

OBSERVATIONS OF THE CRUSTAL STRAINS AT THE TIME OF EARTHQUAKES AROUND KYOTO CITY

By

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Abstract

There were about twenty sensible earthquakes, including two shocks of intensity 3 and 6 shocks of intensity 2, felt around Kyoto City for a period of one month from August 18, 1968.

At Osakayama Observatory observations of the linear strains and the tilts of the crust have been made by means of some arrays and some single points equipped with extensometers or tiltmeters.

According to these observations, a remarkable anomaly seemed to appear in April at latest, and to break out a swarm of earthquakes at the close of the long dry season lasting from October 1967.

Furthermore, the forerunner seemed to appear half a day and half an hour before these earthquakes. Especially, the anomaly in half an hour before the earthquake on August 27 seemed to be a simple expansion of the crust.

The radii of the seismic origin, the rebounded energy and the seismic magnitude were calculated by means of abrupt changes in the crustal strains during these earthquakes.

Using the effects in the crustal strains caused by precipitation, the relation between the heavy rains and the outbreak of the earthquakes and that between the speed of the crustal strain and the maximum strength of the rock-bed are discussed.

1. Introduction

There are many reports on the studies of forerunners made from continuous observations of crustal deformations. For example, in our country a synthesized reports by E. Nishimura [1965] and by I. Ozawa [1967], and abroad by F. Caloi [1964]. The present author (I. Ozawa, [1956]) has been reported similar studies by means of extensometers.

The result of repetitions of precise levelling have demonstrated anomalous changes before and after earthquakes. Some anomalous changes were sometimes visible to the naked eye on seashores and by active faults. But there was no strict evidence as to whether these anomalous changes were caused by the forerunner of remarkable earthquakes or were the afterworkings of the

forerunning shocks. The latter theory may arise from the fact that there is a type of earthquake which has great movement without sensible accelerations. If we support this theory, we must discover whether or not an ordinary earthquake with large accelerations is usually accompanied by an abnormal earthquake which has large displacement without accelerations. However the theory of an abnormal earthquake may only be another name for the "forerunning crustal movement" before an earthquake. According to ordinary theories, an earthquake is a special example of a crustal movement and it is usually accompanied by great acceleration caused by the fracture of a part of the crust. Studies regarding the foreshocks and mechanism of fracture of materials may support the existence of the anomalous phenomena before great earthquakes.

Dr. E. Nishimura [1961] has studied this anomalous change at some stations in Kinki district. But he was only able to study the vague existence of the phenomena. Moreover, there has been no precise study of the aspect of these phenomena.

The present author had an opportunity to study the forerunners before the remarkable earthquakes around Kyoto City in August, 1968. In this paper, he is going to study the phenomena by means of observations of the changes of the crustal strains and tilts, and also to interpret these phenomena from the view point of rock mechanics.

2. Observations

The present author has been performing observations of crustal strains by means of extensometers and tiltmeters at Osakayama Observatory since 1947. The Osakayama Observatory is located at $135^{\circ}51.5'$ of east longitude $34^{\circ}59.6'$ north latitude. This observatory has several observation points located in two old tunnels whose lengths are 664 meters and 675 meters, and were dug in 1876 and 1897, respectively. The neighbouring stratum consists of clay slate and shale belonging to the Chichibu paleozoic era. All observation points are from 70 to 100 meters under the ground. The amplitude of annual variation of the room temperature is 0.18°C , but it is impossible to measure its daily variation.

The instruments used for this study are the extensometers for horizontal linear strains, H-59-B, C and D types (I. Ozawa, [1960]), Sassa type (K. Sassa, et. al., [1952]), roller type and pivot type, and for vertical linear strain, V-59-B and D types (I. Ozawa, [1965]). And also horizontal pendulum type tiltmeters and water-tube tiltmeter were used for tiltings. Table 1 (a) and (b) show the constants and the setting conditions of these instruments.

In order to distinguish between short and long wavelength deformations, every six or two observation points with extensometers or tiltmeters are set

Table I. (a) Constants and setting conditions of extensometers operating at Osakayama Observatory.

Sign	Direction of observation	Type of extensometer	Distant from Otsu entrance	Span of observation	Epoch of observation	Sensitivity in August 1968	Speed of recording
L_2	S 38°W	H-59-B	512m	12 m	Mar., 1961	$0.209 \times 10^{-8}/\text{mm}$	10.4cm/day
L_4	S 38 W	H-59-D	411 "	34 "	Sep., 1964	0.565 "	4.0 "
R_1	S 38 W	Roller	374 "	19.5 "	Oct., 1951	1.30 "	4.0 "
W_1	S 38 W	Sassa	374 "	20 "	Oct., 1948	1.20 "	4.0 "
L'_3	S 38 W	H-59-B	330 "	22 "	May., 1965	0.161 "	288&32.1 "
R_2	S 38 W	Pivot	160 "	19.4 "	Mar., 1968	1.30 "	4.0 "
N'_1	N	H-59-C	310 "	6.55 "	Jan., 1961	0.375 "	4.7 "
N_3	N	H-59-B	170 "	5.60 "	Dec., 1959	0.336 "	4.0 "
E_1	E	H-59-C	310 "	5.30 "	Dec., 1959	0.352 "	4.0 "
E_3	E	H-59-B	170 "	4.80 "	Dec., 1959	0.266 "	4.0 "
C_1	S 52 E	H-59-B	240 "	10.0 "	Jan., 1960	0.323 "	42.4 "
V_3	vertical	V-59-B	170 "	4.6 "	Dec., 1959	0.552 "	4.0 "
V_5	vertical	V-59-D	140 "	6.0 "	Jan., 1963	0.975 "	288 & 4.0 "

Table I. (b) Constants and setting conditions of tiltmeters operating at Osakayama Observatory

Sign	Direction of observation	Type of instrument	Distant from Otsu entrance	Epoch of observation	Sensitivity in August 1968	Speed of recording
A_1	W	horizontal pendulum	370 m	Aug., 1951	0.0109"/mm	4.0cm/day
B_1	N	"	370 "	" "	0.0134 "	"
A_2	W	"	520 "	Nov., 1960	0.0309 "	"
B_2	N	"	"	" "	0.0299 "	"
A_3	W	"	180 "	Dec., 1959	0.0206 "	"
B_3	N	"	"	" "	0.0184 "	"
W_t	N38°E	recording-type water-tube	100-160 "	Jun., 1962	0.00347 "	"

in certain arrays; six points of S38°W component of the horizontal extension in an array of 350 meters' span, two points of those of N and E components in two array of 140 meters' spans, two points of that of the vertical component in an array of 40 meters' span, and three points of W and N tilts in two arrays of 340 meters' spans.

