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ON THE OBSERVATIONS OF THE ABRUPT CHANGE OF THE ELASTIC ENERGY IN THE CRUST IN THE REMARKABLE EARTHQUAKES

By

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Abstract

We have sometimes found sudden changes of the crustal deformation in the observations with extensometers and tiltmeters. These changes are important phenomena to prove that earthquakes are the consequences of the changes of the elastic states in the crust. They are also important to study the mechanism of the earthquake.

The present author has observed with extensometers the sudden changes of the crustal strains in the times of eleven earthquakes. These leaps on the observing extensions are comparable to the magnitudes of the respective earthquakes. Using these magnitudes of the leaps, he has calculated the quantities of the changes of elastic energy in the crust. And the azimuthal pattern of these leaps of strains in the times of earthquakes of Odaigahara, Kitamino and Off. Echizenmisaki.

§ 1. Introductions

We have sometimes found the abrupt changes on the curves of the crustal strains observed with extensometers and tiltmeters in the times of the remarkable earthquakes. These phenomena are important to prove that the earthquakes are the consequences of the change of the elastic state in the crust. This fact has good agreements with that the faults, upheaval, subsidence and other deformations of the crust outbreak in the earthquakes. It is also necessary to prove that the most parts of the crustal movements over the large area on the geodetic measurements are not caused by the changes of the geoid surface, but are caused by the elastic deformations of the crust. The study of the abrupt changes is quite useful for that of the mechanism of the earthquake.

The study of the observations of the abrupt changes of the crustal strains has been hardly found till now. In 1949, the present author (I. Ozawa, 1949) had reported the abrupt changes of the crustal extensions at Osakayama in the Fukui Earthquake and other four earthquakes, and the quantities of the elastic energy in the crust estimated from the abrupt changes in these earthquakes. In 1964, he (I. Ozawa 1964) has again reported those changes in the Kitamino Earthquake and nine other earthquakes. Afterward, F. Press (F. Press, 1965) has reported displacements, strain and tilts at teleseismic distances, and in his report, he had described chiefly the theoretical consideration of the possibility of the outbreaks of those abrupt changes. It is not easy to observe exactly the abrupt changes of crustal extensions, because the extensometer and tilt-meter in usual use are considerably weak for large acceleration. However, our careful observations may accurate that these abrupt changes show the actual strains of the crust. And also, the long period seismographs have sometimes recorded the very long period's oscillations much longer than in their natural periods in the remarkable earthquakes; Some of them were longer than 1 minute (T. Matuzawa 1964, H. Berckhemer and G. Schneider, 1964). It seems that these facts indicate the outbreaks of abrupt deformations of the crust.

The another problem is where the energy of the earthquake is supplied from. In order to interpret this question, it is necessary to estimate the ratio between the energy of the earthquake oscillation and that of the permanent strain generated during the quake. The abrupt strain seems to be important factor to estimate the permanent change of the strain energy in the crust. The present author has also calculated the quantity of the energy of crustal strain by use of observing abrupt strains, and has compared it with the energy calculated from the magnitude of the earthquake.

§ 2. The abrupt change of the elastic energy in the crust.

Let us neglect the static stress of the earth because the observatory is not located in so deep place from the earth's surface that the hydrostatic pressure should be considered. Although the observed secular and annual strains are larger than the abrupt strain, the almost parts of the secular and the annual strain is combined in the thinner layer about ground surface. These strains increase with plastic behavior and are locked by these stresses. Therefore, we may consider that the annual and long period's secular strains have not the important ability to transform into the rebound energy. So, we estimate that the static energy change E of the rebound strain during earthquake is obtained as the linear combination of the squares and multiplications of the principal strain components of the rebound that is

$$E=\mu\left[\frac{1-\sigma}{1-2\sigma}(e_1+e_2+e_3)^2-2(e_1e_2+e_2e_3+e_3e_1)\right] \qquad \cdots\cdots\cdots\cdots\cdots\cdots(1)$$

where μ is the rigidity around the observing span, σ is Poisson's ratio, and e_1, e_2 and e_3 are the principal strain components of the rebound.

