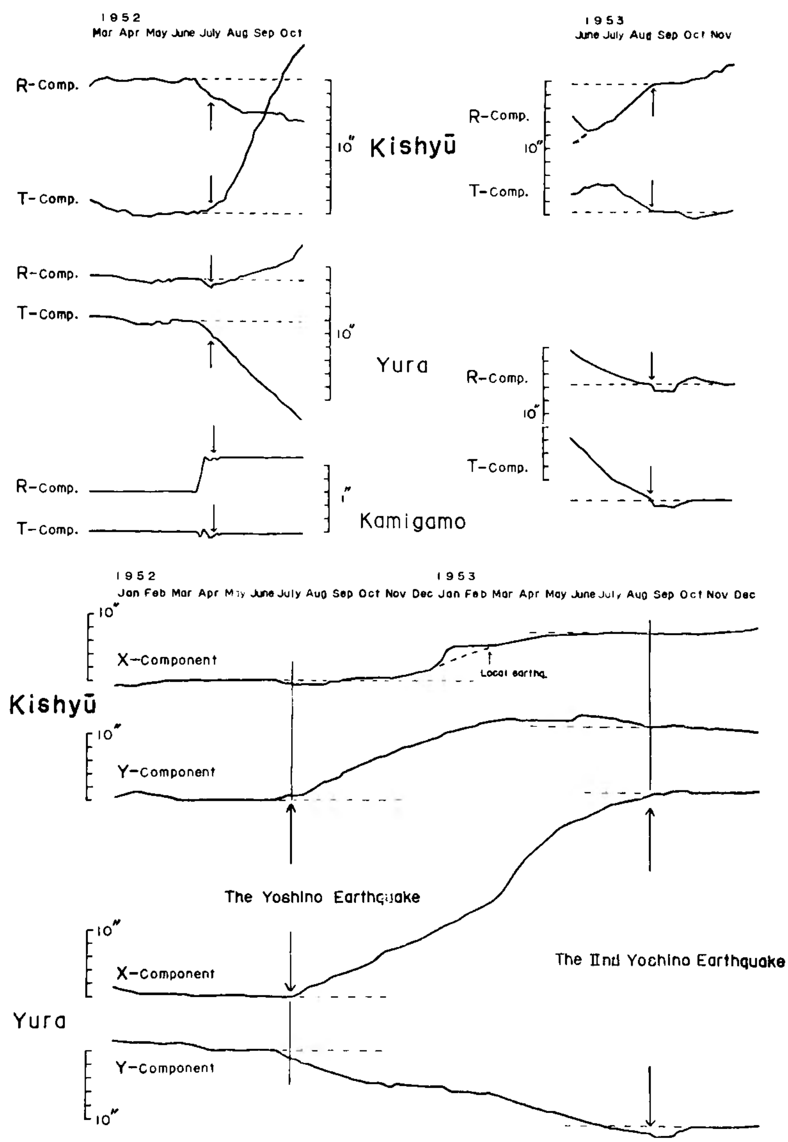


Fig. 6 Upper left : Ground-tilting in radial (R) and transversal (T) components to the epicenter of the Yoshino Earthquake.
Upper right: The same to the epicenter of the Sept. 1-Earthquake.
Lower : Secular ground-tilting in the parallel (X) and the orthogonal (Y) components to common axis of the nodal hyperbolas of both the Yoshino and the Sept. 1-Earthquake. (Ref. Fig. 5)
Arrows indicate the time of occurrence of the Earthquakes.

