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ON THE OBSERVATION OF SECULAR PHENOMENA OF THE TILTING MOTION OF THE GROUND

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ABSTRACT

The observation of crustal deformation at the Kamigamo Geophysical Observatory of Kyoto University, where a highly sensitive tiltmeter is in use, was begun in 1937, and has been continued to the present day. Twenty years of research have thrown some light on questions of importance in geodesy. In the present article I have set out the results of our observation of secular phenomena of the tilting motion of the ground, principally on the basis of the experiments at Kamigamo, but taking into consideration also those conducted at twenty-five other similar stations in Japan. In such work as this, problems arise concerning the reliability of the instruments employed, the solidity of the foundations in which the instruments are set, the disturbing effects of meteorological change, local conditions as they affect the place of observation, and similar matters: I go into those questions in some detail. The conclusion reached in this paper is, that the observation of secular phenomena carried out by means of tiltmeters of a high degree of sensitivity at a sufficient number of places in a limited area are probably to be considered as being of value in detecting the phenomena that preceed destructive earthquakes, provided, of course, that the observations are carefully made and correctly interpreted. Knowledge of such precursory phenomena is of value in determining the nature and mechanism of earthquakes.

1. Introduction

There are two methods used for studying crustal deformation; the one is to trace the process of past crustal deformation in geologically long times by observing the topography, geological structure and some phenomena concerned with them, and the other is to investigate the progressing crustal deformation by means of geodetic methods. The results that are obtained by the former investigation are the integrated deformation with the career of geological ages, and they can, in general, hardly be connected with and applied to the investigation of the nature of the present crustal deformation now in progress. For this purpose the latter method of geodetic measurement has been profitably used. It should be mentioned here that the term "crustal deformation" properly means the upheaval, subsidence, and horizontal displacement of the ground with reference to the mean sea-level or any point assumed to be unchangeable. But recently, it is also used in a more widely extended meaning to describe the phenomena of secular variation in gravity-intensity, plumb-line deviation, geomagnetism, and other geophysical elements which are considered to be caused by or related to the activity or the change of state in the constituent material of the earth's crust. Especially, the crustal deformation, in a wider sense, with relation to the occurrence of destructive earthquake, or the great eruption of volcanoes, has ever been an attractive and important research item in seismology and geodesy.

Investigation of crustal deformation in Japan by level surveying and triangulation was commenced shortly after the Nobi Earthquake in 1891. These survey methods were suitable and productive in studying the relation between earthquake-occurrence and ground-deformation. At present, in our country, the area surveyed has increased yearly, especially in some districts disturbed by great earthquakes where repeated surveying has resulted in important findings (**1**, **2**, **3**, **18**, **19**, **20**). However, as it is difficult, mainly for financial reasons, to carry out this sort of levelling survey and triangulation extensively in a region with frequent repetition, observations with some geodetic instruments of automatic and continuous recording at many fixed stations have gained prevalence, supplementing level- and triangulation-surveys.

In the present article, the observations, especislly those of secular phenomena, of the tilting motion of the ground caused by crustal deformation, made with a highly sensitive tiltmeter and at many different stations in our country are here reported and discussed in some detail. As the silica-tiltmeter of a horizontal pendulum type devised by M. Ishimoto (**4**, **5**) is highly sensitive and easily manipulated, the instrument has been frequently employed, in our country, in the study of earth-tides and, also in the study of the tilting motion of the ground, as a station instrument. In the research field of instrumental-observation of ground-tilting which is supposedly connected with the earthquake-occurrence, many papers have been published since Ishimoto's in 1929 (**4**), by M. Ishimoto (**4**, **5**), U. Inoue and T. Sugiyama (**6**), K. Sassa and E. Nishimura (**7**, **21**), K. Hosoyama (**14**, **16**), E. Nishimura and K. Hosoyama (**15**), T. Hagiwara (**8**), and others. Observations were made mainly with the silica-tiltmeter of the Ishimoto-type, the invar-tiltmeter of the Nishimura-type and others. Hagiwara has suggested that the water-tube tiltmeter which measures the difference between the water level at two points at a great distance apart is more suitable than the tiltmeter of horizontal-pendulum type in the investigation of secular ground-tilting. The relative merits of the instruments of these two types really should be judged from the standpoint of object in phenomena. For the purpose of investigating the minute tilting-motion of the ground as caused by the earth-tides, forerunning phenomena of short duration just before the earthquake-occurrence, and other micro-geophysical changes, the highly sensitive tiltmeter of horizontal-pendulum type is more profitably used. On the contrary, the water-tube tiltmeter is suitable, in general, for the observation of slow ground-tilting of an extended period of several years. Generally, in the observation of secular tilting motion of the ground, the following conditions should carefully be considered. These arguments are applicable to both cases of observation with the water-tube tiltmeter and the horizontal pendulum tiltmeter, but, in the present article, those with the latter are mainly discussed. The principal effects which are considered to disturb the observational results are; (1) degree of instrumental stability, (2) meteorological effect, (3) local character of observation-place and room, and other troublesome effects.

Concerning the degree of instrumental stability, some experimental observations comparing the results of the horizontal pendulum tiltmeter with those of other types were made, and it was ascertained that the tiltmeter with a horizontal pendulum can advantageously be utilized for the study of the secular tilting motion of the ground, when some appropriate precautions are taken against the manipulation of the instrument, the selection of the observation position, etc.

Secondly, on meteorological effects, namely those by daily and annual variation of atmospheric and ground temperature, and, moreover, by rainfall and sunshine have been treated by some researchers (**9**, **10**, **11**, **12**, **13**). It is contended however that a general law on the disturbing effect of meteorological change upon the observed result of ground-tilting cannot so easily be found, as the meteorological change has considerably strong local characteristics in each case of observation. The problem concerning meteorological effects can certainly be solved by the inbedding of the instrument in the observation room, say 100 m or so below the ground surface as any meteorological effect is ostensibly eliminated.

Thirdly, the problem on local character of the observation place is most difficult and essential in this sort of observation. Here, the meaning of "local character" should be examined and classified. It is, in the present paper, used to denote the particular tilting motion of the foundation on which the tiltmeter is set up, the observation room, the observation station, and the obrervation area within a radius of several kilometers.

These three disturbing effects should carefully and fittingly be reduced and corrected in precise observations on tilting motion of the ground, especially on those connected with the earthquake-occurrence. Regarding these points some detailed discussion will be made in the following. In consequence the observed data for the extended 20 years period from 1937 till 1957 at the Kamigamo Geophysical Observatory will first be discussed in reference to the disturbing effects, and afterwards the arguments will be extended to other stations. Finally the trustworthiness of some previously obtained data on peculiar tilting motion of the ground which are supposed to be intimately connected with and to forerun earthquake-occurrence, will be examined and discussed from various aspects. For the sake of facilitating comprehension, the positions of main observation stations will be shown in Fig. 1.

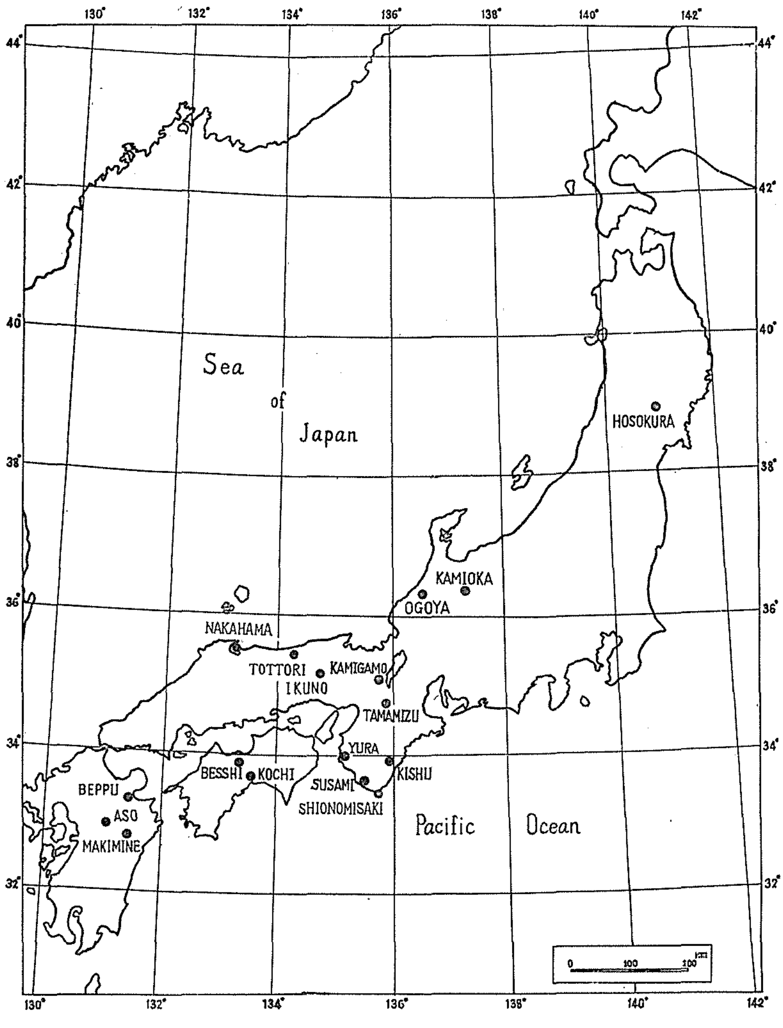

Fig. 1. Position of observation stations.

2. Secular tilting motion of the ground observed at the Kamigamo Geophysical Observatory

The Kamigamo Geophysical Observatory of Kyoto University is located on a mountain top about 100 meters high, in the northern part of Kyoto City. The mountain rock is of the paleozoic system. The instrument is silica-tiltmeter of horizontal pendulum type, and the observation room is in a pit, 9 meters deep under the ground surface.