Let $\sigma=0.25$, and $|e|_{max}$ be the largest absolute value among these principal strain's components, the formula (1) is written as follow

$$E=(1.5\sim7.5)\mu(|e|_{max})^2 \qquad \cdots\cdots\cdots(2)$$

$|e|_{max}$ is considerably larger than the remainders in the general earthquakes as shown afterward. Therefore, the coefficient in formula (2) approximate to 1.5. We may assume that the distribution of the energy of the rebound in the crust except hypocenter is given as

$$E=kr^{-4} \qquad \cdots\cdots\cdots(3)$$

where r is the hypocentral distance of the volume element and k is the specific constant for the pending earthquake. The maximum values of the energy increment has been estimated as about 10^4 erg/cm^3 (Tsuboi, 1964). Therefore, the radius r_0 of the area where the energy increment is the limiting value is written as follow

$$r_0=\sqrt[4]{\frac{k}{E_0}}\approx 0.1\sqrt[4]{k} \qquad \cdots\cdots\cdots(4)$$

where E_0 is the limiting value of the increment energy in unit volume of the crust.

If let the hypocenter be very shallow, and the energy increment per unit volume (E) be equal to E_0 within the hypocentral distance r_0, the total strain energy increment E_t in the crust is written by formulas (3) and (4) as follow

$$E_t=\int_0^{2\pi}\int_0^{\pi}\int_0^{\infty} Er^2\sin\theta' dr\cdot d\theta'\cdot d\varphi+\frac{2}{3}\pi r_0^3E_0=4\frac{2}{3}\pi r_0^3E_0 \qquad \cdots\cdots\cdots(5)$$

where, φ and θ' are azimuth and dip of the position of the volume element for origin where is epicenter, respectively.

§ 3. Observations

The concerned observations have been being performed at Osakayama Observatory. In the beginning, the Sassa type extensometer (K. Sassa et. al., 1952) which is marked as W_1 has been set in the direction of S 38°W-N 38°E on September 1947. The Sassa type extensometer consists of a slackening wire (1.6 mm. in diameter) as a datum measure and a tri-fillar suspensioned weight. The sensitivity of this instrument is about 10^{-8} per one millimeter on the recording paper. The Sassa type extensometer can proof against an earthquake vibration whose intensity is III of Japanese Meteorological Agency. This type extensometer was damaged in the Yoshino Earthquake, but two roller-type extensometers which consists of the datum rods and roller amplifiers with reflecting mirror recovered the absent observations of the Sassa type extensometers. In this paper, the roller-type extensometers (I. Ozawa, 1961), are marked as R_1 and R_2 respectively. In 1959, the present author devised the type of highly sensitive-extensometer (I. Ozawa, 1960), which consists of a datum measure made of super invar rod or tube and a amplifier which is horizontal pendulum type tiltmeter. The mechanism of this amplifier is that the relative displacement of the both ends on the observing span is transformed into the inclination of the axis of the horizontal pendulum of the amplifier, then the inclination is enlarged by the rotating of the horizontal pendulum. This type is called H-59-A, B or C for the horizontal component, and is called V-59-A or B for vertical component, where sign B shows that the supporter of pendulum is standing type (inverted pendulum) and signs A and C show that they are suspension type (vertical pendulum). The magnification of this amplifier is able to be gained up to 2×10^5, and so the sensitivity is able to be adjusted easily to any level between 10^{-10} and 10^{-8} per one millimeter on the record at any time. The observation with this type's instruments in the directions of S 38°W-N 38°E are marked L_2 and L_3, that in S 52°E-N 52°W is done C_1, those in E-N are done E_1, E_2, those in N-S are done N_1, N_2, and those in vertical are done V_3, V_4, V_5. For some years, the observations had been performed with vertical ones whose datums are wire, which are signed V_1 and V_2.

