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OBSERVATIONS OF ABRUPT CHANGES OF CRUSTAL STRAINS DURING EARTHQUAKES

By

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Abstract

The abrupt changes of the crustal strains during the earthquakes have been observed with some components of highly sensitive extensometers.

The relations between the seismic magnitude M and the coefficient k of the transmission of the abrupt change have been obtained as

$$\log k = 1.17M + 4.52.$$

Moreover, the relations between the magnitude M and those of the radius of the fault area r_0 and the total released energy of the crustal strain E_r have been calculated as,

$$\log r_0 = 0.45M + 3.00,$$
$$\log E_r = 1.3M + 13.4.$$

1. Introduction

Most of seismologists would assume the existence of abrupt changes of the crustal strains during earthquake, if the elastic rebound theory is acceptable in the interpretation of the mechanism of earthquakes.

The present author (Ozawa [1949, 1965]) has observed the abrupt changes in the crustal extensions in some earthquakes and has calculated concisely the seismic energies and the radii of the fault areas. His method of the calculations are based on the concept that maximum energy in the crust is constant (for example, Tsuboi [1957]). The author has exerted great effort to obtain numerous exact data of these changes chiefly, because he has feared that the complex analyses without exact data do not contributed to the development of the interpretation of these mechanisms. Nowadays, many interests are focussing on this study of the observations of the abrupt changes, and related papers are constantly appearing.

2. Theory

The present author (Ozawa [1949, 1965]) assumed that the attenuation of the abrupt strains through the crust is proportional to -2.0th powers of the epicentral distances. Thereafter, C. J. Wideman *et al.* [1967] and S. Takemoto *et al.* [1969] obtained experimentally their attenuations have been proportional to -2.5th and -2.4th powers of their epicentral distances, respectively.

On the other hand, C. Tsuboi [1957] has experimental formula of the relation between the seismic magnitude M, measured maximum amplitude in displacement and the epicentral distance r less than 500 km as follows,

$$M=\log A+1.73\log r-0.83. \tag{1}$$

According to the formula (1), the attenuation of the maximum amplitude in displacement is proportional to -1.73th powers of the epicentral distance r. And so we might have a relation between an abrupt strain e at an observatory at a distance r from a focus as

$$e=kr^{-2.73}, \tag{2}$$

and a relation between an elastic energy E of an abrupt strain at the observatory as

$$E=Kr^{-5.46}. \tag{3}$$

The existence of a seismic fault complicate the distribution of the strain and stress in the crust near the fault. However, the isochromatic lines of the stress or strain at distant places from the fault are almost concentric as shown by I. N. Snnedon [1951]. I. N. Snnedon has calculated the stress distributions around faults which were a Griffith crack and a circular crack. According to his study, the isochromatic lines of the stress are almost correspond with coaxial circles about the cracks at the greater distance than the lengths of the

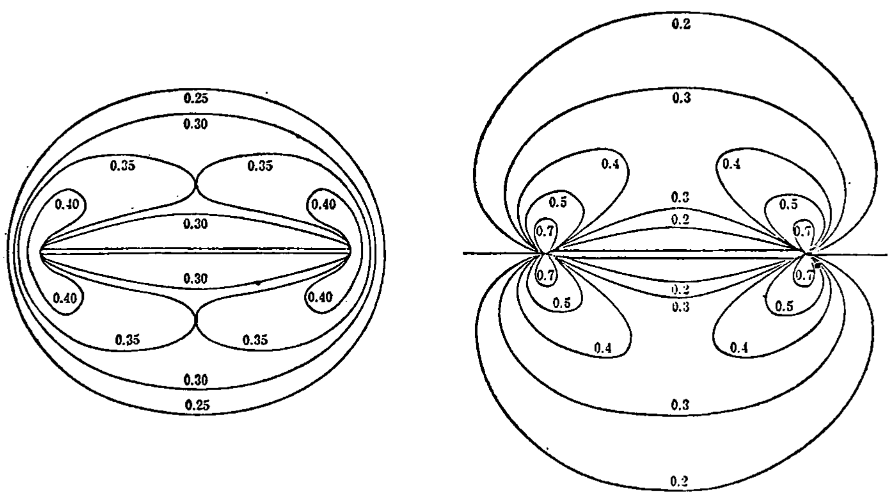

Fig. 1. The contours of equal maximum stresses in the vicinities of a circular crack (left) and of a Griffith crack (right) (after I. N. Snnedon [1951]).