Mean sensitivity of the tiltmeter has been maintained at about 0″.005/mm, and the positive direction of the A-component indicates the tilting motion of the ground downwards to N45°E and the B-component to S45°E. The observation was commenced early in 1937 and has been continued to the present, encompassing a long series of observations. Fig. 2 shows the monthly mean of ground-tilting during 17 years of the 20 years and each component clearly shows the annual variation. Some researchers have discussed the causes of such annual variation, and have concluded that it is caused by seasonal effects such as change of atmospheric temperature, baro-

Fig. 2. *Annual variation of ground-tilting observed at Kamigamo.*

metric pressure, and other meteorological variations. Really, also in the present case, there exists, in general, a great similarity among these changes, as seen in Fig. 2.

But, examing these relations in detail, the following two points peculiar to ground-tilting are easily detected. Namely, the large fluctuation of amplitnde in annual variation and the secular change of the annually mean value with regard to ground-tilting are characteristic, compared with the regular annual variation of atmospheric temperature and pressure, as shown in Fig. 2. More fully discussed, a vector diagram of ground-tilting for each year is described in Fig. 3, and the form of annual variation is roughly said to be similar to the other. The direction of maximum axis in the

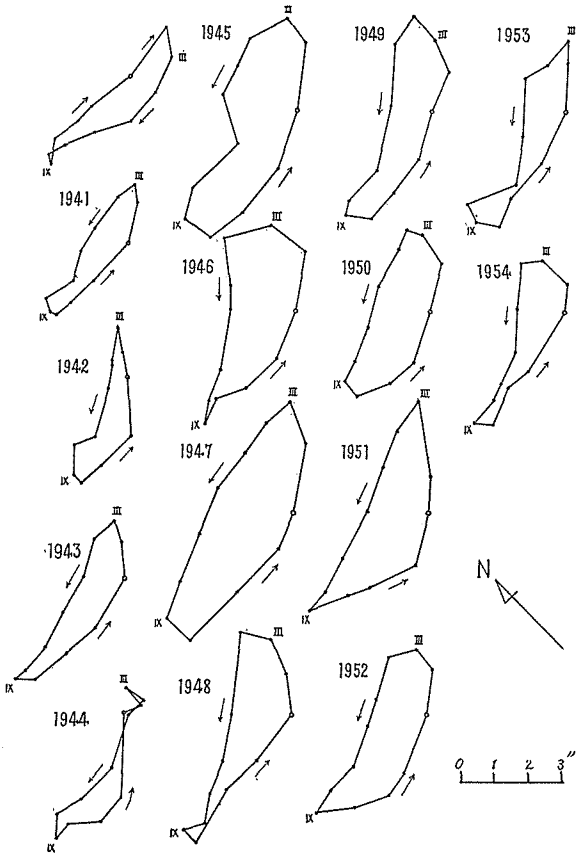

Fig. 3 Vector diagram of annual ground-tilting observed at Kamigamo.

variation being nearly E–W. March and September have the highest variation values. But, in delailed treatment, the fluctuation of amplitude in annual variation, expressed in the yearly change of length of long and short axes in the vector diagram, is clearly observed, and they are ascertained to be intimately connected, as shown in Fig. 4, to yearly change of mean atmospheric temperature. And, as also noted in the figure, the rate of secular variation, as calculated from the residual ground-tilting under the assumption of perfect closure in the vector diagram of annual variation, is somewhat correlated to the yearly total value of rainfall. These correlations between the ground-tilting and meteorological changes are considerably complex in their correspondence and have excessively localized character as seen in each observation at different places. But it is important to get a clear knowledge about these correlations in every case of observation, for the sake of precise and accurate investigation with respect to ground-tilting; whereof, detailed discussion will be made in a later section. Here, for

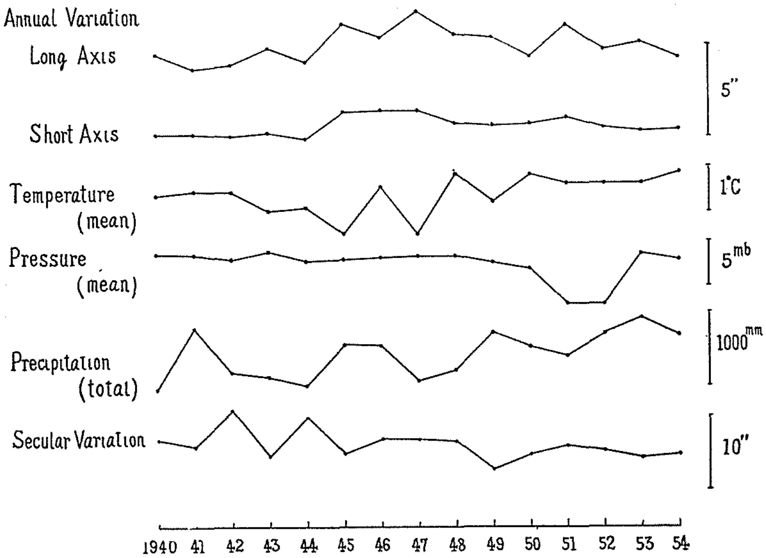

Fig. 4. Elements of secular ground-tilting observed at Kamigamo.

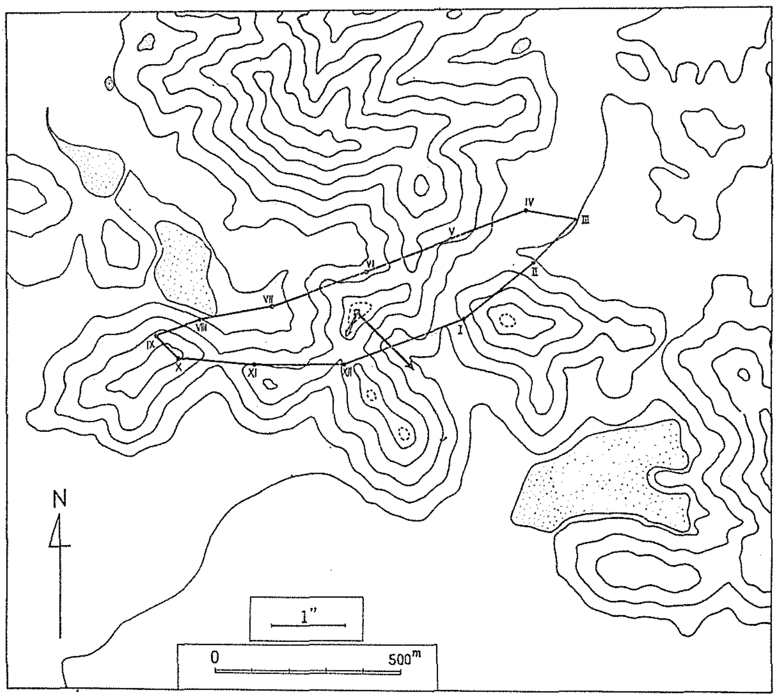

Fig. 5. Modes of annual ground-tilting, secular variation, and rainfall effect at Kamigamo.
closed vector-diagram : annual variation
➡ : secular variation ⇨ : rainfall tilting

the sake of reference, the graph of topography with vector diagrams of mean annual variation, and secular variation of ground-tilting, and, moreover, the direction of ground-tilting, in the case of rainfall at Kamigamo, are schematically shown in Fig. 5. It is questionable as to whether or not there is any significance in the relative directions of ground-tilting caused by its respective changes. Next, with regard to the secular behaviour of ground-tilting as described in the vector diagram, Fig. 6 will be subsequently referred to, the diagram being obtained from the values of the running mean of each 12 months during the 1939–1955 period. From the figure it is seen that the ground has tilted downward to S in the first stage of 1939–1942, then reversely to N in the 1942–1943 stage; again to S in 1943–1945, and, after the slightly oscillating motion, has steadied itself toward S–E, from 1951 until the present. The total amount of ground-tilting at Kamigamo is estimated to be nearly 5″ during the past 17 years.

Finally, concerning the relations between secular tilting motion of the ground observed at Kamigamo, and the occurrence of earthquakes in the neighbouring districts, the secular variations observed by each component tiltmeter (A and B) are separately plotted in Fig. 7 for the convenience of easy understanding with the occurrence of large earthquakes which occurred in the neighbouring area of Kamigamo. The name of earthquakes whose occurrence times are indicated by arrows in the figure are (1) Tottori (Sept. 10, 1943), (2) Tonankai (Dec. 7, 1944), (3) Mikawa (Jan. 13, 1945), (4) Nankaido (Dec. 21, 1946), (5) Fukui (June 28, 1948), (6) Daishoji-oki (Mar. 7, 1952), (7) Yoshino (July 18, 1952).
As great earthquake close by Kamigamo has not occurred during the observation-period, the correlation between the secular variation of ground-tilting and the occurrence of large nearby earthquakes was not definitely ascertained. But if it is examined in detail with the anticipation of finding a correlation some correspondence between will be found, especially conspicuous in case of the Tottori Earthquake of 1943, less markedly in the instance of the Tonankai Earthquake of 1944, the Nankaido Earthquake of 1946, the Fukui Earthquake of 1948, and the Yoshino Earthquake of 1952. In all these examples a particular tilting motion which might be said to be a ground-tilting forecasting the earthquake-occurrence, was observed to have appeared during the period of nearly one year before the earthquake-occurrence. But, as this sort of discussion may contain many difficult and questionable points, a detailed treatment will be postponed to §6.