As an example of the crust at this observatory, Fig. 1 shows the extensions L_2 , N_1 and C_1 in the directions of S38°W, north and S52°E, respectively, and the tilting W_t in the direction of N38°E.

The base line on the direction S38°W at Osakayama Tunnel has been contracting for this past twenty years. This contraction is maximum at the middle of the tunnel, and its mean dimension is 2.6×10^{-6} per annum. But this contraction is slight near the ends of the tunnel. Extensometer L_2 has shown the

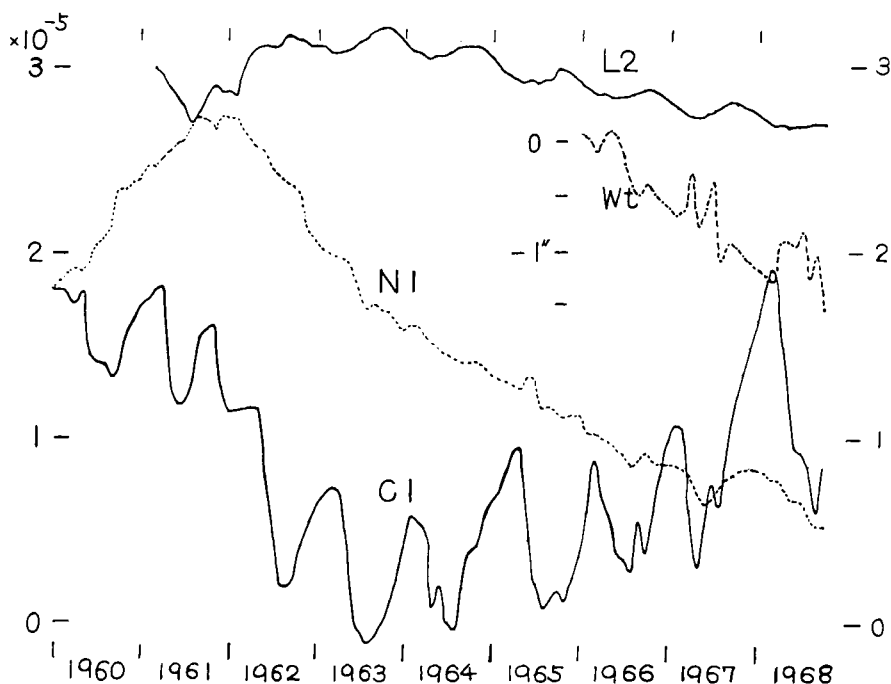


Fig. 1 (a) Changes of the linear strains in the directions of S38°W, S52°E and north, and the tilt in the direction of N38°E at Osakayama.

mean secular contraction as large as 0.2×10^{-6} per annum, and the amplitude of $0.8-0.9 \times 10^{-6}$ in annual variation. From autumn 1967 to spring 1968, L_2 showed an unusual contraction as much as 1×10^{-6} , but since has shown no secular changes or random movement.

Extensometer in S52°E showed as large contraction as 4×10^{-6} per annum in the period from 1960 to 1963, and since has shown a mean extension of 1×10^{-6} per annum. And C_1 showed a considerable extension of 13×10^{-6} for nine months from August 1967 to April 1968. Recently, it has shown remarkable contraction for the six months preceding October 1968. The mean amplitude of its annual variations is 2.5×10^{-6} .

Observation of a water-tube tiltmeter by means of reading taken with two micrometers was begun in June, 1962. This observation shows tilting toward N38°E as much as $1.6''$ for this six years. In January, 1966, automatic recording observation was begun together with micrometer readings. This automatic recording observation shows tilting toward S38°W as much as $1.3''$ for this three year periods. The difference between the observation with the micrometer-reading and that of the automatic recording seems to have been caused by a water leakage in this tiltmeter.