crack as shown in Fig. 1. Further, the stress within the circles whose diameter is equal to the length of the crack is distributed almost constantly except the big ones in the vicinity on the both ends of the crack. We may assume that the strain energy within the circle whose diameter is equal to the length of the crack approximate constant value at just before the earthquake. Hereafter, we call this area the "fault area".

Let the mean value of the strain within the fault area be e_0 and the radius of the fault area which is equal to half of the length of the fault be r_0, then we have

$$e_0 = k r_0^{-2.73}. \tag{4}$$

Equation (4) is able to be rewritten as,

$$r_0 = \left(\frac{k}{e_0}\right)^{1/2.73} = \left(\frac{K}{E_0}\right)^{1/5.46}, \tag{5}$$

where K and E_0 are constants of the attenuation and mean energy density within the fault area. Assume the energy density E of the abrupt change be constant E_0 within the hemisphere of the fault area, and to be $E = Kr^{-5.46}$ outside the fault area; and that the fault area is a hemisphere whose sectional plane is a ground surface. Then, we have the formula of the total energy change E_r in abrupt change by using equations (3) and (5) as follows,

$$\begin{aligned} E_r &= \int_0^{2\pi}\int_0^{\pi}\int_0^{\infty} Er^2 \sin\theta' dr\cdot d\theta' d\varphi + \frac{2}{3}\pi r_0^3 E_0 \\ &= 7.373 E_0 r_0^3 = 7.373 E_0 \left(\frac{k}{e_0}\right)^{1,099}. \end{aligned} \tag{6}$$

3. Observations

Osakayama observatory is situated 135°51.9′ of the east longitude and 34°59.6′ of the north latitude in two main tunnels whose lengths are 656 m and 664 m and in two connective tunnels whose lengths are about 10 m. The bedrock in the tunnels consists of clay-slate belonging to the Chichibu palaeozoic system. Six extensometers of four kinds of the S38°W component, were placed at the intervals of 100 m, 40 m, 0 m, 40 m and 170 m. Two extensometers of two kinds of the east and the north components respectively, were placed at intervals of 140 m. One extensometer of the S52°E component has been placed in the connective tunnel. Two extensometers of two kinds of the vertical component have been at the interval of 30 m. These instruments of the horizontal components were devised to be an earthquake-proof for the observation of the abrupt changes. According to our study, it seems that the observed changes during the earthquakes are not instrumental noises, but real crustal strains in many cases. The amplitude of the abrupt change is neither proportional to the seismic intensity at an observatory, nor an amplitude of the strain vibration. We find the abrupt change in teleseism is found in the shear wave phase whose observed amplitude is much smaller than that in the surface