Much of the foregoing discussion referring to the data obtained by the long period of observation nearly 20 years at the Kamigamo Geophysical Observatory will undoubtedly be supported and advanced by the numerous data observed at other observation stations which are more than 25 attached to Kyoto University and which are advantageously distributed in a dense net throughout Japan. In the next section the observed data at these stations are treated.

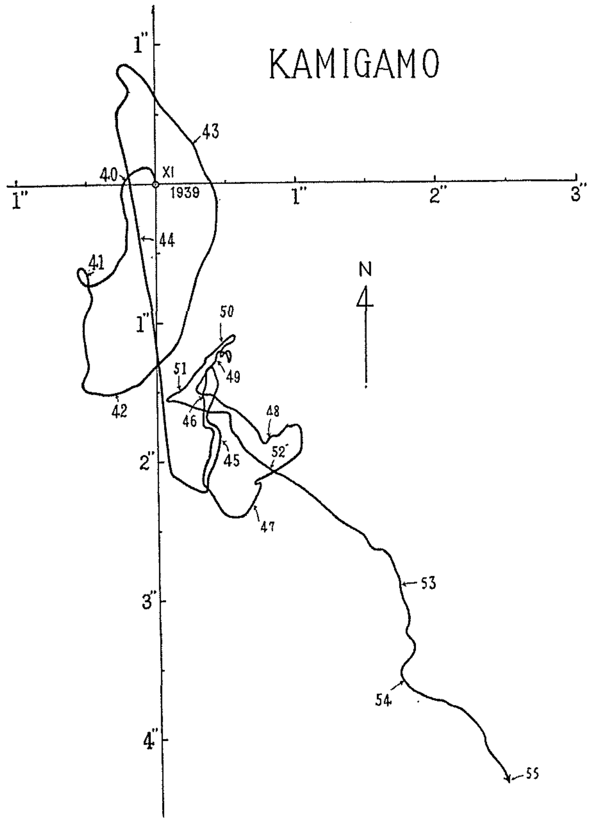

Fig. 6. Vector-diagram of secular ground-tilting observed at Kamigamo.

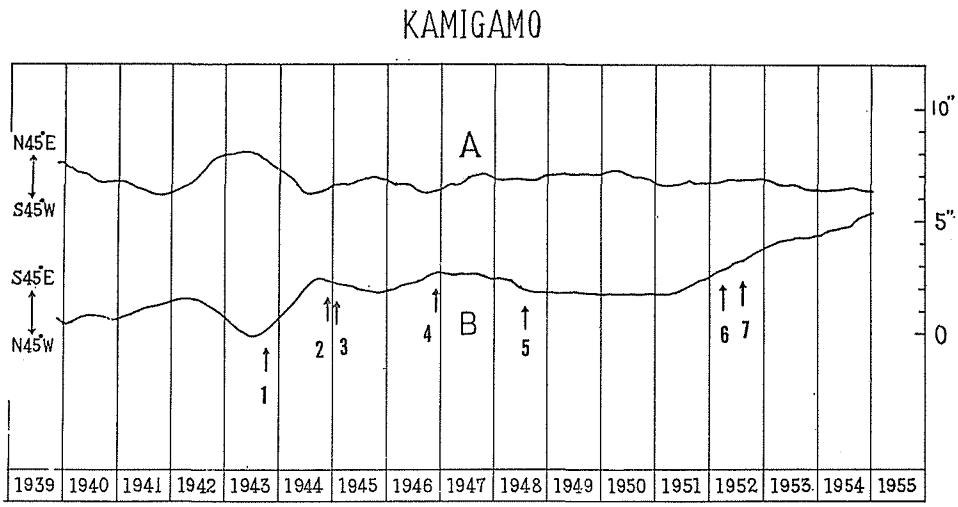

Fig. 7. Relation between the secular ground-tilting expressed in two orthogonal components and the neighbouring destructive earthquakes observed at Kamigamo.

Table 1

Station \ Condition		Position E	Position N	Height on sea level	Geological formation of ground rock	Under-ground depth of observation room	Type of tiltmeter (horizontal pendulum)	Epoch of observation
Makimine	1	131°27′	32°37′	130 m	Paleozoic	165 m	Silica (1942–47) Superinvar (1948–)	1942– the present time
	2	〃	〃	〃	〃	165	Superinvar	1952– the present time
Beppn	1	131 30	33 16	10	Alluvial sand and volcanic lava	2	Silica	1937–38
	2	〃	〃	20	〃	3	〃	1937–39
	3	〃	〃	30	〃	2	〃	1937–39
	4	〃	〃	150	〃	5	〃	1938–39
Kōchi		133 32	33 34	10	Paleozoic	40	Superinvar	1949– the present time
Bessi		133 19	33 52	660	Chlorite-schist	750	〃	1949–51
Shionomisaki		135 47	33 28	8	Porphyrite	5	〃	1955– the present time
Kishu		135 53	33 52	90	Tertiary sandstone and shale	60	〃	1957– the present time
Susami		135 30	33 32	5	Paleogene	10	〃	1948– the present time
Yura		135 07	33 57	10	Mesozoic sandstone and shale	30	〃	1951– the present time
Tamamizu		135 49	34 48	250	Paleozoic	30	〃	1948–51
Kamigamo		135 46	35 04	190	Paleozoic	9	Silica	1937– the present time
Ikuno	1	134 50	35 10	440	Liparite	237	Superinvar	1951– the present time
	2	〃	〃	〃	〃	326	〃	1952–53
	3	〃	〃	〃	〃	719	〃	1943–53
Nakahama		133 15	35 30	10	Alluvial sand	2	Silica	1938–40
Ogaya		136 33	36 17	210	Tertiary tuff	300	Superinvar	1948– the present time
Kamioka		137 19	36 21	920	Gneiss	800	〃	1952– the present time
Hosokura		140 54	38 48	130	Tertiary	160	〃	1944– the present time
Tottori		134 17	35 31	150	Liparite	200	〃	1955– the present time
Aso	1	131 00	32 53	540	Volcanic rock	22	Silica	1937–40
	2	131 03	32 53	1130	〃	10	〃	1937–40
	3	131 07	32 57	520	Volcanic ash	3	〃	1937–40
	4	131 05	32 53	1150	Volcanic lava	1	Silica (1937–43) Superinvar (1953–)	1937–43 1953– the present time
Iimori		135 26	34 15	220	Chlorite-schist	40	Superinvar	1943–45
Ide		135 49	34 48	150	Paleozoic	15	〃	1951– the present time
Abuyama		135 34	34 52	200	Paleozoic	20	〃	1938– the present time
Osakayama		135 51	34 59	130	Paleozoic	150	〃	1947– the present time
Tsuchikura		136 18	35 36	400	Paleozoic	170	〃	1953– the present time
Osarizawa		140 45	40 11	320	Tertiary tuff and shale	300	Silica	1944–46
Suhara		135 12	34 03	5	Chlorite-schist and breccia	60	Superinvar	1955– the present time

3. Secular ground-tilting observed at various observation stations

The total number of our stations for observing the crustal deformation is nearly 33 during the past 20 years. Some of them were temporary stations during the first few years for studying special items, but the majority of them were permanent stations which have been increased each year, the number of the permanent stations being 19. We intend to increase the number of stations, all being equipped with a tiltmeter, an extensometer, a gravity-variometer, a magnetic variometer, and other instruments, to 25 permanent stations during the international geophysical year of 1957–1958. In Table 1, the details of each observation station are described, including the temporary, the permanent stations, and the scheduled stations.

In the following sections, the data obtained at various stations where the geological conditions, the depth of the observation room, the topography and other circumstances differ widely from each other, will be analysed and discussed as regards the type of instrument, the instrument-foundation, the meteorological effect, and the local character of the ground-tilting. In Figs. 8a–8n, some examples of the mode of

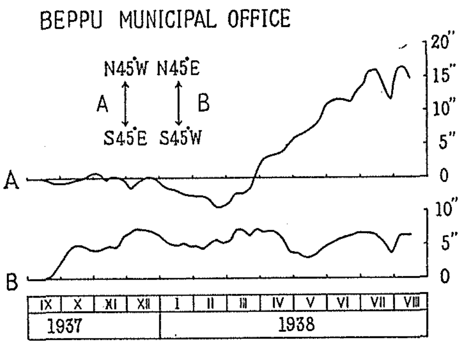

Fig. 8a.

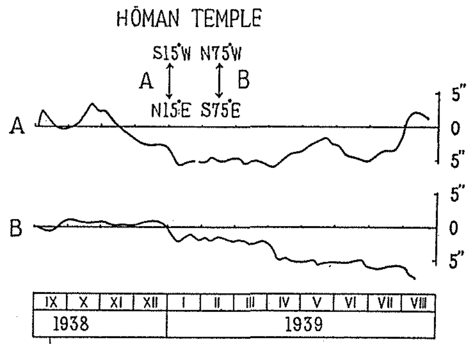

Fig. 8b.

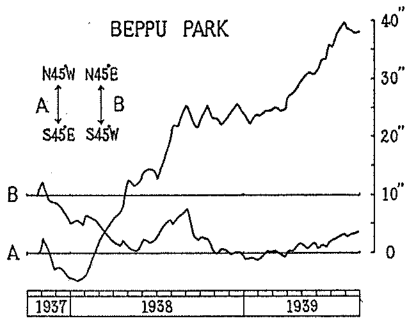

Fig. 8c.