According to the observations with these extensometers, the abrupt changes of straining have been observed in the times of remarkable earthquakes like the Odaigahara, Himeji, Kitamino, Echizen-misaki and Niigata Earthquakes. In the Odaigahara Earthquake, all of seven extensometers in horizontal components have recorded contractional jumping strain and all their vertical components have done extensional jumping; the earth's crust has been contracted abruptly in all the horizontal directions and also has been extended in the vertical direction. In the Himeji Earthquake, the earthcrust has been strained in same manner with that in the time of the Odaigahara Earthquake. In the Kitamino Earthquake, they have recorded larger extension in south-east to north-west component, have done less extension in south-west to north-east, and have done middle contraction in east to west and in south to north. And all components of four vertical components have recorded extensional jumping. In the Echizen-misaki Earthquake, their two components (N_1 and N_2) in the north to south direction have recorded extensional jumping of $40\sim50\times10^{-8}$ and their two components (E_1 and E_2) in the east to west have done same small contractional jumping of $4\sim5\times10^{-8}$. Especially, one (E_1) of two east-west components of these extensometers has the amplifier part in the western end of its datum-measure, on the contrary, the other (E_3) has it in the eastern end of it. But both extensometers have recorded same contractional jump-

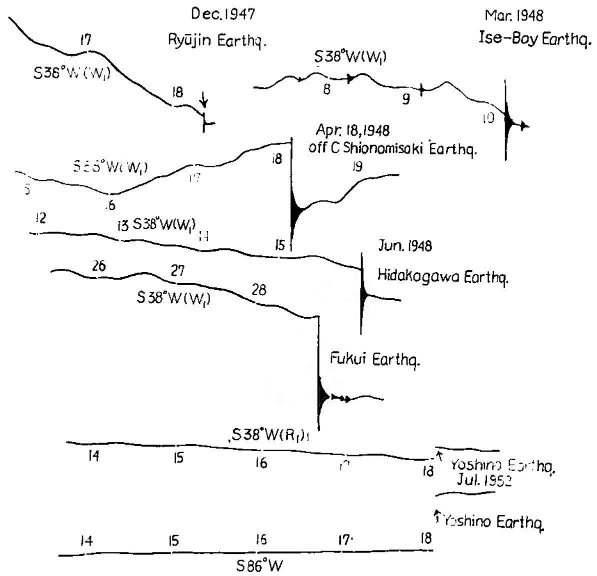

Fig. 1 (a). The Crustal Extensions at Osakayama before and after the Earthquakes of Ryujin, Ise-Bay, Hidakagawa, Fukui and Yoshino.

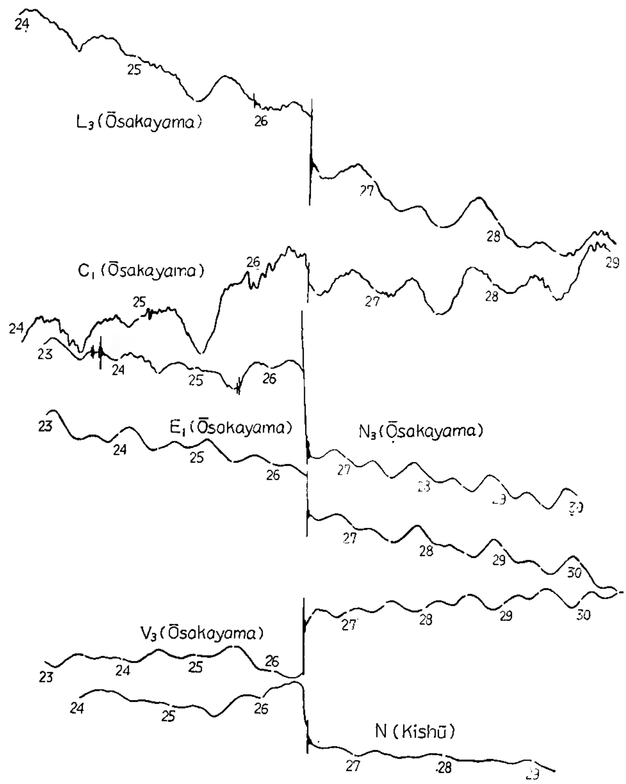

Fig. 1 (b). The Crustal Extensions at Osakayama and Kishu before and after the Odaigahara Earthquake.