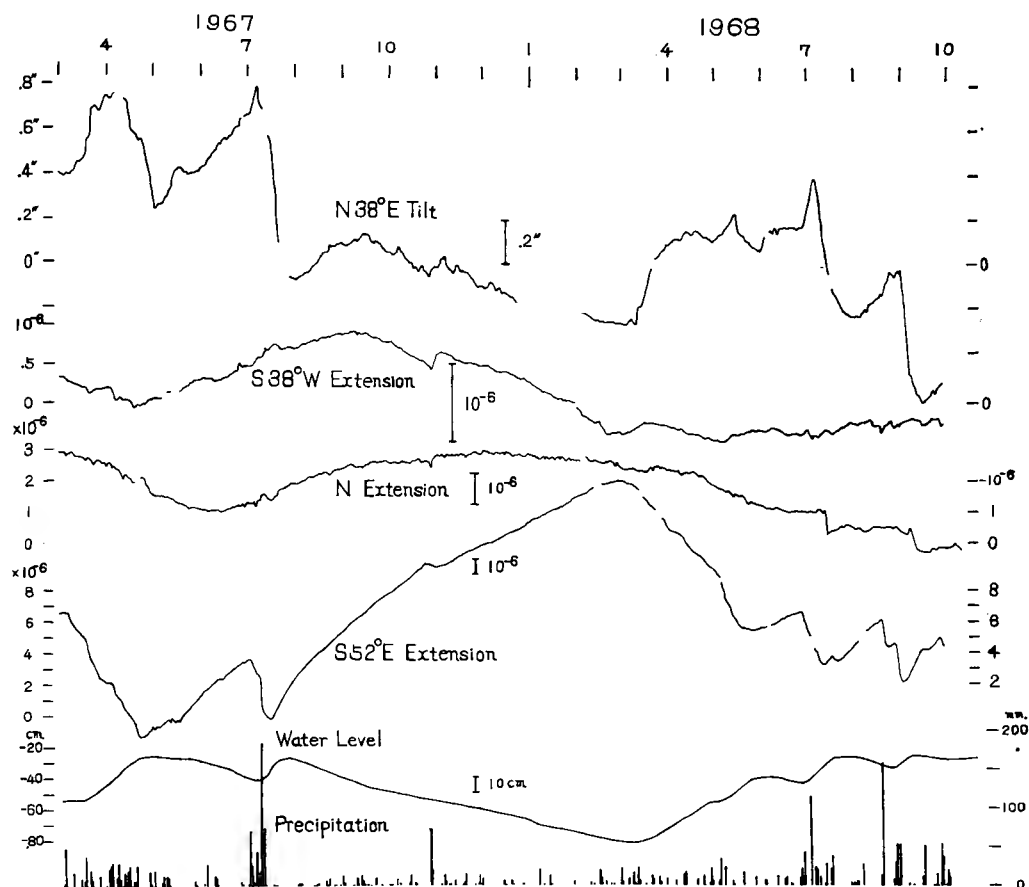


Fig. 1 (b) Changes of the linear strains in the directions of S38°W, S52°E and north, the tilt in the direction of N38°E and the level of ground water at Osakayama. Daily precipitations at Kyoto.

At a glance, we can find enough anomalous changes at the middle of March, 1968 on the observation curve. At this time, there was no day when precipitation reached more than 23 mm. Inspecting these observation curves and the daily precipitations which are shown in the lower part of Fig. 1, we can distinguish easily the effects of the precipitations on the crustal deformations.

Speaking generally, the typical model of the precipitation effect on the tilt component in N38°E is shown in Fig. 2. The figures of the effects remain similar all year round, but their size does not remain equal in every season. Especially, large effects seem to follow long dry seasons. The effects of precipitation in the south-east tilting are rapid; the peaks of their effects appear within one or two days after the start of heavy rains. But effects in the north-east tilting are gradual; the peaks appear after a number of days. The recovery

of the effect is usually slower than the progress of the effect and the speed of recovery is different in different seasons. Also the recovery sometimes seems to be larger than the primary effect caused directly by precipitation in $N38^\circ E$ tilt. The effects in the vertical strains are complex; there is maximum contraction some hours after the start of heavy rains, which later turn to a large extension.

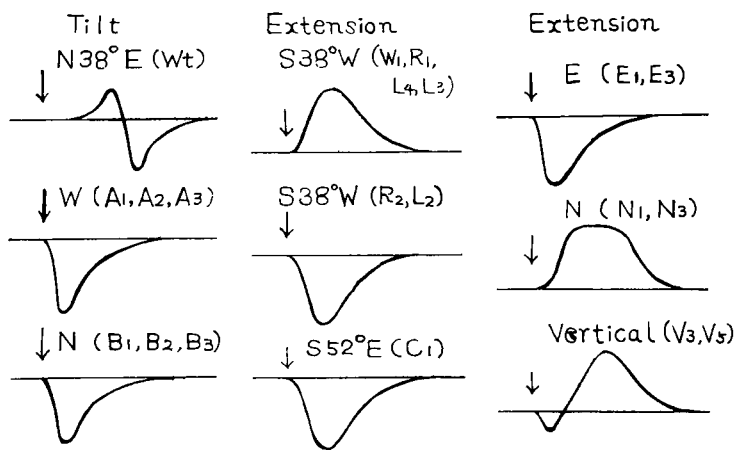


Fig. 2. Typical models of the precipitation effect on the crustal strain and tilt at Osakayama.

For a period of one month following, the remarkable earthquake at Kamiwachi-cho in August 18, 1968, origin time: 16h 12m, there were two shocks of intensity 3 (grade according to the Japan Meteorological Agency), six shocks of intensity 2 and eight shocks of intensity 1. The earthquake was located at a distance of 54 km from Osakayama Observatory. Its magnitude was calculated as 5.3 by means of the abrupt changes in the earthquake. The epicenter of the remarkable earthquake which occurred on August 27 was the center of Kyoto City; longitude 135.66° east, latitude 35.00° north, and at a distance of 10 km from Osakayama. Its seismic intensities were 3 at Kyoto, Osaka and Nara, and its magnitude was calculated to be 4.1 by means of the abrupt changes of the crustal strain in this earthquake.

Photo. 1 (a), (b),and (h), and Photo. 2 (a), (b),and (h) show the strainings and tiltings before and after the earthquakes on August 18 and 27, 1968, respectively.

The anomalous changes of the strains and tilts which first started about 1 a. m. on August 18 may be seen in these Photos. 1. L_2 extensometer set at the south-east end of the array shows the maximum contraction around the time of the earthquake. Extensometer L_4 situated on the steady rock bed consisting

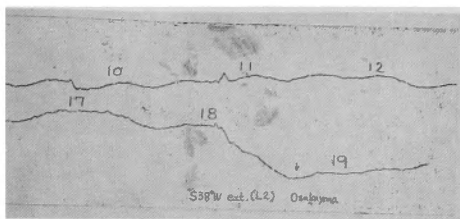


Photo. 1 (a). Record of extensometer L_2 in the period of the earthquake on August 18, 1968.

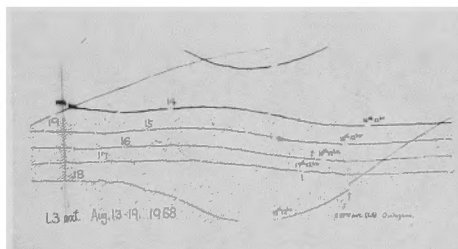


Photo. 1 (b). Record of extensometer (L_3) in the direction of $S38^\circ W$ in the period of the earthquake on August 18, 1968.

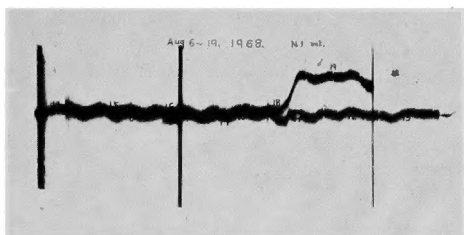


Photo. 1 (c). Record of extensometer (N_1) in the direction of the north in the period of the earthquake on August 18, 1968.