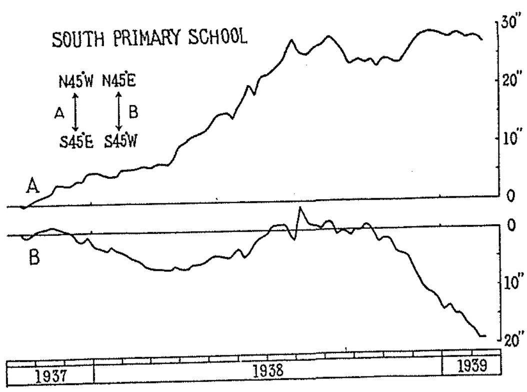

Fig. 8d.

secular ground-tilting observed at various stations are shown. As seen in these figures, the mode of ground-tilting differs widely for each station, namely, one shows a periodic motion like an annual variation, and the other a chronic motion toward a certain direction. The former is generally observed at stations with a shallow seated observation room, shallower than about 10 m, and the latter is often observed at stations with a deeply seated observation room, more than several hundred meters deep, which is usually a part of an adit in a metal mine. From these facts, it can simply be explained that an observation in a shallow room is largely affected by meteorological changes, such as daily and seasonal changes of air-temperature and ground-temperature, and the amount of precipitation. The observation in a deep room is usually disturbed by a gradual but progressive deformation of an adit by the rock pressure more than one-thousand atmospheric pressure and its change caused by mining at the neighbouring adit. Really, it is observationally ascertained that the progressive tilting motion to

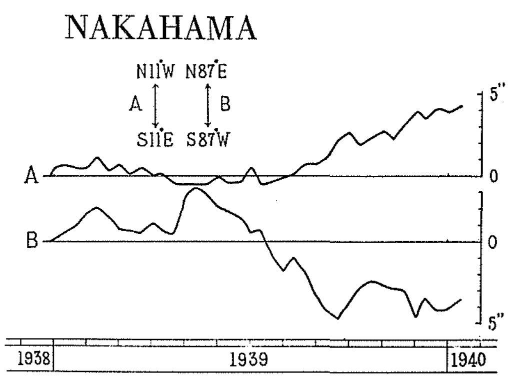

Fig. 8e.

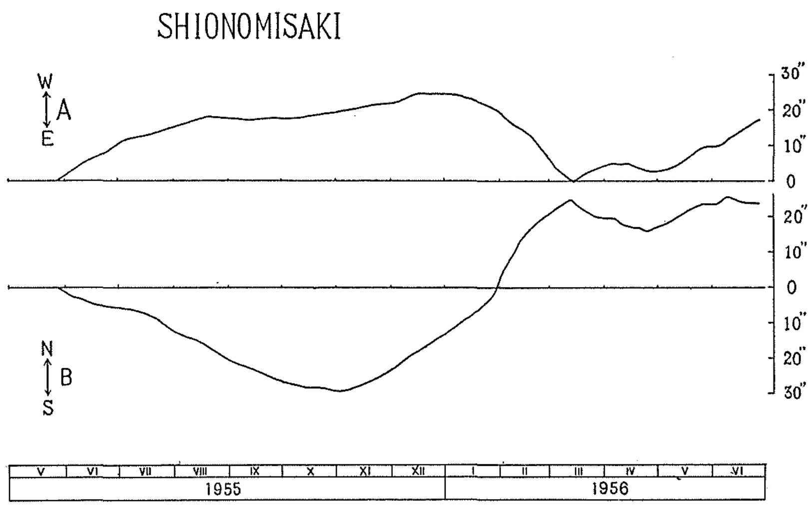

Fig. 8f.

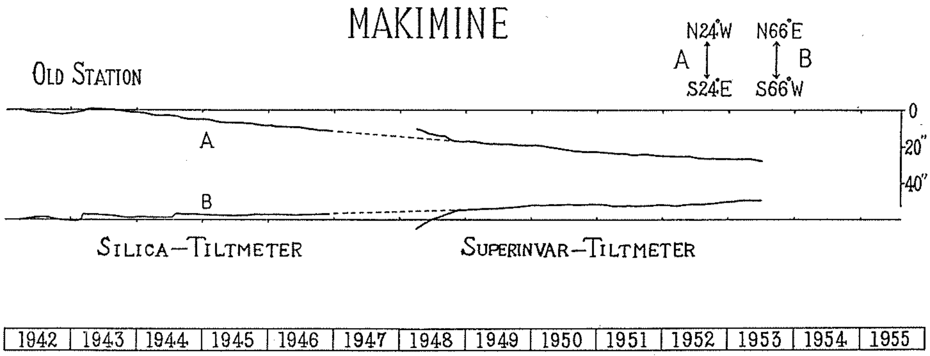

Fig. 8g.

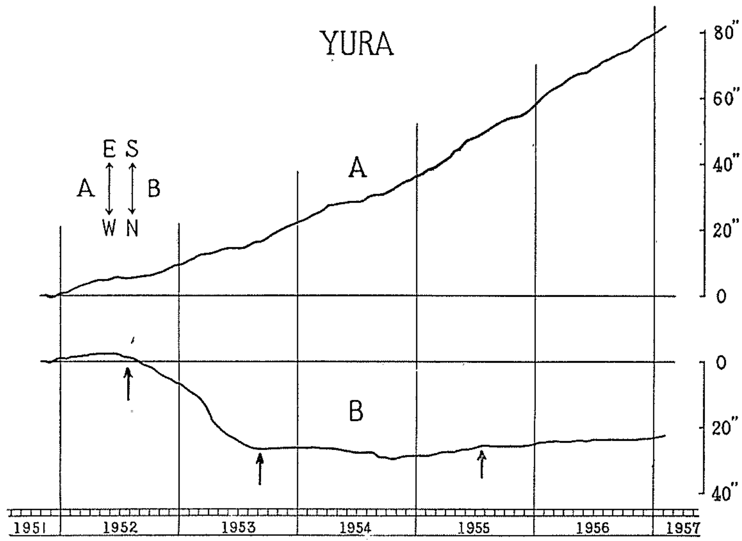

Fig. 8h.
Arrow indicates the time of occurrence of neighbouring large earthquakes.

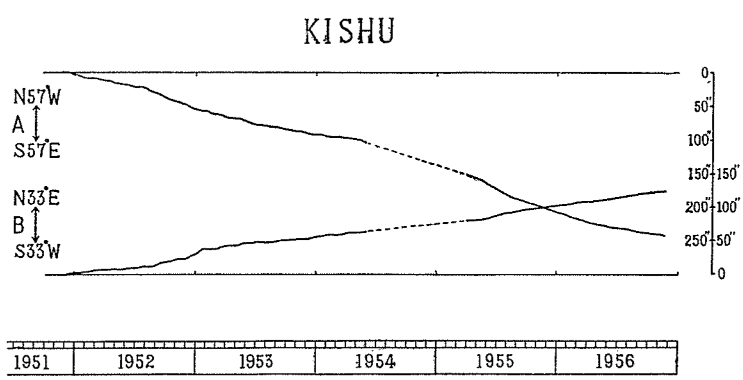

Fig. 8i.

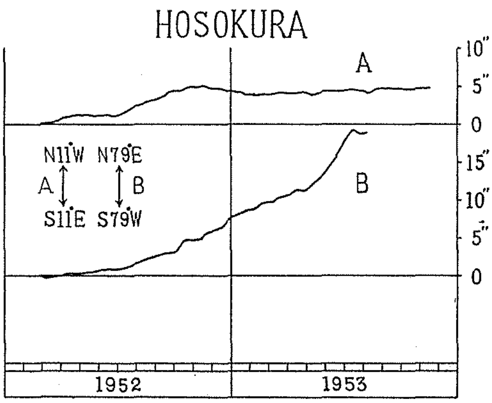

Fig. 8j.

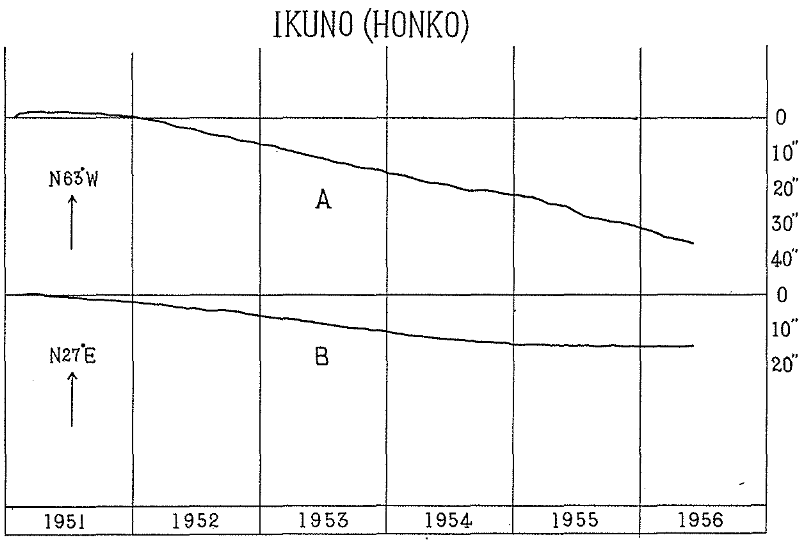

Fig. 8k.

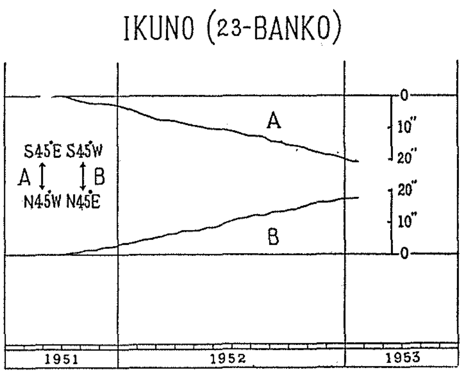

Fig. 8l.

one direction observed at a shallow seated room is, in the usual case, exceedingly small, in spite of a large daily and seasonal variation of ground-tilting, and rainfall-influence. On the contrary, however, observation in a deep seated room is little affected by meteorological change and seasonal variation. Some details on the relative merit of the underground depth of an observation room will be referred to in a later section.