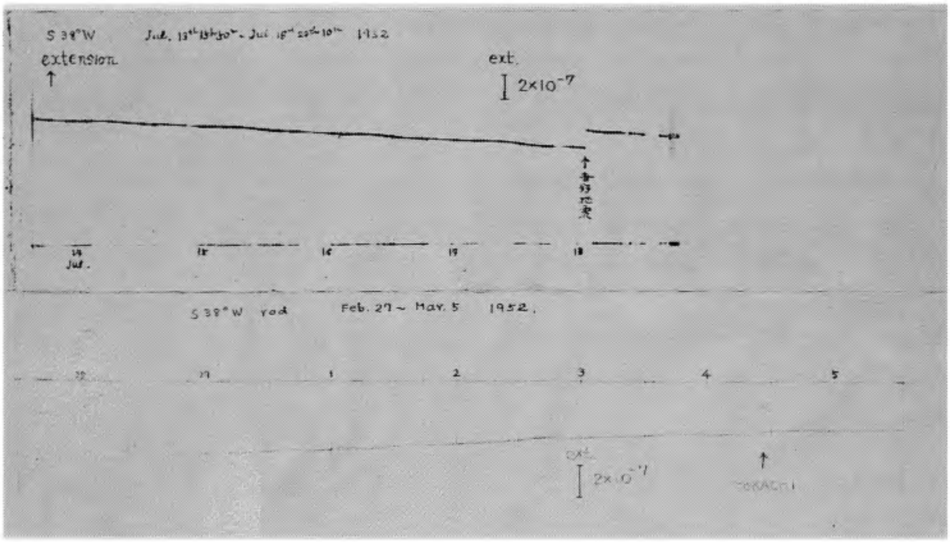

Photo. 1(a). The abrupt change in the crustal strain in the direction of the S38°W at Osakayama during Yoshino Earthquake (July 1952) and Tokachi Earthquake (Mar. 1952), observed with pivot type extensometer.

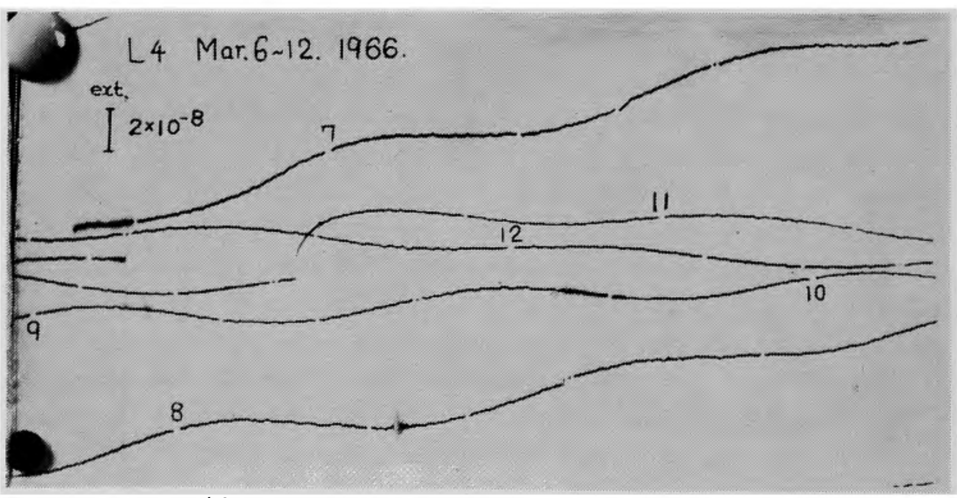

Photo. 1(b). The abrupt change in the crustal strain in the direction of the S38°W at Osakayama during the earthquake in the suburb (Mar. 1966), observed with H-59-D type extensometer.

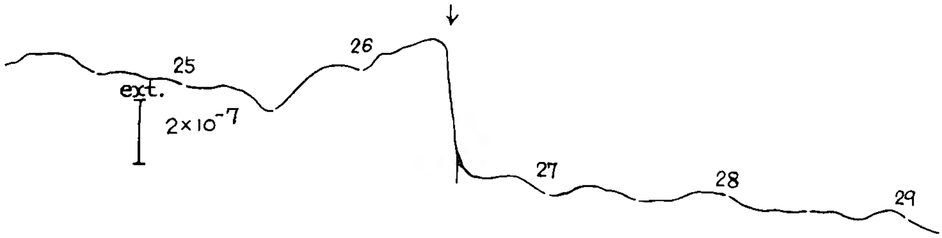

Photo. 1(c). The abrupt change in the crustal strain in the direction of the north at Kishu Mine during Ōdaigahara Earthquake (Dec. 1960), observed with H-59-C type extensometer.