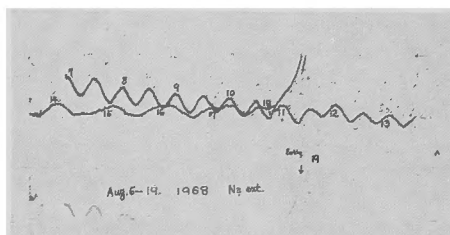


Photo. 1 (d). Record of extensometer (N_3) in the direction of the north in the period of the earthquake on August 18, 1968.

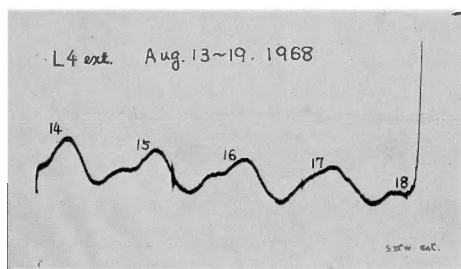


Photo. 1 (e). Record of extensometer (L_4) in the direction of $S38^\circ W$ in the period of the earthquake on August 18, 1968.

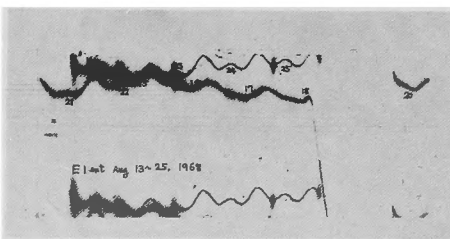


Photo. 1 (f). Record of extensometer in the direction of the east in the period of the earthquake on August 18, 1968.

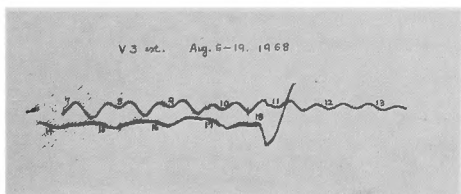


Photo. 1 (g). Record of extensometer (V_3) in the direction of the vertical in the period of the earthquake on August 18, 1968.

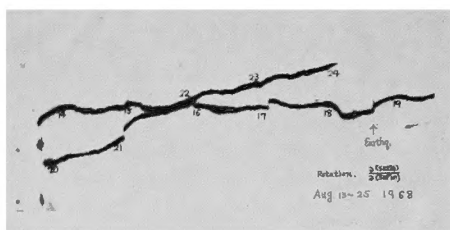


Photo. 1 (h). Record of rotationmeter (R_0) in the component of $\partial(S52^\circ E) \partial(S38^\circ W)$ in the period of the earthquake on August 18, 1968.

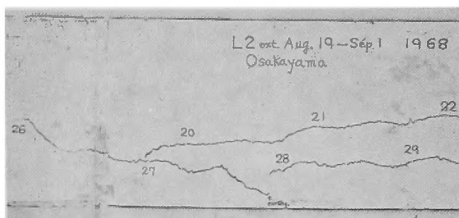


Photo. 2 (a). Record of extensometer L_2 in the direction of $S38^\circ W$ in the period of the earthquake on August 27, 1968.

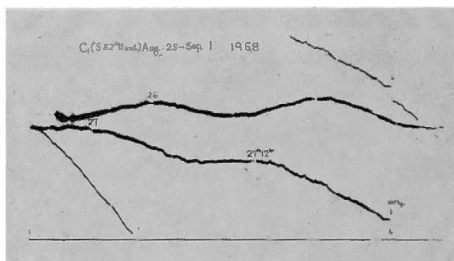


Photo. 2 (b). Record of extensometer (C_1) in the direction of $S52^\circ E$ in the period of the earthquake on August 27, 1968.

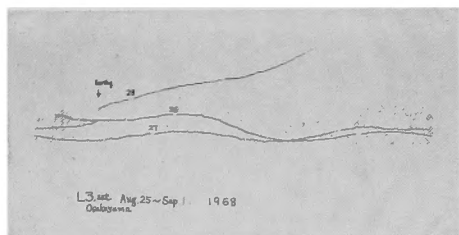


Photo. 2 (c). Record of extensometer (L_3) in the direction of $S38^\circ W$ in the period of the earthquake on August 27, 1968.

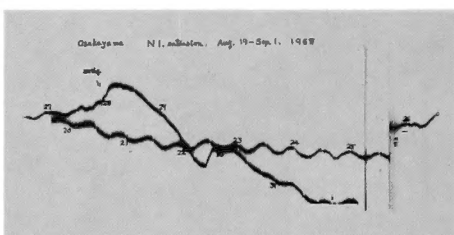


Photo. 2 (d). Record of extensometer (N_1) in the direction of the north in the period of the earthquake on August 27, 1968.

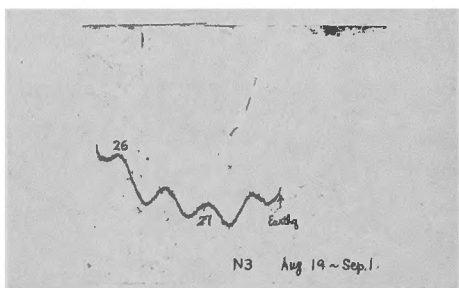


Photo. 2 (e). Record of extensometer (N_3) in the direction of the north in the period of the earthquake on August 27, 1968.

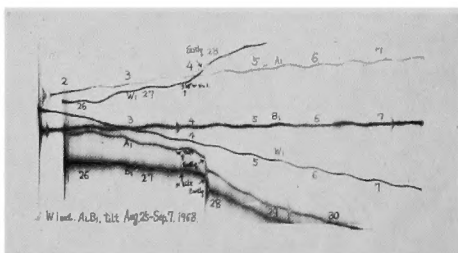


Photo. 2 (f). Record of extensometer (W_1) and tiltmeters (A_1 , B_1) in the period of the earthquake on August 27, 1968.

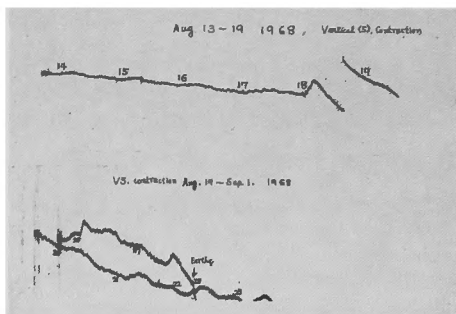


Photo. 3 (a). Records of extensometer (R_2) in the direction of $S38^\circ W$ in the periods of the earthquakes on August 18, and 27, 1968.