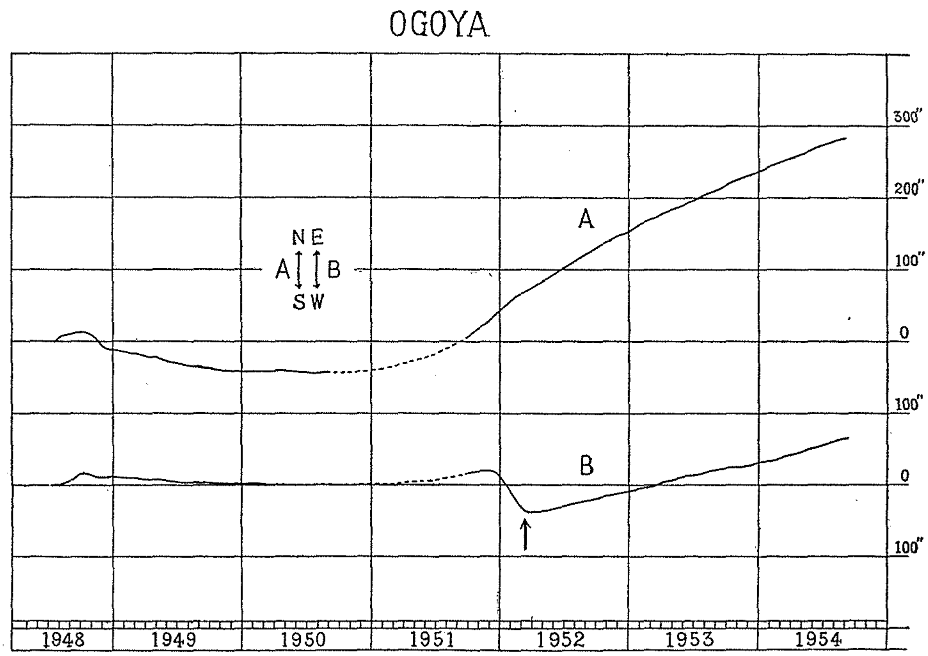

Fig. 8m.
Arrow indicates the time of occurrence of Daishoji-oki Earthquake.

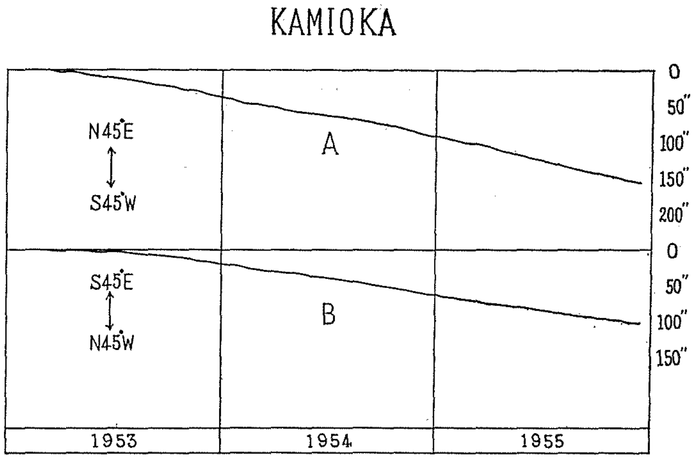

Fig. 8n.

3. Effects of various causes upon the secular observation of ground-tilting

It has already been remarked in the previous section that the secular observation for tilting motion of the ground is generally disturbed by various causes. For the sake of precise study on the nature and mode of real ground-tilting, these disturbing causes must be carefully examined and completely removed. Some detailed treatments are made in the present section concerning these causes.

(1) Type of tiltmeter

As the principal parts of a silica-tiltmeter with a horizontal pendulum are made of fused silica, the direct temperature effect upon the pendulum is very small. The tiltmeter of this type shows good stability in a long series of observations, and really the original silica-tiltmeters set up early in 1937 at Kamigamo have been operated until the present time without interruption. But the making of a tiltmeter of this type needs special skill, consequently, when it is damaged, it is practically impossible to repair it when being used in the field. Moreover, micro-oscillations are frequently observed in the tiltgram of the silica-tiltmeter even when the tiltmeter is set in a deep seated room. The sources of these micro-oscillations have not yet been definitely identified, but they are supposed to have mainly originated from the micro-oscillation of the silica-pendulum moved by the minute circulation of air in the circular cylinder, covering the pendulum parts, which is, of course, air-tight. This disturbance is considered to be mainly attributable to the point of light weight of inertia mass, weighing only 1 gram, in a horizontal pendulum.

E. Nishimura constructed the superinvar-tiltmeter of horizontal pendulum type to remove these inefficiencies in the silica-tiltmeter. To put it more precisely, the main parts of the tiltmeter, the horizontal pendulum and its supporting-frame, are made of superinvar alloy, the weight of inertia mass, the radius of suspension superinvar wire, the length of pendulum-arm and the height of supporting-frame being 15 grams, 15μ, 10 cm and 20 cm respectively. However, only for the material of inertia mass pure electric copper plated with gold is especially used to preclude any magnetic effect. By means of these improvements the micro-oscillation as frequently observed in those cases of obser vation in which the silica-tiltmeter is used, is greatly reduced in frequency and amplitude. Concerning the function-comparison between the silica- and superinvar-tiltmeters, some test observations were made at several stations in a comparatively short period of several months. Of these results obtained by short period observation, both tiltmeters were ascertained to show the same results, with regard to both periodic earth-tidal change and secular ground-tilting. As an example of the long-period comparison observation between the silica and- superinvar-tiltmeters, Fig. 8g is conveniently referred to, where the secular ground-tilting observed at Makimine is plotted. Though it is regrettable that there is no simultaneous observation using two tiltmeters, it is clearly shown in Fig. 8g that observations both with the silica-tiltmeter (1942–1946) and the superinvar-tiltmeter (1949–1953) have similar ground-tilting toward common direction, excepting the abnormal change in the initial epoch just after the commencement of the observation in both cases. Fig. 9 indicates the comparison between two superinvar-tiltmeters of the same type made at the Abuyama Seismological Observatory, Kyoto University, during the period from January to April 1951. In this case the comparison was made by one component, and both tiltmeters have been

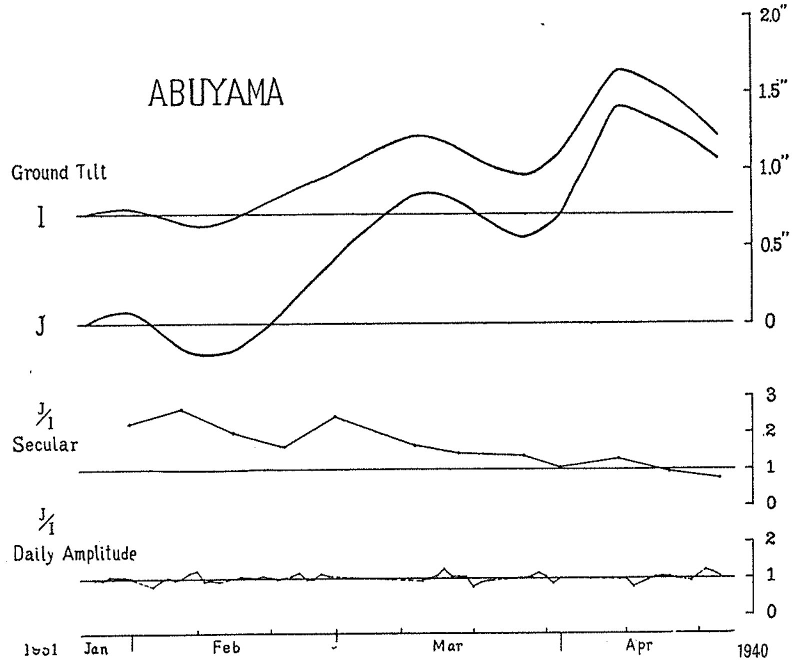

Fig. 9. Comparison observation with two superinvar tiltmeters at Abuyama.

set in the same direction with similar sensitivity of 0".116/mm. As seen in Fig. 9, both tilting motions show a similar tendency, but their secular variation quantities seem to be somewhat different. The ratio of amount of tilting-motion J/I is about 2 at the initial stage, but becomes gradually nearly unity. From these and other cases it is losely concluded that the secular ground-tilting is, in general, disturbed during the initial stage, just after the setting up of the instrument. However, it gradually reaches a normal state after a few months, at most, from the initial observation. But it should be emphatically remarked that the ground-tilting of short period, such as earth-tidal change or daily-variation and others, is observed, in perfect similarity of form and amplitude, with two tiltmeters of the same type or of different type.

As an example of the former case of the same type, the ratio of amplitde of daily gronnd-tilting observed at Abuyama is plotted every day. This means that the short period ground-tilting is little affected by the disturbing effect of setting up the instrument. And as in the latter case of a different type the result of a comparative observation between the superinvar-tiltmeter and the mercury-tiltmeter during 7 months at Yura was in some detail reported by the writer (**16**). Here, the disturbing effect of the initial setting up of the instrument for the secular ground-tilting and the perfect coincidence of two tiltmeters with respect of the short period ground-tilting, are both clearly ascertained as was done at Abuyama.