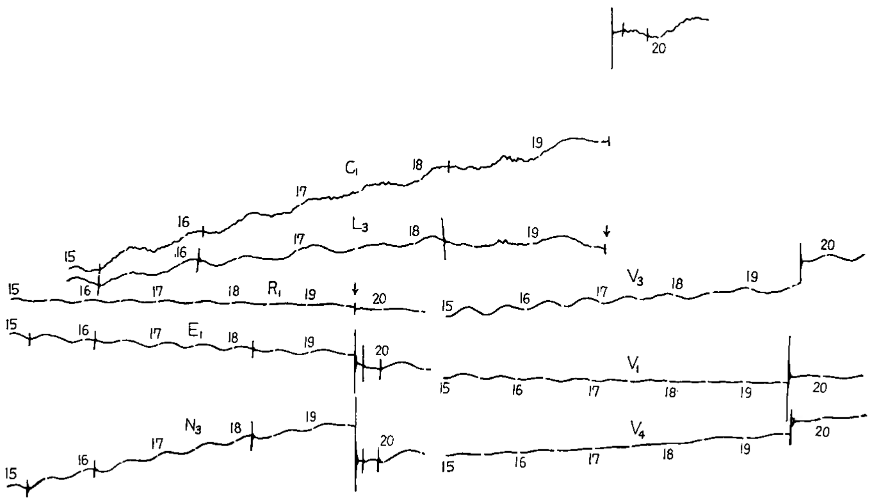

Fig. 1 (c). The Crustal Extensions at Osakayama before and after the Kitamino Earthquake.

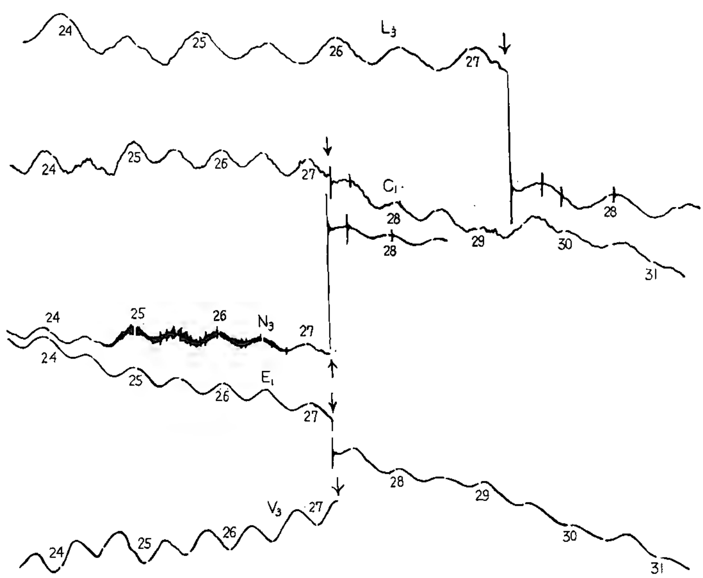

Fig. 1 (d). The Crustal Extensions at Osakayama before and after the off Echizen-misaki Earthquake.