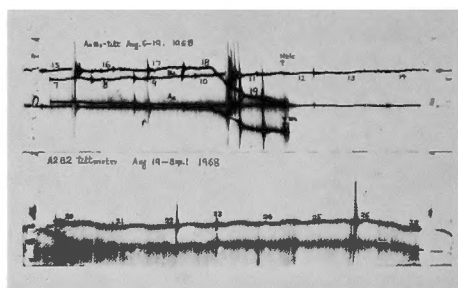


Photo. 3 (b). Records of tiltmeter (A_2 , B_2) in the periods of the earthquakes on August 18 and 27, 1968.

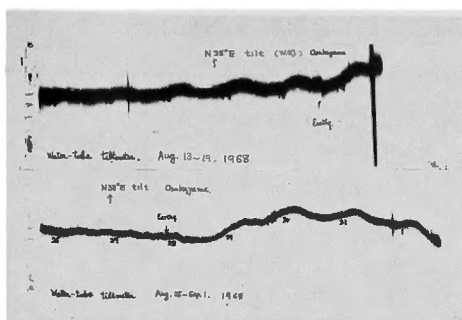


Photo. 3 (c). Records of water tube tiltmeter in the periods of the earthquakes on August 18 and 27, 1968.

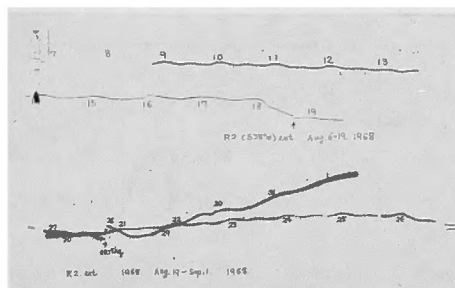


Photo. 3 (d). Records of extensometer (L_2) in the periods of the earthquakes on August 18 and 27, 1968.

of clay slate in the middle, the deepest point under the ground, in the tunnel. The length of its span is 34 meters, L_4 usually records the stable tidal strain. But, it shows micro irregular change for a few hours, and then shows the extension with anomalous speed of 35×10^{-8} per hour till the earthquake occurs. Its total extension may amount to 1×10^{-5} . Extensometers W_1 , R_1 in the middle part of the tunnel show similarly remarkable extensions. Extensometer L_3 shows anomalous contraction from 1 a. m. till 11 a. m. and then shows extension till noon August 19. Extensometer R_2 at the end of the north-east of the array of the $S38^\circ W$ shows anomalous contraction from 1 a. m. August 18 to the time (4 p. m. August 18) of the earthquake. According to the above results, the crust is deformed in wrinkles to a width of some hundreds meters. Extensometers N_1 and N_3 show the anomalous extensions starting from 1 a. m. August 18. The extension in N_1 stopped at 11 a. m. and then the earthquake broke out at the ridge of the anomalous extension. Extensometers E_1 and E_3 show the rapid contraction which took place from 1 a. m. at speeds of -5×10^{-8} and -2×10^{-8} per hour.

The vertical extensions V_3 and V_5 first show the remarkable contraction from 1 a. m. till around 4 a. m. August 18 and then show extension.

Horizontal type tiltmeters and the rotationmeter show also that the crust started anomalous tilting toward the south-east and anomalous shearing at 1 a. m. and continued until the time of the earthquake, respectively.

Table 2 (a) shows the observed starts maximum speeds and maximum deflections of the anomalous strains and tilts before the earthquake took place, and the abrupt changes during the earthquake on August 18, 1968.

The following is a study of crustal movement at the time of the earthquake on August 27, 1968. This earthquake occurred at 9h 52m p. m., and was quickly accompanied by two shocks of intensity 2. The extensometers show anomalous changes twice; i. e., eight or nine hours, and half an hour before the earth-

Table 2. (a) First anomaly of the crustal strains before the earthquake on August 18, 1968

Sign of instrument	Component	Start of anomaly	Maximum speed of strain per hour	Accumulated anomaly before earthquake	Abrupt change in earthquake	Remark
L_2	S38°W extension	17d 23h	$-2.93 \times 10^{-8}/\text{hr.}$	-6.12×10^{-8}	0.167×10^{-8}	
L_4	"	18d 02h	+35.0 "	100 "	—	
W_1	"	18d 02h	+ 4.4 "	20.6 "	0.720 "	
R_1	"	18d 03h	+ 2.5 "	18.8 "	little "	
L_3	"	18d 01h	-1.02 "	-4.70 "	0.708×10^{-8}	{extend at first, later contract
		18d 10h	+0.86 "	+0.48 "		
R_2	"	18d 02h	-2.6 "	-16.5 "	-0.182 "	
E_1	East	18d 02h	-5.03 "	150 "		
E_3	"	18d 03h	-2.15 "	20 "		
N_1	North	18d 01h	4.4 "	19.70 "	little	
N_3	"	18d 01h	3.1 "	97 "	-4.80×10^{-8}	
V_3	Vertical	18d 01h	-2.96 "	-9.22 "	—	{extend at first, later contract
		18d 04h	+3.22 "	+19.81 "		
V_5	"	18d 01h	-2.00 "	-8.68 "	-36.25 "	{extend at first, later contract
		18d 05h	+2.24 "	+9.70 "		
C_1	S52°E	18d 01h	-7.5 "	-37.2 "	0.42 "	
A_1	West tilt	18d 22h	-0.019"/hr.	-0.145"	-0.015"	
B_1	North tilt	"	-0.025 "	-0.268 "	-0.009 "	
A_2	West tilt	18d 03h	-0.033 "	-0.32 "	-0.083 "	
B_2	North tilt	"	-0.062 "	-0.57 "	-0.081 "	
A_3	West tilt	18d 01h	-0.006 "	-0.07 "	-0.008 "	
B_3	North tilt	"	-0.012 "	-0.11 "	-0.099 "	

quake. For example, extensometer L_2 is S38°W shows an anomalous contraction of 3.6×10^{-8} at eight hours and the anomalous extension of 0.21×10^{-8} which took place at 32 minutes before the earthquake, respectively. The anomalous contraction about eight hours before the earthquake is almost equal to the size of the abrupt change which occurred during the earthquake. It seems that anomalous contraction before the earthquake rebounded by abrupt extension to the initial condition of the crust. These two stages of anomaly before the earthquake were recorded by extensometers L_2 , L_3 , C_1 , N_1 , V_3 , V_5 and R_2 . According to the array observation at the extension in S38°W, we find wrinkled strain has a width of some hundred meters, the same as at the time of the earthquake on August 18. Table 2 (b) shows the anomaly for the periods of eight or nine hours before the earthquake, the abrupt changes etc. in the earthquake on August 27.