Generally speaking, the disturbing effect of instrumental error upon observations over a longer period, that is, a period of several years, has not yet been examined. While the task of making comparison observations over a period of say 50 or 100 years, using several tiltmeters of the same type or of different types at some suitable observation rooms would be an operose one, it is at the same time a most essential which should be undertaken for the furtherever of accurate knowledge of the nature of secular ground-tilting. However, under the present circumstances, the following method for verifying the authenticity of observed secular change is readily, though tentatively, used in practical cases. One tiltmeter set of a horizontal pendulum type is constituted of two pendulums orthogonally arranged to each another, that is A– and B–pendulums. When the ground tilts in the direction of the B–pendulum, it is enlargedly recorded by A–pendulum, by slightly disturbing the degree of horizontality of B–pendulum, in other words, changing the free period of B–pendulum slightly. Although these changes in pendulum-period are usually minute, but in case of the accumulation of secular ground-tilting during several years, they reach measurable amount. And in practical cases, this simple method has been occasionally and advantageously used to examine the reality of secular change of ground-tilting. In almost all cases, the secular changes observed are ascertained to be the real ground-tilting itself, and not those apparently observed by instrumental and other errors.

(*2*) *On instrument-foundation*

Several kinds of foundation on which the tiltmeter is set have been used in our present observations. These are natural rock, granite foundation artificially shaped, and concrete foundation, discriminatingly used according to the circumstances and conditions of the observation room. If the instrument could be set on natural rock, it is the most desirable observationally, but as such favourabe conditions are seldom obtainable, the artificial foundations are generally used. The granite-foundation, artificially shaped (usually in the size of $50\times100\times10$ cm), is also suitable for secular observation of ground-tilting when a certain care is taken to establish a firm connection between the granite-foundation and the base rock. But, under some circumstances, a reinforced concrete-foundation, usually in the size of $100\times150\times30$ cm, is used for the ordinary observation. Whenever the concrete foundation is utilized the disturbing effects caused by the deformation of the foundation during the process of the concrete solidifying and the creeping phenomenon of the foundation by the heavy instrument, and other unknown origins should be carefully examined. Generally, where a concrete-foundation is employed it is not used for nearly 6 months after concretion, and moreover the data observed during the initial period of about 6 months are adopted only as a reference in the study of secular ground-tilting. For example, the data observed at Makimine is referred to in Fig. 8g. The superinvar-tiltmeter was set up in 1948 on the same concrete foundation which has been used for a silica-tiltmeter from 1942 to 1946. As shown in Fig. 8a, the ground-tilting has the same tendency in both cases excepting half a year's abnormal change observed in the early period of observation. Consequently, the concrete-foundation can satisfactorily be used when some care is taken in securing a firm connection between the foundation and base rock, prevention of the deformation caused by concrete-solidification, and the creep phenomenon, and moreover, certain attention is paid to the treatment of data gained in the initial stage after setting up the instrument.

A test observation on the nature of concrete- and granite-foundation was made at Ikuno. Namely, two superinvar-tiltmeters of the same type were set on two different foundations, one of concrete and the other of granite of nearly the same size, which are placed 2 m apart in the same adit, and several month's observation for comparison was carried out. The result was that the secular ground-tilting observed was sufficiently similar for both tiltmeters, excepting in the initial month's data. From this it is generally concluded that any sort of foundation will sufficiently serviceable for tiltmetric observation of secular ground-tilting when specific attention is paid to the elimination of undesirable, disturbing effects.

(3) Meteorological effect

The effects of meteorological changes upon the ground-tilting have been discussed by some researchers. These effects are exceedingly large in amplitude and are extremely complicated in character when observation was conducted on the ground surface or in a shallow seated room. On the temperature change of air and soil or rock, their effects directly upon the parts of the instrument were ascertained to be negligible by some test experiments. Especially since the parts of horizontal pendulum and its supporter are made of fused silica (its linear expansion coefficient being 4×10^{-7}) or superivar alloy (its linear expansion coefficient being 3×10^{-7}), the temperature effect upon the instrument itself is neglected in ordinary instances. But especially the effect of the daily and seasonal changes of temperature upon ground-tilting is generally much greater (several scores of times) in amplitude compared with earth tidal ground-tilting in an observation in a shallow seated room. From observations of ground-tilting by a superinvar-tiltmeter at an ordinary underground room of 2 meters depth below the ground surface, recording at the same time the air temperatures both outside and inside the observation room, it was ascertained that the daily variation of ground-tilting was observed in accordance with the change of the outdoor temperature, not so much with the change of room temperature the phase of which is 2 hours behind that of outdoor temperature. From these and other sorts of experimental observation the so-called daily and seasonal variations of ground-tilting are interpreted as mainly attributable to the buckling deformation of the building and ground in which the observation room is situated. Air and soil (or rock) temperature changes cause this buckling deformation in a complex manner under various conditions with regard to the surrounding topography of the observation station, the amount of solar radiation, the geological formation, and many other conditions.

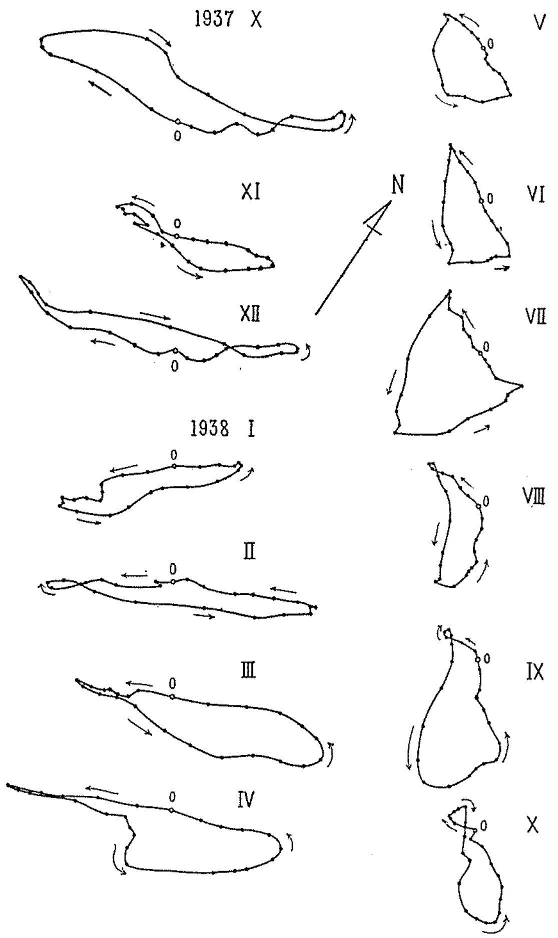

Fig. 10. Mode of daily ground-tilting observed at Beppu Park.

The form of the daily ground-tilting variation is peculiar to the particular observation station, but its quality, not to mention its amplitude, is never constantly observed a day by day or season by season. An example is shown in Fig 10 in which is plotted the monthly averaged forms of daily ground-tilting observed at Beppu Park in 1937–1938 where the observation room is 3 m below the ground surface of alluvial sand. The complexity of the daily variation at one station is considered to have originated from the widely differing conditions of solar radiation, level of underground water, and moisture content of soil.

On the relation between the underground depth of the observation room and the amplitude of daily and annual variation of ground-tilting observed, some discussions have been made by K. Sassa (**12**, **13**) and the writer. It is roughly concluded, from many tiltmetric observations at stations and rooms of widely differing conditions, that the daily and annual variations are seldom observed at a deep-seated observation room, that is to say, more than 20 m below the ground surface. In Table 2, some examples with regard to the relation between the amplitude of annual variation and room's depth are shown. But, concerning the preceding argument, exceptions are sometimes observed, namely, the comparatively large daily and annual variations observed at a deep seated room, and, on the contrary, the small daily and annual variations at a shallow seated room. These circumstances cannot definitely be confirmed unless a practical observation is carried out in the very room for the period of at least one year.

Table 2

Station \ Condition		Underground depth of observation room	Mean double amplitude of annual variation of ground-tilting	Averaged value of secular ground-tilting per annum	Geological formation
Beppu	1	2 m	16″	18″	Alluvial sand
	2	2	22	13	”
	3	3	20	26	”
	4	5	2	7	Volcanic layer
Kamigamo		9	6	1	Paleozoic
Yura		30	0	22	Mesozoic sandstone and shale
Kishu		60	0	33	Tertiary sandstone and shale
Hosokura		160	0	17	Tertiary
Makimine		165	0	4	Paleozoic
Ikuno	1	237	0	7	Liparite
Ogoya		300	0	82	Tertiary tuff
Ikuno	2	326	0	27	Liparite
	3	719	0	22	”
Kamioka		800	0	70	Gneiss

The small effect of barometric pressure change upon ground-tilting will be discussed elsewhere, though this effect seems to play an important role in the gravimetric observation.

The effect of rainfall upon ground-tilting is a most troublesome problem in cases of observation in a shallow seated room. The range of ground-tilting caused by heavy rainfall reaches several hundreds times as large as that of earth tidal change or several scores times as large as that of daily variation. The trouble exists not only in large amplitude, but also in the complexity of behaviour strongly affected by its hysteresis, as is fully discussed by K. Sassa (**12**, **13**). Ground-tilting caused by heavy rainfall in a short duration of time shows a simple form, but it is sometimes difficult to treat fully the real manner of its recovery.