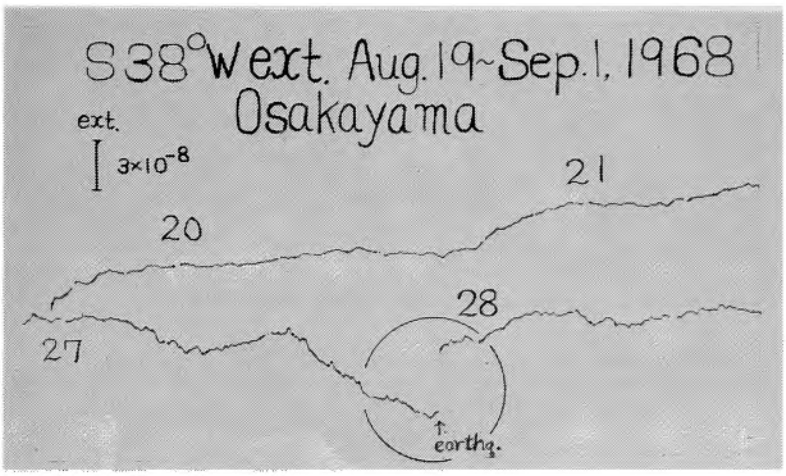

Photo. 1(d). The abrupt change in the crustal strain in the direction of S38°W at Osakayama during the earthquake at Kyoto City (Aug. 1968), observed with H-59-B type extensometer.

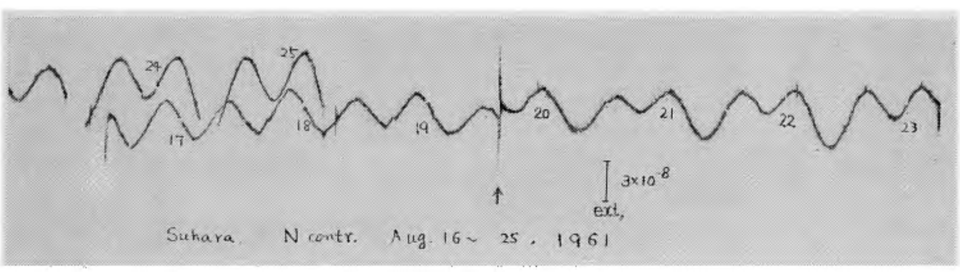

Photo. 1(e). The abrupt change in the crustal strain in the direction of the north at Suhara during Kitamino Earthquake (Aug. 1961), observed with H-59-A type extensometer.

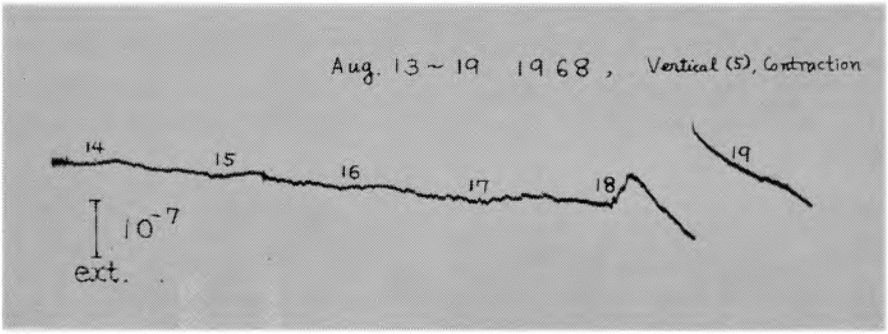

Photo. 1(f). The abrupt change in the crustal strain in the vertical at Osakayama during the earthquake in Kamiwachi (Aug. 1968), observed with V-59-D type extensometer.

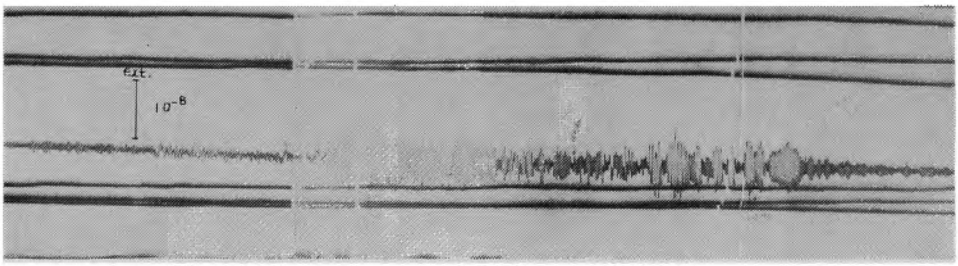

Photo. 2. The seismic record in the crustal strain observed with extensometer at Osakayama during the earthquake in Peru (Oct. 1966).