Table 3 shows the anomaly at about half an hour before the earthquake.

According to Table 3, we can see that all extensometers show anomalous extensions half an hour before the earthquake. Therefore, we realize that the

Table 2. (b) First anomaly of the crustal strains before the earthquake on August 27, 1968

Sign of instrument	Component	Start of anomaly	Maximum speed of strain per hour	Accumulated anomaly before earthquake	Abrupt change in earthquake	Remark
L_2	S38°W extension	27d 13h	$-1.98 \times 10^{-8}/\text{hr}$	-3.62×10^{-8}	4.15×10^{-8}	
W_1	"	"	2.2 "	12.0 "	1.44 "	
R_1	"	"	2.0 "	15.6 "	little	
L_4	"	"	4.0 "	20 "	—	
L_3	"	"	-1.98 "	-1.87 "	1.61×10^{-8}	
R_2	"	"	-0.65 "	-3.1 "	9.75 "	
C_1	S52°E extension	"	2.16 "	-13.3 "	-5.26 "	
N_1	North extension	"	2.16 "	8.53 "	-1.54 "	
N_3	"	"	0.66 "	5.85 "	—	
E_1	East extension	"	-1.95 "	-12.82 "	-0.951 "	
E_3	"	"	-2.80 "	-12.37 "	-2.79 "	
V_3	Vertical extension	27d 13h 27d 15h	-1.53 " +1.49 "	-4.44 " +3.97 "	—	{extend at first, later contract
V_5	"	27d 13h 27d 15h	-2.15 " +1.52 "	-11.41 " -9.65 "	+5.26 "	"
R_0	$\frac{\partial(S52^\circ E)}{\partial(S38^\circ W)}$	27d 13h	+1.49 "	+3.97 "	7.34 "	
W_t	N38°E tilt	27d 13h	little	little	0.004"	
A_1	West tilt	"	-0.009"/hr.	-0.044"	-0.087 "	
B_1	North tilt	"	-0.009 "	-0.043 "	-0.1012 "	
A_2	West tilt	"	-0.025 "	-0.133 "	0.0711 "	
B_2	North tilt	"	-0.036 "	-0.266 "	—	
A_3	West tilt	"	-0.004 "	-0.040 "	-0.0494 "	
B_3	North tilt	"	-0.002 "	-0.024 "	-0.214 "	

crust of the earth at Osakayama was compressed eight or nine hours before the earthquake, it then expanded immediately before it was broken.

The water-tube tiltmeter in N38°E does not show the deflecting anomaly, but shows the periodic changes of period of three or four hours during half a day before the earthquake.

A uniform fall in the water level in the well near extensometer V_5 from July 30 to September 1 as follows.

Date	Jul. 19	Jul. 30	Aug. 6	Aug. 13	Aug. 25	Sep. 1	Sep. 7
Water level	-27.6cm	-27.2	-29.0	-30.9	-34.3	-30.3	-26.4

A barometer of medium sized type placed in this tunnel shows that on August 18, the maximum value was 992.2 mb at 7 a. m. and minimum values were 988.0 mb at 1 a. m. and 6 p. m., and on August 27, the maximum value

Table 3. Second anomaly of the crustal strains before the earthquake on August 27, 1968

Sign of instrument	Component	Start of anomaly before earthquake	Size of anomaly
L_2	S38°W extension	31 min.	0.376×10^{-8}
L_3	"	{52 "	0.83 "
		{27 "	0.68 "
R_2	"	70 "	0.8 "
C_1	S52°E extension	{31 "	2.33 "
		{72 "	3.23 "
N_1	North extension	30 "	0.88 "
V_3	Vertical extension	65 "	3.3 "
V_5	"	45 "	1.65 "
R_0	$\frac{\partial(S 52^\circ E)}{\partial(S 38^\circ W)}$	32 "	2.4 "
W_t	N38°E tilt	60 "	-0.003"
A_2	West tilt	30 "	+
B_2	North tilt	30 "	+

was 986.4 mb at midnight the minimum value was 982.6 mb at 6 p.m.. As mentioned above, the variation of pressure is smaller than 4 mb on the both days.

3. Considerations

Both of the remarkable earthquakes which occurred in and around Kyoto City on August 18 and 27 broke out directly after heavy rains with precipitations as follows: 158.5 mm on August 18, 30.0 mm, on August 26 and 53.5 mm on August 27, respectively. There was no day when precipitation was higher than 50 mm from October 27, 1967, when it was 74.4 mm, except July 2, 1968, when it was 114.5 mm. These earthquake occur at the start of the rainy season after a long dry season quietly.

It has been said, to quote, for example M. K. Hubbert and W. W. Rubey [1960] that the maximum strength of bed rock is decreased when saturates into the cracks of the rock, especially those of sedimentary rocks. Maximum strength decreases in proportion to the hydrostatic pressure of the saturated water. Moreover, the distribution of the internal stress is made not hydrostatic but continuous. And the weak zone in the crust where it is in the shadow of a large stress which is not continuous is broken by the generation of continuous stress. Actually, we saturate water in a rock when we dig a hole in a rock-bed. In such a case we can always observe phenomena where because of precipitations strains and tilts increase at a few hundreds meters under the ground. We often notice that changes at a few hundreds meters are larger than those some ten meters under the ground. This fact may be explained by

the fact that the pressure of saturated water increases in proportion to the depth. For example, although extensometer L_4 at the deepest point in this tunnel, is on the hardest rock, and it has a span of 34 meters, the effects caused by precipitation are greater here than at the other places in the tunnel where extensometers were placed on shallow rock. The speed of the extension on L_4 was 35×10^{-8} per hour on August 18. Treating the crust as a modified Kelvin's solid, the generated stress τ by the speed of the extension e is given as follows

$$\tau = 2\mu\dot{\gamma} + 2\eta\ddot{\gamma},$$

$$\dot{\gamma} = e,$$

where μ is the rigidity of the crust, η , the coefficient of the solid viscosity, γ and $\dot{\gamma}$ are the shear strain and its speed through the crust. The dimension of μ is 10^{11-12} , and that of η is