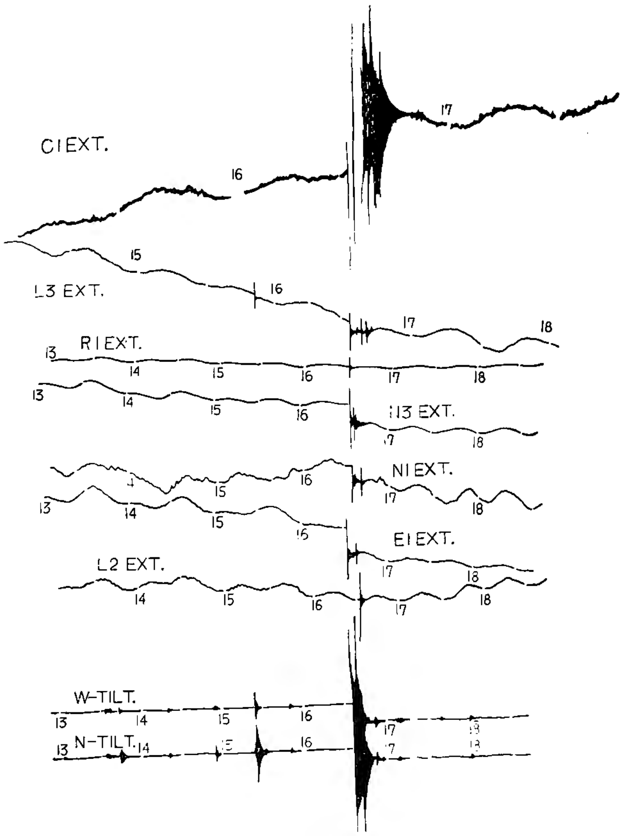

Fig. 1 (e). The Crustal Extensions and Tiltings at Osakayama before and after the Niigata Earthquake.

ing. Therefore, these jumpings seem to be not the effects by earthquake vibration or the ground tilting, but the effects by crustal-strain. The times required to complete the jumpings have not been obvious, however these occurrences are at beginnings of the earthquakes' motions. The jumping has accompanied a forerunning oscillations on S 38°W-N 38°E component (L_3) in the time of the Kitamino Earthquake. But long periods' microseisms or a teleseisms had been recorded for about three hours before this earthquake. It seems that the times required to complete these jumpings are perhaps between several seconds and a few minutes. In particularly, it seems to be longer than about ten minutes on the tiltgram in the time of the Chilean Earthquake. We are going to observed precisely it. The magnitudes of these observed jumping strains and the constants of the relating earthquakes are shown in Table 1. Fig. 1, (a), (b), (c), (d) and (e) show the observing records of the extensometers in these earthquakes.

Table I. Energy of Crustal Strain by Sudden Change during Earthquake.

Date of Earthquake	Epicenter		Magnitude of Earthquake	Hypo-central Distance	Magnitude of Observed Leap of Extension	Absolute Mean of the Leap in Horizontal Component	r_0	log E_t (erg.)	log E_M (erg.)	log k
	Region	Location								
1947, 12, 18.	Ryujin-mura	33.8°N 135.3°E	5.4	150 km.	$\times 10^{-8}$ − 0.4 in S38°W	$\times 10^{-8}$ 0.4	km. 0.94	20.09	19.90	23.91
1948, 3, 10.	North p. of Ise	34.8°N 136.7°E	5.3	75	− 1.5 in S38°W	1.5	0.92	20.07	19.75	23.85
1948, 4, 18.	Southward of C. Shiono-misaki	33.1°N 135.6°E	7.2 MG=7.3	200	−23.0 in S38°W	23.0	9.60	23.19	22.60 (22.75)	27.93
1948, 6, 15.	R. Hidakagawa	33.8°N 135.5°E	7.0 MG=6.9	150	− 7.4 in S38°W	7.4	4.08	21.99	22.30 (22.15)	26.44
1948, 6, 28.	Fukui	36.1°N 136.3°E	7.3	150	−22.4 in S38°W	22.4	7.28	22.75	22.75	27.41
1952, 7, 17.	Yoshino	34.4°N 135.8°E	7.0	80	13.7 in S38°W (R1) 142.4 in S86°W (R2)	78.1	7.07	22.71	22.30	27.40
1960, 12, 26.	Ōdaigahara	34.2°N 136.2°E	6.0	94	−1.89 in S38°W (L3) −1.08 in S38°W (W1) −0.79 in S52°E (C1) −5.70 in S29°E (29) −3.77 in North (N1) −27.5 in North (N3) −5.65 in East (E1) −5.50 in East (E3) 28.1 in Vertical (V3) 45.6 in Vertical (V4)	7.19	2.52	21.37	20.80	25.61
1961, 5, 7.	Himeji	35.1°N 134.4°E	5.9	115	−0.30 in S38°W (L3) −1.95 in S38°W (L2)	< 1.00	1.15	<20.23	20.64	24.24