Table 1. Characters of abrupt change and earthquake

Earthquake	Year	$\|e\|$ mean $\times 10^{-8}$	Focal distance r km	log k	M	log r_0	log E_r
Ryūjin	1947	0.4	150	11.19	5.4	5.56	21.04
Ise Bay	1948	1.5	75	10.95	5.3	5.48	20.76
Nankai	〃	23.0	200	13.29	7.2~7.3	6.33	23.35
Tanabe	〃	7.4	150	12.46	7.0~6.9	6.02	22.43
Fukui	〃	22.4	150	13.44	7.3	6.38	23.51
Tokachi	1952	1.05	1050	13.91	8.2	6.59	24.15
Yoshino	〃	78.1	80	12.74	7.0	6.13	22.74
Ōdaigahara	1960	7.19	94	11.89	6.0	5.82	21.81
Himeji	1961	1.0	115	11.28	5.9	5.59	21.13
Kitamino	〃	11.82	140	12.58	7.0	6.07	22.57
Echizenmisaki	1963	18.33	106	12.44	6.9	6.02	22.41
Niigata	1964	4.86	496	13.70	7.5	6.48	23.79
Sakahara	1966	0.62	16	8.73	3.7	4.66	18.37
Tokachi	1968	2.35	925	14.11	7.9	6.63	24.25
Kamiwachi	〃	2.34	54	10.75	5.4	5.40	20.85
Kyoto	〃	6.84	20	10.03	4.6	5.24	20.08
Mino	1969	2.23	135	11.81	6.7	5.80	21.75

wave phase (Photo. 2). The relation between the sign of the strain and the azimuth or dip is systematic.

Table 1 shows the mean amplitude of observed values with many components of the extensometers, and the characters of the earthquakes; the origin data, the distance from the focus r, the magnitude M of the earthquake and so on. k, r_0, E_t,...... in the Table 1 are computed by use of the mean abrupt strain and the distance from the focus.

4. Considerations

The relation between the seismic magnitude M and k is shown in Fig. 2, and the relation is formulated as

$$\log k = (1.17 \pm 0.33)M + (4.52 \pm 0.69). \qquad \text{(I)}$$

Moreover, the relation between the seismic magnitude M and the radius of the fault area r_0 are shown in Fig. 3, and the relation is formulated as

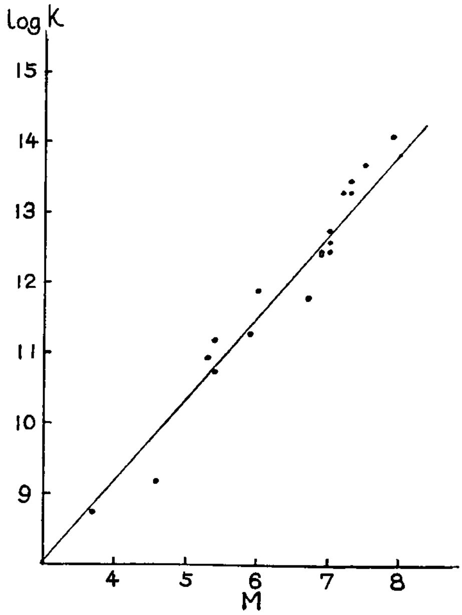

Fig. 2. The relation between the seismic magnitude M and log k. The full line is $\log k = 1.17M + 4.52$.