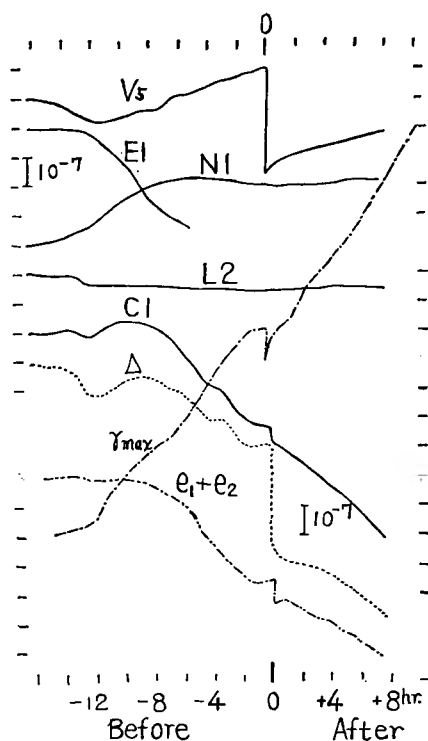


Fig. 3 (a). Anomalies of the strain components before and after the earthquake on August 18, 1968.

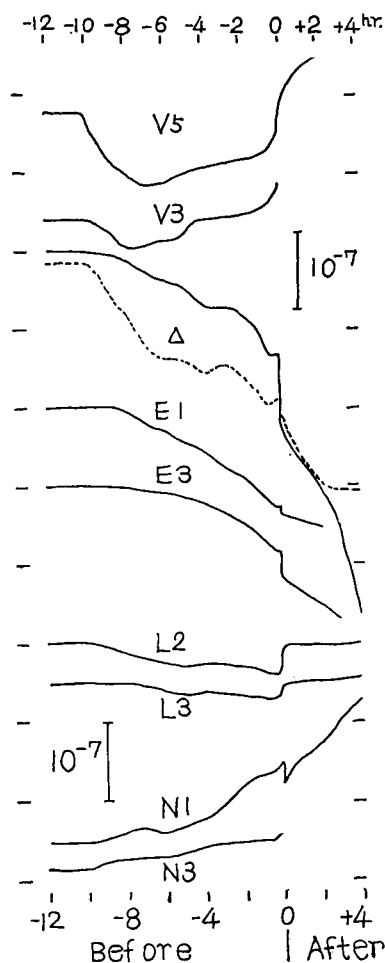


Fig. 3 (b). Anomalies of the strain components before and after the earthquake on August 27, 1968.

10^{22-20} for the mean of the crust. The dimension of η was ever found as 10^{14} in an origin of an earthquake (I. Ozawa, 1966), and usually is found as the smaller value in a ground of a land-slide. Using the value of e of L_4 on August 18, we get the equation here $\eta\dot{\gamma}$ is equal to $10^{12}\sim 10^4$. The upper limit of this value is much greater than the maximum strength of the rock, 10^9 . Therefore, this value seems to show that the ground is going to break. On the other hand, where the extensometer is set on the bed rock with cracks in it the η of it sometimes reduces remarkably. If we take the former point of the view, we find that the rock bed is broken by the rapid shear before the dimension of the shear is accumulated to 10^{-3} .

Next, we are going to study the elastic mechanism of the forerunner which occurred about half a day and half an hour before the earthquakes.

Fig. 3 (a) shows anomalies of the some strain components since midnight on August 18, 1968. These anomalies are calculated by subtracting periodic variations like tidal strains and annual changes. In this figure, the dilatation Δ and the maximum shear γ_{max} are calculated with some various strain elements. Similarly, Fig. 3 (b) shows those of the earthquake on August 27, 1968. We find remarkable compressions in the first stage of the start of the anomalies and in the period of a few hours after the earthquake. The maximum compression appears some three or four hours after the start of the anomalies before both these earthquakes. The strain components of the anomalies at a period of time three hours after the start of these anomalies, at 4 a.m., on August 18 and 3 p.m. on August 27, in the following table (Table 4) and their azimuth patterns are shown in Fig. 4 (a) and (b).

Also, the components and the azimuthal pattern of anomalous changes which accumulated about half a day before these earthquakes on August 18 and 27, are shown in Table 5 and Fig. 4, respectively.

e_1 and e_2 in Table 4, 5 etc. are the main strain components.

Table 4. The components of the anomalous strains 3 hours after the start of the anomaly

	August 18, 1968.	August 27, 1968.
$e_{\theta\theta}$	1.97×10^{-8}	-3.48×10^{-8}
$e_{\phi\phi}$	-2.50×10^{-8}	-6.89×10^{-8}
$e_{\theta\phi}$	-1.36×10^{-8}	13.34×10^{-8}
e_{rr}	-7.78×10^{-8}	-7.93×10^{-8}
Δ	-8.31×10^{-8}	-18.33×10^{-8}
γ_{max}	4.68×10^{-8}	13.76×10^{-8}
e_1	2.07×10^{-8} in 171.5°	1.67×10^{-8} in 127.8°
e_2	-2.61×10^{-8} in 81.5°	-12.07×10^{-8} in 37.8°

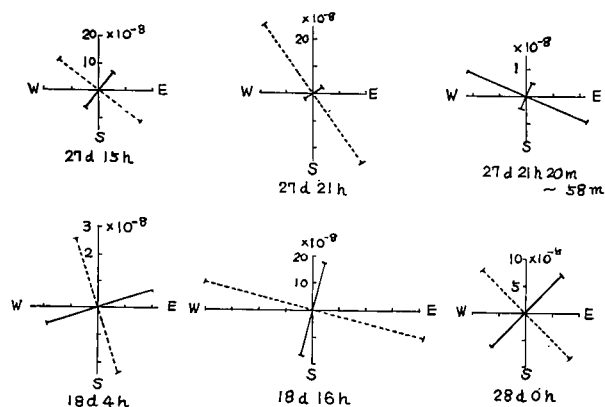


Fig. 4. Sizes and directions of main strains of the anomalies.