In Fig. 11 the amount of ground-tilting observed at Yura caused by rainfall in a comparatively short time is plotted against the amount of precipitation concerned. From this it should be simply stated that there is a linear relation, roughly speaking, between the amounts of ground-tilting and precipitation at Yura. And the precipitation less than 10 mm does not affect the ground-tilting in this case. The observation room

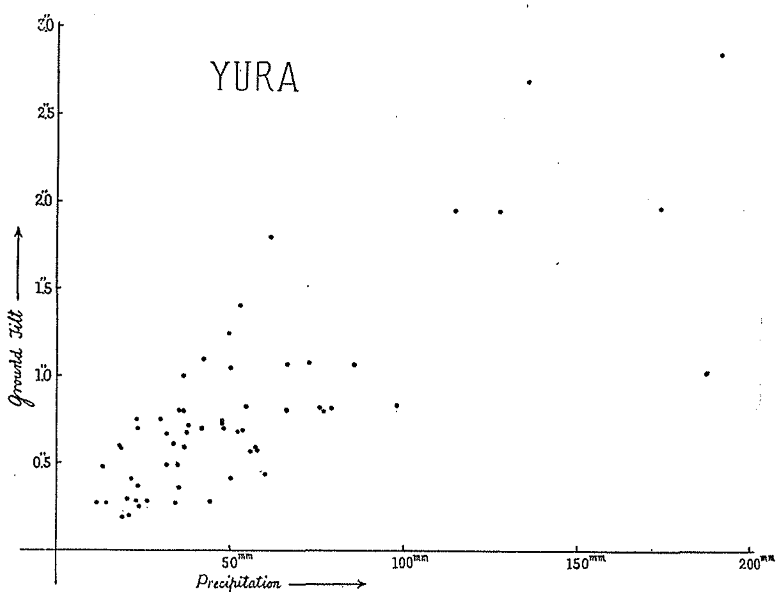

Fig. 11 Relation between the amount of ground-tilting caused by rainfall and the amount of precipitation observed at Yura.

is situated 30 m below the ground surface at the side of small mountain, the geological formation being tertiary sandstone and shale, and the ground sloping downward to the foot of the mountain by the effect of rainfall as though the mountain expanded by an increase of moisture content in the soil and rock, or the elasticity of soil and rock apparently decreased by rainfall.

In conclusion the disturbing meteorological effect should be reduced to as small an amount as possible for the purpose of studying the real, and, in ordinary cases, minute tilting motion of the ground such as those of earth tidal change or crustal deformation related to earthquake-occurrence, volcanic eruption, and other crustal change. One of the simple and effective ways to avoid the disturbance of meteorological origin is to set up the observation room at appropriately deep underground in firm rock, say about 100 m~200 m below the ground surface. It is to be remarked here that the observation at a room too deep, that is to say, more than several hundred meters, is also inadequate for studying the secular ground-tilting, because the deep seated room is greatly deformed by tremendously great rock-pressure, thus disturbing the observation for real ground-tilting of the area concerned. Regarding this some detailed discussions will be made in the following section.

(4) *Local character in secular ground-tilting*

As seen in the foregoing figures, the individual characteristics of secular ground-

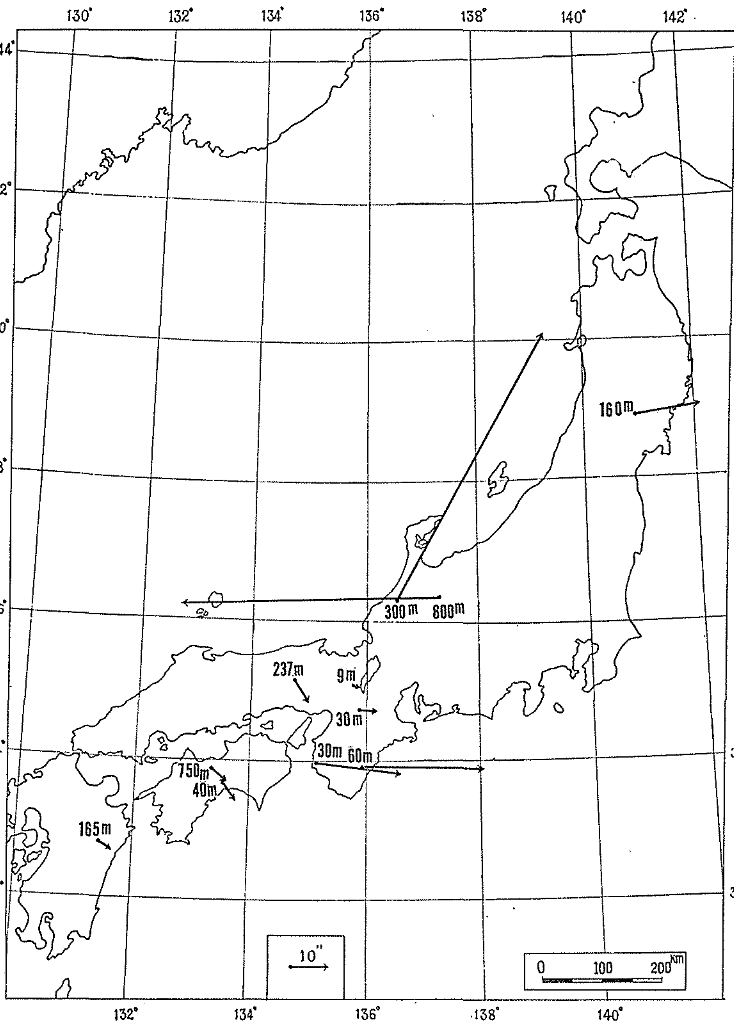

Fig. 12. Averaged amount and direction of secular ground-tilting per annum observed at some stations, the side-figure being the depth of observation room.

tilting observed at various stations are quite diversified displaying the peculiarity of their respective stations. These local characteristics are thought to originate from the local deformation of the ground related to the observation room conditions. The secular ground-tilting observed in a deep seated room is, in general, much greater in degree compared to the observation made in shallow seated room. This is simply interpreted to be conduced by the large deformation of the observation room in adit caused by a great rock-pressure constantly exerted consequently, secular ground-tilting being observed has naturally a large amplitude and strong peculiarity. As the secular ground-tilting observed in a shallow seated room is comparatively small without the influence of rock-pressure, it is considered to be suitable for the observation of secular ground-tilting, but it is inconvenient in the point of large disturbing influence by meteorological change as hitherto discussed. For this purpose a suitable observation room which is little affected by meteorological change and rock-pressure, should be selected for good observation. A close examination of these will be treated in the next section. In Fig. 12, some examples of the amount and direction of secular ground-tilting are shown. The arrow in the figure indicates the averaged amount and directions of downward tilting motion per annum, and the side figure indicates the depth of the observation room. Properly speaking, Fig. 13 is intended to show the diversity of secular ground-tilting and its local character, but it is both interesting and suggestive that a major part of tilt-vector tends toward the easterly direction with the exception of two stations. This may be an accidental coincidence, but it deserves a further investigation.

5. Suitable observation station for secular ground-tilting

For the purpose of investigating the earth-tidal tilting of the ground or the micro-tilting motion forerunning earthquakes and other minute ground-tilting, the tiltmeter must be maintained at a high sensitivity. The amplitude of the earth-tidal change is about $0''.03$, and the forerunning micro-tilting as observed at Ikuno before the occurrence of the Tottori Earthquake in 1943 was $0''.09$, and other change, generally called as micro-tilting motion of the ground is less than $0''.01$. On the other hand, the ground-tilting caused by meteorological change reaches $1 \sim 10''$, which greatly disturbs the observation of earth-tides and micro-tilting. As already mentioned, the meteorological effect is proportionately reduced by the use of a deep observation room, but conversely the effect by rock-pressure increases with depth.

In connection with the problems of observation room conditions the problem of relative merit of the type of tiltmeter should be simultaneously considered. I have already mentioned that a water-tube tiltmeter is considered to be better suited for the observation of secular ground-tilting than that of horizontal-pendulum type. But the use of the water-tube tiltmeter is inconvenient for observing minute ground-tilting, such as earth-tides, phenomena forerunning earthquakes and other micro-changes, because of its low sensitivity and intermittent measuring ability. Then, for the purpose of observing all kinds of ground-tilting such as earth-tidal change, micro-tilting motion and secular ground-tilting at one station, the problems of what type of tiltmeter and at which depth the observation room is the most suitable, should fully be examined.

Concerning these problems of the ground-tilting's amplitude of annual variation, the average amount of secular variation per annum, and the observation-room depth, reference to Table 2 will reveal that three stations– i.e. Kamigamo, Makimine, and Ikuno (I)– are suitable stations. These three stations selected from about 33 stations functioning over a period of 20 years, are optimum selections because the daily and annual variation caused by meteorological and seasonal change, and, moreover, the most undersirable disturbances of rainfall are all negligible. The secular tilting-motion observed at these three stations is favourably small compared with those at other stations, this fact being the most reliable evidence of stable conditions of the observation room. There is no standard method for selecting the optimum observation room but it must be chosen to be suitable after one or two years' test observations at any given place. And it is eagerly hoped to set up both tiltmeter of horizontal-pendulum type and water-tube type at the same room of stable condition, and by this sort of simultaneous observation the nature of secular ground-tilting is expected to be rightly and fruitfully investigated.

6. Charcteristic tilting-motion connected with earthquake-occurrence

The large upheaval and subsidence of ground in the epicentral area before and after the occurrence of destructive earthquakes have been studied by the method of precise levelling and triangulation, and many detailed reports have been published in Japan. Especially these in case of the great Kwanto Earthquake in 1912 and the great Nankaido Earthquake in 1946 are representative in their amount of deformation. These results were all deduced from the data by re-survey of the epicentral area before and after the earthquake occurrence. On the other hand, the continuous observation of this kind of phenomena forerunning the destructive earthquake instead of intermittent surveys, have produced some reports recently published employing the continuous observation of tiltmeters and extensometers in the study of destructive earthquakes by K. Sassa and E. Nishimura (**21**) and others. K Sassa and E. Nishimura (**21**) have observed some minute but characteristic ground-tilting several hours before the occurrence of the destructive Tottori Earthquake in 1943, and several other earthquakes. I. Ozawa and I. Takada (**21**) have observed the forerunning phenomena taken from the results of the observation of ground-strain by extensometer in case of Yoshino Earthquake in 1952 and others. The writer has also reported some examples of characteristic ground-tilting which were observed several months before the occurrence of destructive earthquakes in Daishoji in 1952, and Yoshino in 1952 (**14**, **15**, **16**, **21**).