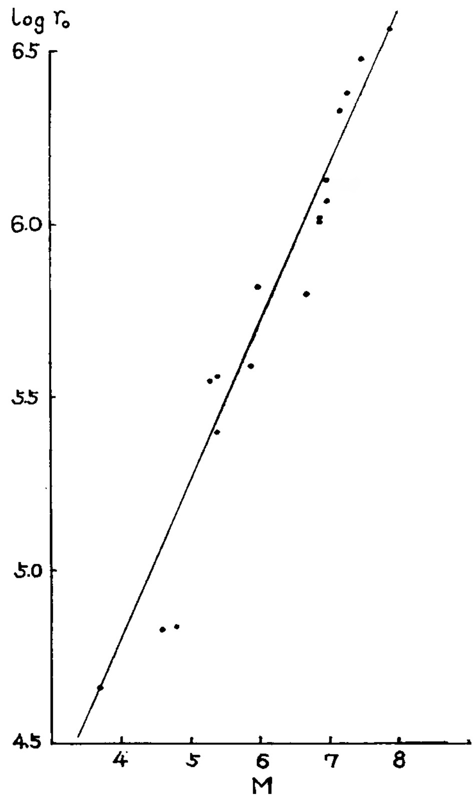

Fig. 3. The relation between the radius of the fault area r_0 and seismic magnitude M. The full line is $\log r_0 = 0.45M + 3.00$.

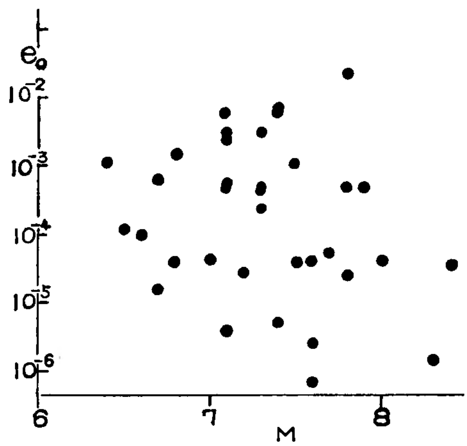

Fig. 4. The relation between the mean e_0 of the maximum strain in the fault area and seismic magnitude M.

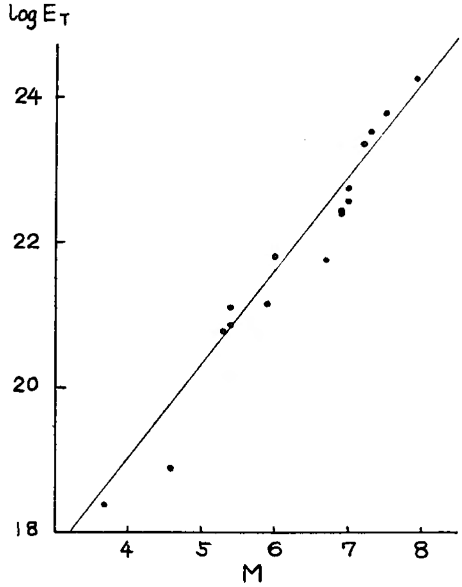

Fig. 5. The relation between the total released elastic energy E_T and magnitude M. The full line is $\log E_T = 1.3M + 13.4$.

$$\log r_0 = (0.45 \pm 0.03)M + (3.00 \pm 0.16). \qquad \text{(II)}$$

In these calculations, the maximum strain is assumed as 10^{-4}. This maximum strain has been estimated by C. Tsuboi [1957], from his study of analysis of the triangular surveyings before and after the great earthquakes. This result is supported also by our calculations as follows. From the relation between the seismic magnitude M and the length of the fault and the equation (4), we have the relation between magnitude M and the mean e_0' of the maximum strain in the fault area as shown in Fig. 4. And we evaluate the round value of the mean strain e_0 as 10^{-4}, too.

The relation between the elastic energy E per unit volume and the maximum main strain e_1 is written as

$$E = (1.5 \sim 7.5)\mu e_1^2, \qquad (7)$$

where μ is the rigidity of the crust.