Table 5. The components of the anomalous strains in the periods for half a day before the earthquakes on August 18 and 27, 1968

	August 18, 1968.	August 27, 1968.
$e_{\theta\theta}$	14.86×10^{-8}	-8.20×10^{-8}
$e_{\phi\phi}$	-39.23×10^{-8}	-19.58×10^{-8}
$e_{\theta\phi}$	26.19×10^{-8}	33.58×10^{-8}
$e_{\tau\tau}$	-13.59×10^{-8}	-10.53×10^{-8}
Δ	-37.96×10^{-8}	-38.31×10^{-8}
γ_{max}	60.10×10^{-8}	35.65×10^{-8}
e_1	-42.24×10^{-8} in 102.9°	3.84×10^{-8} in 144.4°
e_2	17.86×10^{-8} in 12.9°	-31.62×10^{-8} in 54.4°

We also calculated the strain components of the anomaly at half an hour before the earthquake on August 27, and show the strain components in Table 6 and Fig. 4.

From Table 6 and Fig. 4 we are able to discover that the anomaly at half an hour before the earthquake is almost simple extension. This is a noticeable phenomenon on a precess of an earthquake's breakout.

We also calculated the strain components of the abrupt changes in these earthquakes on August 18 and 27, and their components are shown in Table 7,

Table 6. The strain components of the anomaly in the period for half an hour directly before the earthquake on August 27, 1968

$e_{\theta\theta}$	0.87×10^{-8}	$e_{\phi\phi}$	2.09×10^{-8}
$e_{\theta\phi}$	-1.49×10^{-8}	$e_{\tau\tau}$	2.00×10^{-8}
Δ	4.96×10^{-8}	γ_{max}	1.93×10^{-8}
e_1	2.44×10^{-8} in 115.3°		
e_2	0.52×10^{-8} in 25.3°		

Table 7. The strain components of the abrupt changes on August 18 and 27, 1968

	August 18, 1968.	August 27, 1968.
$e_{\theta\theta}$	-2.38×10^{-8}	-1.00×10^{-8}
$e_{\phi\phi}$	3.68×10^{-8}	-1.55×10^{-8}
$e_{\theta\phi}$	1.93×10^{-8}	9.27×10^{-8}
e_{rr}	-36.25×10^{-8}	-5.26×10^{-8}
Δ	-34.95×10^{-8}	-7.81×10^{-8}
γ_{max}	6.61×10^{-8}	9.28×10^{-8}
e_1	3.96×10^{-8} in 351.1°	3.36×10^{-8} in 43.0°
e_2	-2.66×10^{-8} in 81.1°	-5.92×10^{-8} in 133.0°

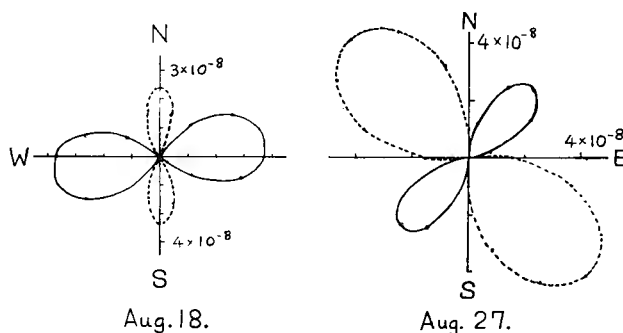


Fig. 5. Azimuthal patterns of the abrupt changes in the earthquakes on August 18 and 27, 1968.

and their azimuthal patterns in Fig. 5, respectively.

The maximum shear is much larger than the dilatations in either earthquake. The areal strain is positive on August 18, and is negative on August 27. According to the seismographic observations, the initial motion of the earthquake was "pull" on August 18, and was "push" on August 27. The dilatations are not so great in these abrupt changes, but are quite considerable for some hours after the earthquakes.

From these abrupt changes, assuming the maximum strain in the crushed areas as 11^{-4} , the radii of the crushed areas of these origins, the total changes of the strain energies in these earthquakes. Also employing the B. Gutenberg's theory of the relationship between the seismic magnitude and the seismic energy, $\log E = 1.5M + 11.8$, and these values of the strain energies which are calculated by means of the observation of the abrupt change (I. Ozawa [1965]), the magnitudes of both earthquakes may be calculated as 4.9 and 3.5–3.6, respectively as follows.

Date of earthquake	August 18	August 27
Radius of crushed area r_0	360–450 m	185–229 m

Change of elastic energy E_t	$0.68-1.37 \times 10^{20}$ erg.	$0.93-1.76 \times 10^{18}$ erg.
Magnitude calculated from E_t	5.3-5.6	4.1-4.3.

4. Summary

Sensible earthquakes occurred about twenty times including two shocks of intensity 3 and six shocks on intensity 2, around Kyoto City for a period of one month from August 18, 1968. We studied relationships between these earthquakes and the results of observations of crustal deformations with extensometers and tiltmeters at Osakayama Observatory. We made observations of the linear strains of an array with five points in the S38°W direction, of those with two points in the north, the east and the vertical directions. We also made a single observation of the linear strain in the S52°E and that of the shear strain with a rotationmeter in the direction of the S52°E per S38°W. Observations of the east and the west components of the tilting were made in array at three points.

According to these observations which were made over period of many months, anomalous changes seemed to be generated at the latest in April, 1968. And earthquakes which were the result of this anomaly appeared at end of a long dry season towards the later part of August 1968.

From the rheological considerations, we are able to discover rapid deformation of the crust caused by heavy precipitation seemed to fix the time when there was an outbreak of these local earthquakes. Sometimes, the rheological stress $2\eta\dot{\gamma}$ seems to be much greater than the elastic stress $2\mu\dot{\gamma}$ and also than the maximum strength of the rock.

The anomalous changes of the strain and tilt occurred first about half a day before the remarkable earthquakes on August 18 and 27, and secondary about half an hour before the earthquake on August 27 where was near directly. The remarkable compressions appeared some hours after the start of the first anomaly, and an expansion appeared during the second anomaly.

The areal strain of the abrupt change was positive, and the initial motion on the seismograph was "pull" in the earthquake on August 18. But in the earthquake on August 27, the areal strain was negative and the initial motion was "pull".

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