In the present section, three cases of characteristic secular ground-tilting which are supposed to be connected with the occurrence of neighbouring destructive earthquakes are selected from our tiltmetric observations and discussed, especially, in point of reliability, taking the various disturbing effects mentioned above into consideration. The three cases concerned are the secular ground-tilting ones observed at Kamigamo, Ogoya and Yura. A discussion of these examples will follow:

(a) The Kamigamo investigation:

As already described, the tiltmetric observation at the Kamigamo Geophysical Observatory has been continued for 20 years, and its secular ground-tilting observed is exceedingly small and little disturbed by the meteorological effect, that is, the station is reasonably stable and suitable for observation of ground-tilting for a long period. During the period of observation any destructive earthquake within a 100 km radius from Kamigamo, with the exception of the Yoshino Earthquake, have not occurred, yet seven destructive earthquakes were felt within 200 km distance from Kamigamo. Their names, dates of occurrence, magnitude in Pasadena Scale, and distance of epicenter from Kamigamo are respectively listed as follows:

Name	Date	Magnitude	Epicentral distance
Tottori	Sept. 10, 1943	$7\frac{1}{2}$	150 km
Tonankai	Dec. 7, 1944	8	150
Mikawa	Jan. 13, 1945	7.1	120
Nankaido	Dec. 21, 1946	8.2	230
Fukui	June 28, 1948	$7\frac{1}{4}$	130
Daishoji-oki	Mar. 7, 1952	$7\frac{1}{4}$	160
Yoshino	July 18, 1952	7	70

In Fig. 7, the occurrence-time of these earthquakes is plotted in reference to the secular tilting curve. As may clearly be seen in the graph, characteristic ground-tilting had been observed for nearly one year before the occurrence of these destructive earthquakes with the exception of two cases at Mikawa and Daishoji-oki. At first sight we might question whether this strange character is to be interpreted as merely an accidental coincidence or really a significant fact. For further study this characteristic ground-tilting observed before the earthquake-occurrence is expressed in tilt-vector with the position of the epicenter of seven destructive earthquakes in Fig. 13. As clearly seen in the figure, these fine forerunning ground-tiltings are all pointing to nearly the respective epicentral direction seen from Kamigamo, in other words, the ground commences a tilting motion downward to the direction of the epicenter nearly one year before the earthquake-occurrence. and continues its motion until the day of the earthquake, and after the earthquake, ceases or reverses its preceding motion. If this correspondence between the earthquake-occurrence and characteristic ground-tilting can be assumed to be real, this kind of tilt-metric observation should be considered to afford a promissing way to foretell the occurrence of destructive earthquake and reveal the nature of the earthquake itself.

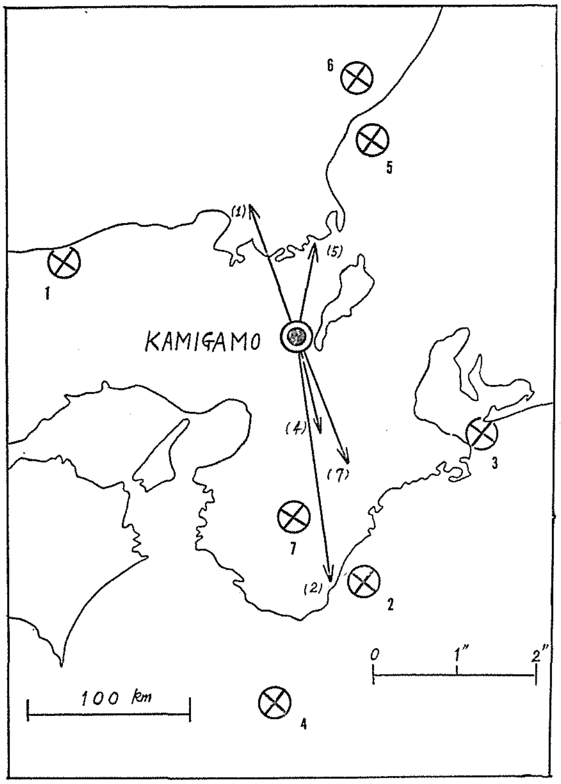

Fig. 13. Secular ground-tilting observed before the occurrence of destructive earthquakes observed at the Kamigamo Geophysical Observatory.

(1) Tottori, IX, 1943 (2) Tonankai, XII, 1944
(3) Mikawa, I, 1945 (4) Nankaido XII, 1946
(5) Fukui, VI, 1948 (6) Daishoji-oki, III, 1952
(7) Yoshino, VII, 1952.

(b) The Ogoya investigation:

Concerning the characteristic ground-tilting observed at Ogoya, some detailed papers have already been published (**14**). In this section a brief account will be given. A destructive earthquake named Daishoji-oki Earthquake occurred on March 7, 1952, 40 km NW of Ogoya. In this case, an abnormally large ground-tilting was observed, as shown in Fig. 8m, especially conspicuous in the B–component which records the ground-tilting in the EW–direction. It began during the first three months before the earthquake-occurrence, and the total amount and direction are estimated to be nearly 70″ in three months and in the same direction of NW when both A and B components are taken into account (see Fig. 4 in (**21**)). This severe tilting motion was reversed several days after the earthquake-occurrence, as seen in the B–component in Fig. 8m, but it recovered its original state after nearly one and half years. The amount of secular ground-tilting observed at Ogoya is, by nature, enormously large as seen in Fig. 8m and Table 2, according to the weak geological formation of tertiary tuff.

But, the to-and-fro tilting motion as observed in the B-component in the present case is supposed to be a real crustal deformation related to the earthquake, because the large, secular ground-tilting caused by the deformation of the adit-room affected by a powerful rock-pressure of 100 bars, is generally considered to be linearly increasing with time toward a certain direction. That the characteristic ground-tilting observed before the earthquake-occurrence at Ogoya shows also the downward motion to the direction of the epicenter seen from Ogoya, is in good accord with those discussed in the Kamigamo case, and increases the reliability of the existence of the phenomena of ground-tilting foretelling the earthquake-occurrence.

(c) Tne Yura investigation:

The observation at Yura is greatly disturbed by the effect of rainfall, and its secular variation is also considerably large as described in Table 2. But, as the annual variation is little observed, and moreover, the prominent earthquakes have frequently occurred in the neighbourhood of Yura, the relation between the secular ground-tilting and occurrence of earthquake is conveniently discussed in spite of rather poor

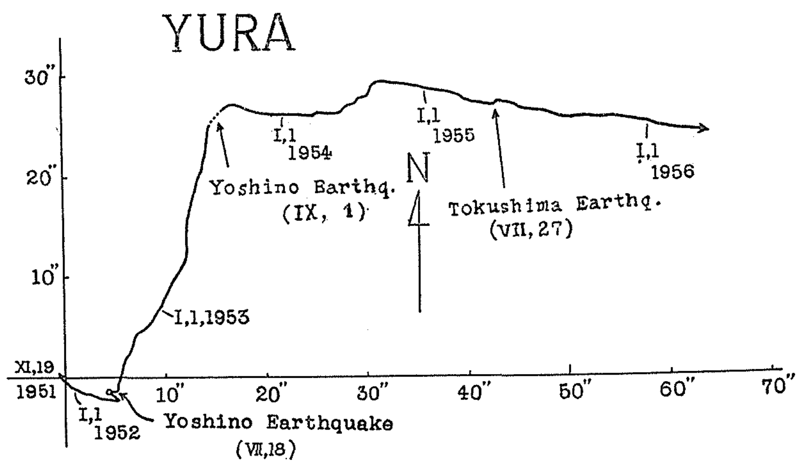

Fig. 14. Vector-representation of secular ground-tilting observed at Yura Observation Station.

Arrow indicates the occurrence time of large earthquakes in the neighbourhood of Yura.

conditions of the observation room. The secular ground-tilting observed in two components and the composed tilt-vector are shown in both Fig. 8h, and Fig. 14. During the observation period, three destructive earthquakes occurred in the neighborhood of Yura. Namely, the epicenter of the Yoshino Earthquake, July 18, 1952, was 60 km distant and in an E-direction from Yura; the earthquake in Yoshino district, September 1, 1953, had nearly the same epicenter as that in 1952; and the epicenter of the earthquake near Tokushima, July 27, 1955, was nearly 60km distant and in W-direction from Yura. Their seismic magnitudes are all nearly 7 using the Pasadena Scale as reference. In the case at Yura, only the secular ground-tilting observed before the occurrence of the Yoshino Earthquake showed a like tendency such as those discussed in the preceding two cases of Kamigamo and Ogoya. Namely, the ground has tilted downwards to the direction of epicenter (E-direction) more thau a half year before the occurrence, and after that the direction of ground-tilting has changed in a nearly orthogonal direction (NNE). With regard to the other two earthquakes, this relation does not hold. But it is to be remarked that the time of occurrence in other two earthquakes are both situated at the turning point on the curve of tilt-vector. Especially the earthquake in Yoshino district in 1953 affords a conspicuous example of this relation. Further investigation is eagerly desirable to advance the knowledge in this research field.

In concluding this section, it is strongly suggested that characteristic secular ground-tiltings ever observed at some stations, in nearly a period from several months to one year before the occurrence of destructive earthquakes, are supposed to be the really existing phenomena intimately connected to the earthquake. It will afford, in the near future, a powerful clue to foretell the occurrence of destructive earthquakes and advance knowledge on the nature of earthquakes.

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