					−0.60 in S38°W (W1) −1.02 in North (N1) < −0.24 in East (E3) < −1.5 in S29°E (29) 5.80 in Vertical (V3)					
1961, 8, 19.	Kitamino	36.1°N 136.8°E	7.0	140	25.4 in S52°E (C1) −1.29 in North (N1) −13.7 in North (N3) −3.45 in East (E1) −26.5 in East (E3) 0.60 in S38°W (L3) 1.25 in Vertical (V3) 2.6 in Vertical (V2) 2.35 in Vertical (V1)	11.82	4.84	22.22	22.30	26.74
1963, 3, 27.	Off C. Echizen-misaki	35.9°N 135.9°E	6.9	106	−7.42 in S38°W (L′3) −2.02 in S52°E (C1) 39.10 in North (N1) 51.8 in North (N3) −5.12 in East (E1) −4.49 in East (E3) >0 in Vertical (V3, V4)	18.33	4.54	22.14	22.24	26.63
1964, 6, 16.	Niigata	38.4°N 139.2°E	7.5	496	−0.82 in S38°W (L3) −0.30 in S38°W (L2) 12.33 in S52°E (C1) −0.78 in S38°W (R1) −8.20 in North (N3) −2.87 in North (N1) −8.75 in East (E1) −25.1 in Vertical (V3)	4.86	10.95	23.04	23.04	28.16

§ 4. Analyses and results.

From the observed jumpings as stated above, the abrupt changes of the elastic energy in the crust are estimated. Some vertical components of the extensometer had some weak points for earthquake motion whose acceleration was large, because the dampers of their scale rods had been lacking. So the vertical components are excepted from the data for the numerical calculations. As our observations might contain some accidents in the machineries, we have used the absolute means $|e|_{mean}$ of all horizontal components of the observed jumping instead of the absolute maximum of the principal strain $|e|_{max}$ in formula (2) to estimate the change of elastic energy. We estimate the rigidity around the observatory about 10^{11} c. g. s., then the change of specific elastic energy is nearly as

$$E \doteqdot 10^{12}(|e|_{mean})^2.$$

We obtain quantity of k from this relation and formula (3), do that of r_0 from this and formula (4) and do that of E_t from this and formula (5). The values of $\log k$, $\log E_t$, $\log E_M$ and r_0 are shown in Table 1. Further, the values of $\log E_t$ are compared with those of $\log E_M$ which are calculated from these seismic magnitudes (M) and the relation of Richter and Gutenberg as

$$\log_{10} E_M = 11.8 + 1.5M,$$

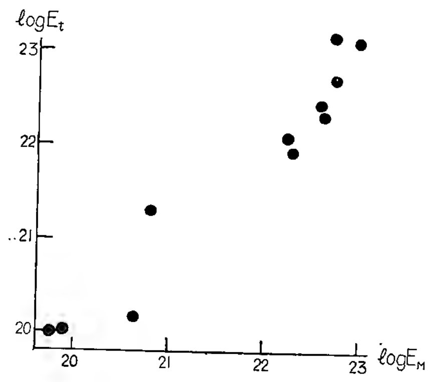

Fig. 2.

and are shown in Fig. 2. According to this figure, the value of E_t is linearly proportional to that of E_M, moreover they are nearly equal to each other. According to Table 1, the values of r_0 are 9.60 km. in the southward of Cape Shionomisaki, 7.28 km. in the Fukui Earthquake, and so on. The radius r_0 calculated above is equal to about one half of that of the after-shock's area (T. Utsu and A Seki, 1955, K. Goto, 1962) in the Fukui Earthquake. It is natural that the crustal volume strained to the limit is a little smaller than that of the aftershock region.

Next, the azimuthal patterns of the jumping strains in the Odaigahara, the Kitamino and the Echizen-misaki Earthquakes are analyzed and are shown in Fig. 3. The elements of their horizontal strains ($e_{\theta\theta}$, $e_{\phi\phi}$, $e_{\theta\phi}$) the horizontal principal strains (e_1, e_2) and their directions, the maximum shears (γ) and the horizontal areal strains ($e_{\theta\theta}+e_{\phi\phi}$) are shown as followings, where θ is colatitude and ϕ is longitude in the earth coordinate.