change of ground-tilting appeared on the beginning of July (nearly two weeks before the Earthquake) at both stations of Kishyū and Yura, and also at Kamigamo, as clearly seen in Fig. 6. Concerning the case of the Earthquake on September 1, 1953, it remained in question whether the anomalous ground-tilting which was only observed at Kishyū and not observed at Yura, as seen in Fig. 6, was a real ground-tilting forerunning the occurrence of the Earthquake or not. This problem might conveniently be referred to a succeeding discussion of this section. With regard to the ground-tilting after the Earthquake (the post-earthquake ground-tilting), their modes in two cases of the Earthquakes of No. 1 and No. 3 were markedly different from each other. Namely, in case of the Earthquake of No. 1, the grounds at both station of Kishyū and Yura showed a large, peculiar tilting motion which lasted one year long, as will later be discussed. Contrary to the case above mentioned an appearance of post-earthquake ground-tilting in case of the Earthquake No. 3, was as indicating the termination of a sequence of ground-tilting connected with each other. This problem will also be discussed in the following.

The push-pull distributions of first motion in two cases of the Earthquake on July 18, 1952 (No. 1) and September 1, 1953 (No. 3) were represented in Fig. 5. As seen in the Figure, it may safely be said that those two Earthquakes were generated by same mechanism of cone-type rather than a quadrant one. Moreover both Earthquakes including several succeeding Earthquakes which were listed above (No. 1–No. 8) were regarded belonging to a series of earthquakes in Yoshino District, because no remarkable earthquake having a focal depth of nearly 70 km has occurred in Yoshino District during 17 years before the Earthquake of No. 1 (July 18, 1952) and during 6 years after the Earthquake of No. 8 (Nov. 19, 1956) to the present time (December, 1962). As seen in Fig. 5 and also in the above list of Earthquakes, the main shock of this series of earthquake was one on July 18, 1952 (No. 1), and a sub-main shock was one on September 1, 1953 (No. 3); the other Earthquakes being considered to have a character of the aftershock. It is a very interesting fact that a line connecting the epicenters of three remarkable shocks (No. 1, No. 3, and No. 8) was paralled to the anticline-axis of new orogenic movements in Kinki Province, as represented in the thick and thin broken lines in Fig. 5.

For the purpose of investigating the relation between the activity of this series of earthquakes and the corresponding ground-tilting observed at Kishyū and Yura, the observed data at both stations were resolved into two components of X and Y. The directions of X and Y were parallel and orthogonal to the line connecting the epicenters of three remarkable shocks, as shown in Fig. 5. The secular ground-tilting thus resolved into two components at Kishyū and Yura was shown in Fig. 6. As clearly seen in Figure, the anomalous ground-tilting connected with this series of Yoshino Earthquakes appered 2 weeks before the first main shock (July 18, 1952) and lasted to the time of the second main shock (September 1, 1953). The amount and direction of the anomalous ground-tilting concerned were given in vector form in Fig. 5. It was presumed from those figures that the anticline-axis was uphove and its wing side subsided during the active period of this series of Earthquakes. The secular ground-tilting during the period of long before the Earthquake on July 18, 1952 (No. 1) could not be discussed because the commencement of observation at both stations of Kishyū and Yura was that of since November, 1951. But the mode of secular ground-tilting after the Earthquake on September, 1953 (No. 3) could be referred to the vector-diagram of secular ground-tilting observed at Yura during the period of November, 1951—August, 1962 which was represented in Fig. 7. From this figure it was reasonably explained that the anomalous, rapid ground-tilting observed at Yura during the period of July, 1952—September, 1953 corresponded with the active stage of this series of Earthquakes, and the succeeding, slow ground-tilting during the period of October, 1953—November, 1956 was related with the settling stage of this series of Earthquakes. The result obtained in this section might greatly be serviceable for the development of study on the relation between the seismic activity and the crustal deformation in a small, restricted area under consideration of its geotectonic structure and movement.