Let $|e_1| \gg |e_2|$, $|e_3|$ be the usual condition in the seismic area, then we have

$$E = 1.5\mu e_1^2. \qquad (8)$$

Therefore, we may estimate the relation between the maximum energy E_0 and the mean strain e_0 within the fault area as follows,

$$E_0 = 1.5\mu e_0^2. \qquad (9)$$

Estimating that the shear wave velocity and the density of the crust are 2.82 km/sec and 2.7 g/cm^3, respectively, and maximum mean strain e_0 within the fault area be $e_0 = 10^{-4}$, we have the maximum elastic energy E_0 as 3,100 erg/cm^2. Then, we have the total change of the elastic energy E_r in the whole crust during of the earthquake as tabulated in Table 1. The relation between the total energy E_r and the seismic magnitude M in the Table 1 is shown in Fig. 5 and formulated as,

$$\log E_r = (1.3 \pm 0.1)M + (13.4 \pm 0.4). \tag{III}$$

This result is nearly equal to relations obtained by C. F. Richter *et al.* [1956] and M. Båth [1958] as follows,

$$\log E_s = 1.5M + 11.8 \quad : \quad \text{C. F. Richter,}$$

$$\log E_s = 1.44M + 12.24 : \quad \text{M. Båth.}$$

According to these results, the energy E_r estimated from the release of the permanent strain by the abrupt change is equivalent to the energy E_s estimated by radiation as seismic waves from the focus.

The ratio R of the strain energy E_r to the wave energy E_s obtained by Richter is formulated as

$$\log R = \log E_r - \log E_s = 1.63 - 0.17M. \tag{IV}$$

According to this result (IV), E_r is usually larger than E_s because the magnitude M is not larger than 9.6. And also, the larger the magnitude increases, the smaller the ratio becomes.

Let the shape of the fault area be assumed to be a semi-spheroid whose sectional plane is the ground surface and contains the axis, fault, of the revolutional body, and whose longer and shorter axes are equal to the length L of the fault and the depth h of the fault, respectively. And also assume that

$$2r_0{}^3 = Lh^2. \tag{10}$$

K. Iida [1965] has obtained the relation between fault length and seismic magnitude as,

$$M = 0.76 \log L + 2.27. \tag{11}$$

From Iida's formula (11), the assumption (10) and our result (II), we have the relation between the depth h of the fault and the magnitude M as,

$$\log h = 0.045M + 5.27. \tag{V}$$

For example, it gives the depths of the fault as 3.9 km and 4.3 km where the magnitudes M are 7 and 8, respectively.

Finally, the abrupt changes in the crust are of great interest in studying the property of the crust for permanent strain and of the generative forces of earthquakes (Ozawa [1965, 1966]).

We have had a few opportunities to observe these abrupt changes of larger than 10^{-8}, but many such opportunities for those changes of larger than 10^{-9}. Thus, it is necessary to maintain a routine observation in a high sensitivity of more than 10^{-8} or 10^{-9}.

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References

Båth, M., 1958; The energies of seismic body waves and contributions in geophysics, Pergamon, London, **1**, 1-16.

Iida, K., 1965; Earthquake magnitude, earthquake fault and source dimensions, J. Earth Sci., Nagoya Univ., **13**, 115-132.

Ozawa, I., 1949; On the strain of earth-crust observed in Osakayama-tunnel, Bull. Disast. Prev. Res. Inst., Kyoto Univ., **2**, 115-121.

Ozawa, I., 1965; On the observations on the abrupt change of the elastic energy in the crust in the remarkable earthquakes, Spec. Contr. Geophys. Inst., Kyoto Univ., **5**, 125-137.

Ozawa, I., 1966; On the observations of the crustal strains before and after the earthquake near the city of Kyoto, *Zisin* (J. Seism. Soc. Japan), **19**, 217-225.

Richter, C. F. and B. Gutenberg, 1956; Magnitude and energy of earthquakes, Ann. Geof., Roma, **9**, 1-15.

Snnedon, I. N., 1951; *Fourier transforms*, Pergamon, London.

Takemoto, S. and M. Takada, 1969; Moderate earthquakes in the northern part of Kinki district and strain step associated with these earthquakes, *Zisin* (J. Seism. Soc. Japan), **23**, 49-60.

Tsuboi, C., 1957; On the magnitude of earthquakes, *Zisin* (J. Seism. Soc. Japan), **10**, 6-23.

Wideman, C. J. and M. W. Major, 1967; Strain steps associated with earthquakes, Bull. Seism. Soc. America, **57**, 1429-1444.