1) Odaigahara Earthquake

$e_{\theta\theta}=(-10.5\pm 3.6)\times10^{-8}$,

$e_{\phi\phi}=(-1.8\pm 4.0)\times10^{-8}$,

$e_{\theta\phi}=(-5.9\pm14.4)\times10^{-8}$,

$e_1=(-0.9\pm 6.9)\times10^{-8}$; N ($69.8°\pm24.5°$) E,

$e_2=(-11.4\pm 5.5)\times10^{-8}$; N ($159.8°\pm24.5°$) E,

$\gamma=\pm(10.5\pm 4.4)\times10^{-8}$,

$e_{\theta\theta}+e_{\phi\phi}=(-12.3\pm 2.6)\times10^{-8}$.

2) Kitamino Earthquake

$e_{\theta\theta}=(0.6\pm 8.1)\times10^{-8}$,

$e_{\phi\phi}=(-6.9\pm 8.4)\times10^{-8}$,

$e_{\theta\phi}=(56.9\pm39.9)\times10^{-8}$,

$e_1=(25.5\pm20.6)\times10^{-8}$; N ($138.8°\pm44.7°$) E,

$e_2=(-31.8\pm20.6)\times10^{-8}$; N ($48.8°\pm44.7°$) E,

$\gamma=\pm(57.4\pm39.6)\times10^{-8}$,

$e_{\theta\theta}+e_{\phi\phi}=(-6.3\pm5.8)\times10^{-8}$.

3) Echizen-misaki Earthquake

$e_{\theta\theta}=(37.1\pm 8.2)\times10^{-8}$,

$e_{\phi\phi}=(-13.1\pm 8.5)\times10^{-8}$,

$e_{\theta\phi}=(13.1\pm40.5)\times10^{-8}$,

$e_1=(43.4\pm14.3)\times10^{-8}$; N ($161.6°\pm38.2°$) E,

$e_2=(-19.4\pm14.4)\times10^{-8}$; N ($71.6°\pm38.2°$) E,

$\gamma=\pm(62.7\pm32.9)\times10^{-8}$,

$e_{\theta\theta}+e_{\phi\phi}=(24.0\pm5.9)\times10^{-8}$.

According to this analyses, the directions of the principal axis are equal to those of the epicenters in these earthquakes. The Osakayama Observatory is in the quadrants of "pull" of the initial motions and the jumpings in the directions of the epicenters are contractions in the times of the Odaigahara and the Kitamino earthquakes. On the other hand, it is in the quadrant of

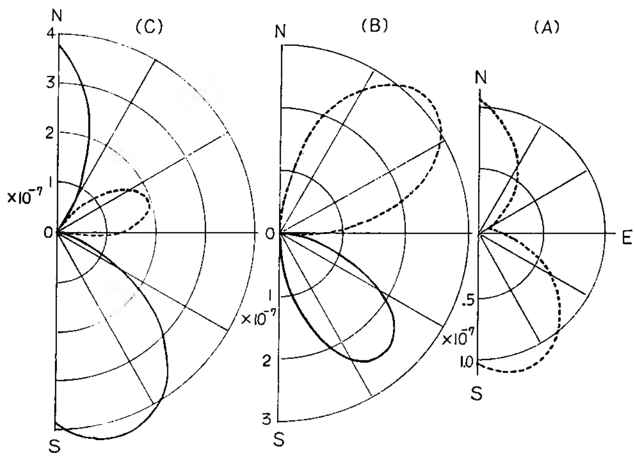

Fig. 3. The Azimuthal Pattern of the Abrupt Extensions at Osakayama in the Times of the Earthquakes of (A) Odaigahara, (B) Kitamino and (C) off Echizen-misaki. Solid Line is Extension and Dotted Line is Contraction.