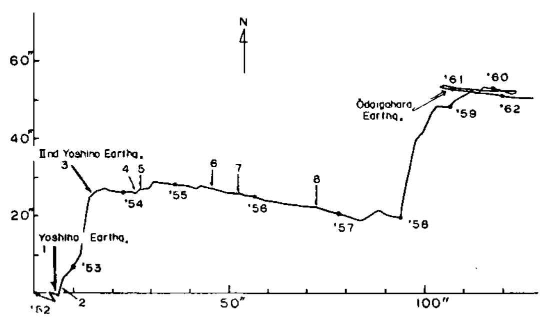


Fig. 7 Vector-diagram of secular change of ground-tilting observed at Yura.
Arrows indicate the time of occurrence of the series of Earthquakes in Yoshino District in the above List.

6. Case of a Series of Hyūganada Earthquakes

The Hyūganada is the sea area which lies between Kyūshū Province and Shikoku Province, and one of the seismically active zones in Japan. The observation station of Makimine was founded in 1942, its position being shown in Fig. 8. In this section, the secular ground-tilting observed at Makimine was discussed in connection with a series of earthquakes originated in Hyūganada during a period of April, 1960—May, 1961 with epicenters within 100 km in distance from Makimine. They were listed in the following:

No.	Date			Epicenter °N	Epicenter °E	Depth km	Magnitude
1	Apr.	16,	1960	32.4	132.0	0	4.7
2	June	6		33.3	132.1	0	4.0
3	July	10		31.9	131.9	40	4.7
4	Aug.	5		32.1	132.1	20	4.5
5	Sept.	4		32.0	132.0	20	5.1
6		26		32.5	132.0	20	5.6
7	Oct.	29		31.9	131.5	0	4.0
8	Nov.	7		32.4	132.1	60	5.8
9	Dec.	31		31.7	131.6	0	4.4
10	Jan.	6,	1961	31.8	131.6	20	4.5
11		8		31.5	131.7	0	4.0
12		17		32.4	131.5	0	3.7
13	Feb.	11		32.2	131.9	0	4.3
14		18		32.2	131.6	0	3.5
15		19		32.5	131.8	0	4.0
16*		27		31.6_0	131.8_5	40	7.0
17	Mar.	30		32.9	131.9	60	4.7
18	Apr.	4		32.4	132.2	0	4.7
19	May	2		31.4	131.8	20	4.7

* The so-called Hyūganada Earthquake, its aftershocks are omitted.

Their epicenters were also plotted in Fig. 8. Among these earthquakes the Earthquake on February 27, 1961 was the most remarkable and accompanied by

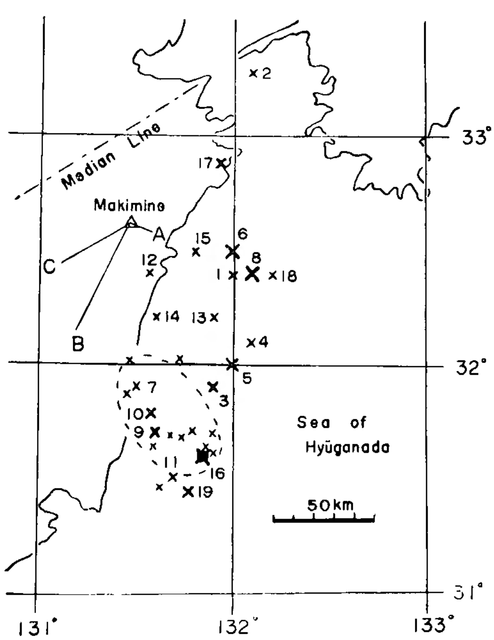


Fig. 8 Distribution of epicenters of major Earthquakes originated in the Hyūganada. (April, 1960—May, 1961)
Solid line *A*, *B*, *C*: direction of analysed components
Ellipse: aftershock area of the Feb. 27-Hyūganada Earthquake
The numerals correspond to the number of Eathquakes in the List.

a series of fore-shocks and aftershocks.

In the present case the secular ground-tilting observed at Makimine may conveniently be resolved into three components of *A*, *B* and *C*. The directions of *A* and *B* were orthogonal and parallel to the axis of seismic belt in the present series of Earthquakes concerned, and the direction of *C* was parallel to the great geotectonic structure named Median Line in Japan. These were shown in Fig. 9, and some remarkable characters were found in the mode of secular ground-tilting in reference with the earthquake-occurrence. Namely, one was a distinct dissimilarity between the modes of ground-tilting of long period (April, 1960—May, 1961) observed in the orthogonal (*A*) and parallel (*B*) components. During this one year, the amount of secular ground-tilting in the orthogonal component was extremely small (less than 0.1″) and, contrary to this, that in the parallel component reached to 4.6″, its movement being monotonous inclining towards the *SSW* direction. This movement of upheaval in northern area and subsidence in southern area were common in the area of Makimine and also belonged to the large geotectonic movement in the wide area of eastern part of Kyūshū Province which was observed by survey of precise levelling. A second remarkable character was of an appearance of ground-tilting curve in parallel direction (*C*) to Median Line. As clearly seen in Fig. 9, this period concerned (April, 1960—May, 1961) might conventionally be divided into two sub-periods of the first (April—November, 1960) and the second (December, 1960—May, 1961) epoch respectively. These sub-divisions were reasonably made from the following two points,—one the slight difference in the inclination angle of curve of general ground-tilting and the other the difference in type of anomalous ground-tilting directly connected with individual Earthquakes. A third noticeable character was found in reference with the curve of orthogonal component (*A*). In this case almost all remarkable Earthquakes (excepting a series of small fore-shocks and aftershocks of the main shock on February 27, 1961) occurred at the time of the beginning of an upward stage of the up-and-down fluctuation in curve of secular ground-tilting in orthogonal direction. A fourth interesting fact was with respect to the amplitude and duration of anomalous ground-tilting directly connected with individual remarkable Earthquakes. It was clearly observed in both curves of orthogonal (*A*) and parallel (*B*) components, but more easily followed in the curve of parallel component (*C*) to Median Line. In detail, the anomalous ground-tilting of saw-tooth shape was observed with decreasing amplitude and shortening duration with time in two sub-divisions of epochs, one being from April to November, 1960 (I-division) and the other from December, 1960 to May, 1961 (II-division). These modes of anomalous ground-tilting connected with a series of earthquakes were fairly coincident with the result