"push" of the initial motion and the jumpings are extension in the time of the Echizen-misaki Earthquake. The relations between either the jumpings are contraction or extension and either the initial motions of P-waves are rare or dense seem to be in opposition in these three earthquakes and in the Niigata earthquake. This author thinks that the P-waves are transmitted from the origins of the destroying points of the crust, but the abrupt strains are converged into the origins and so the directions of the strains are facing to that of the P-waves. We are going to study further this relation in following papers.

Moreover, all differences of pairs among three principal strains are considerably large; maximum shears are larger in these earthquakes. So, we may write formula (2) as follows

$$E \approx 1.5\mu(|e|_{max})^2. \tag{2'}$$

According to Table I, and results of 1), 2) and 3), the signs of e_1+e_2 are always different from those of e_3, and then we obtain the relation as

$$|\gamma| > |e_1+e_2+e_3|.$$

Namely, the quantity of the horizontal maximum shear is generally larger than that of the cubical dilatation. The author suggests that these observed jumping strains seem to be the indispensable quantities to explain the seismic energy sources and the geodetic movements accompanied of these earthquakes (Kasahara, K., 1957, Nakano, S., 1964, Maruyama, T., 1964), otherwise we have to imagine the bublle emission from the crust or the appearance and disappearance of mass in the crust.

§ 5. Acknowledgements

In conclusion, the author wishes to express his hearty thanks to Dr. K. Sassa of the emeritus professor of Kyoto University and many authorities for studies of crustal movement for their encouragements.

References

Berckhemer, H. and Schneider, G., 1964. Near Earthquakes Recorded with Long Period Seismograms. Bulletin of seismological Society of America, Vol. 54, pp. 973-985.

Goto, K., 1962. On the Relation between the Distribution of After-Shocks and the Magnitude. "Zisin" Journal of the Seismological Society of Japan, Vol. 15, pp. 116-121.

Gutenberg, B. and Richter, C. F., 1956. The Energy of Earthquakes. Journal of Geological Society of London. Vol. 112, pp. 1-14.

Kasahara, K., 1957. The Nature of Seismic Origins as Inferred from Seismological and Geodetic Observations. Bulletin of Earthquake Research Institute of Tokyo University, Vol. 35, pp. 473-532.

Maruyama, T., 1964. Statical Elastic Dislocation in an Infinite and Semi-infinite Medium. Bulletin of Earthquake Research Institute of Tokyo University, Vol. 42, pp. 289-368.

Matuzawa, T., 1963. Study of Seismology. pp. 46.

Nakano, S., 1964. The Crustal Deformations due to the Source of Crack Type (2). Memoirs of the Osaka Institute of Technology, Vol. 9, pp. 37-79.

Ozawa, I., 1949. On the Strain of Earth-Crust Observed in Osakayama-tunnel. Bulletin of the Disaster Prevention Research Institute Kyoto University, No. 2, pp. 115-121.

Ozawa, I., 1960. On the Extensometer of Which Magnifier is a Zöllner Suspension Type Tiltmeter and the Observations of the Earth's Strain by Means of the Instruments. Journal of the Geodetic Society of Japan, Vol. 6, pp. 1-5.

Ozawa, I., 1963. Comparative Observations of Crustal Strain by Means of Wire-Type, and Rod-Type Extensometers. Journal of the Geodetic Society of Japan, Vol. 7, pp. 1-6.

Press, F., 1965. Displacement, Strains, and Tilts at Teleseismic Distances. Journal of Geophysical Research, Vol. 70, pp. 2395-2412.

Sassa, K., Ozawa, I. and Yoshikawa, S., 1952. Observation of Tidal Strain of the Earth. Disaster Prevention Research Institute Bulletin 3, pp. 1-3.

Tuboi, C., 1956. Earthquake Energy, Earthquake Volume, After-Shock Area, and Strength of the Earth' Crust. Journal of Physics of the Earth, Vol. 4, pp. 63-66.

Utsu, T. and Seki, A., 1955. A Relation Between the Area of After-Shock Region. "Zisin", Journal of Seismological Society of Japan, Vol. 7, pp. 233-240.