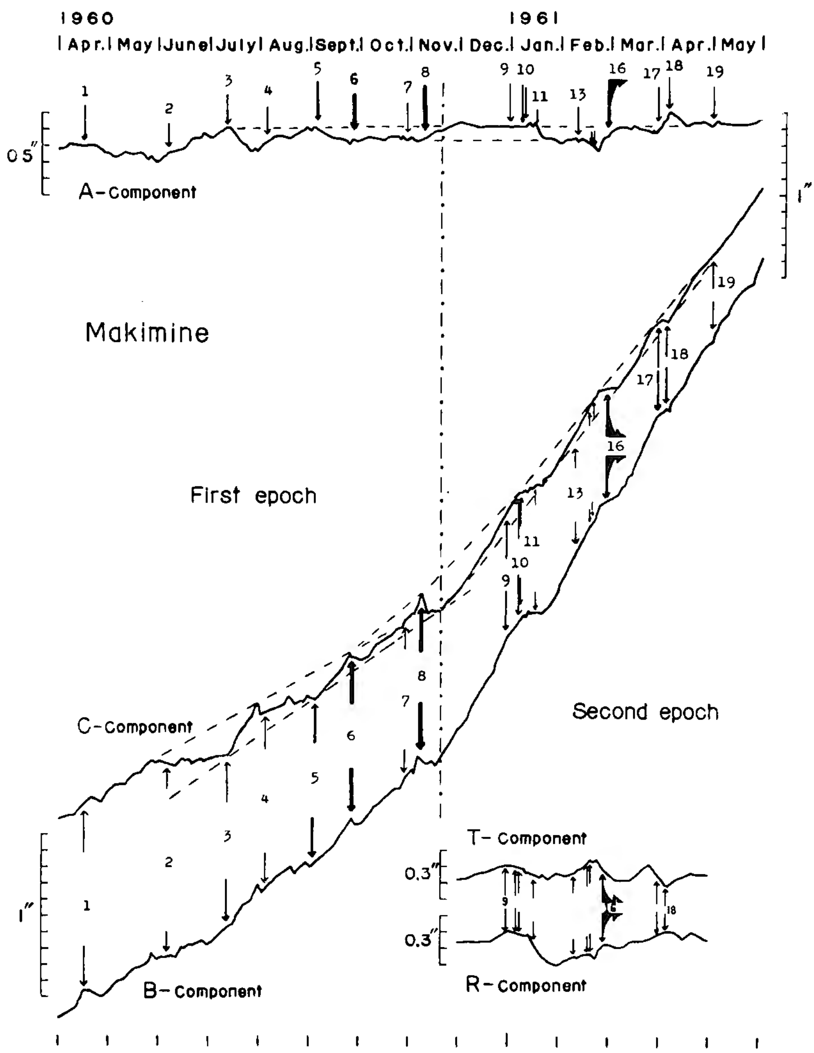


Fig. 9 Secular ground-tilting in the components of *A*-, *B*-, and *C*- direction. (Ref. Fig. 8)
Lower right: Ground-tilting at Makimine in radial (*R*) and transversal (*T*) components to the epicenter of the Feb. 27-Hyūganada Earthquake.
Arrows indicate the time of occurrence of Earthquakes.

in treatment on crustal strain characteristics by H. Benioff.

The observed facts above mentioned were very interesting and suggestive for the study on the relation between the seismic activity in a certain restricted area and its corresponding mode of crustal deformation in its epicentral region. Moreover they might greatly be important for investigation on the generation mechanism of earthquake and moreover be serviceable for the advancement of study on prediction of a destructive earthquake.

Besides the series of Earthquakes treated in the present section in the area of Hyūganada, another series of earthquakes in this area was also observed during the periods before April, 1960 and after June, 1961. On these other series and also the present series, more detailed treatment will be made in a succeeding paper of near future publication.

7. Summary

To briefly summarize the above obtained results, the characteristics of the present investigation were in its treatment of a series of earthquakes in a small, restricted area during a certain period with reference to the crustal deformation (ground-tilting) near their epicenters instead of the former treatment on a single large earthquake. In case of the former treatment, the anomalous ground-tilting which appeared in a comparatively short time (several hours to several days) before and after the earthquake could easily be observed, but those in longer periods (several months to several years), if existing, could never be discussed in reliable condition. The present method of treatment on a series of earthquake gave us some important results with respect to the connection of secular crustal deformation with a seismic activity in a small, restricted area. Especially with respect to two cases of Yoshino and Hyūganada, the relation between the geodetic movement and the secular ground-tilting which was largely modified by the seismic activity in their respective areas, was clearly observed. Moreover, from these results, even the difference of generation mechanism of earthquakes at Yoshino District from that at Hyūganada District could reasonably be assumed. Namely, the rebound theory as generation mechanism of earthquake could conveniently be applied to explain the mode of crustal deformation, taking the push-pull distribution of first motion of seismic wave into consideration as observed at the series of shallow Hyūganada Earthquakes, and, on the other hand, the theory of magmatic intrusion as origin of an earthquake was fairly applicable to the series of a little deeply seated Yoshino Earthquakes. Moreover, there were various cases on the problem of permanent set of crustal deformation connected with earthquakes. Namely, main part of the permanent sets appeared before the earthquakes in some cases, and after the earthquake in other cases. There were also some cases in which the anomalous ground-tilting connected with an earthquake completly recovered and there remained no permanent set. A systematic argument on these problems of "mode of secular ground-tilting connected with a series of earthquakes", "permanent set of ground-tilting" and "generation mechanism of earthquake in reference with crustal deformation and crustal structure" will be made in future publications.