26. *Seismometrical Study of the Imaichi Earthquake on Dec. 26, 1949.*

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1. Introduction.

On the morning of Dec. 26, 1949, Imaichi, Nikkô and the adjacent villages of Tochigi Pref. were severely shaken at 8 h 17 m and at 8 h 25 m (Japanese Civil Standard Time). The writer executed the seismometrical study of this earthquake. Original seimograms as observed at twelve meteorological stations and at the Earthquake Research Institute, Tokyo University, were analysed by the writer himself. Furthermore, seismological reports from 62 meteorological stations throughout Japan were placed at his disposal. Based on these data, the location of epicentres and the construction of travel-time curves were carried out.

2. Effect of the superficial layer.

At first a tentative epicentre was located as 139° 39.′5 E long. and 36° 41.′9 N lat. by means of arrival times. Travel-time curve of the first earthquake thus constructed showed the assumed epicentre to be fairly satisfactory. Next, the focal depth was tentatively determined by means of the duration of preliminary tremor τ, by the formula;

$$\sqrt{\varDelta^2+h^2}=k\tau$$

where $\varDelta$, h and k denote the epicentral distance, the focal depth and Omori constant respectively. But the values of thus determined from τs at various stations were very divergent. This might have been due not only to oservation errors, but also to the fact that the effect of the superficial low-velocity layer is larger than the effect of the focal depth in case of such shallow earthquake, to say nothing of the mistake of identification of τ, with $\overline{P}-S^*$; $P^*-\overline{S}$; or P^*-S^* instead of $\overline{P}-\overline{S}$. This can be seen from the following considerations. In Fig. (1), d and H indicate the thickness of the superficial (sedimentary) layer and the granitic layer respectively. U and V correspond to the propaga-

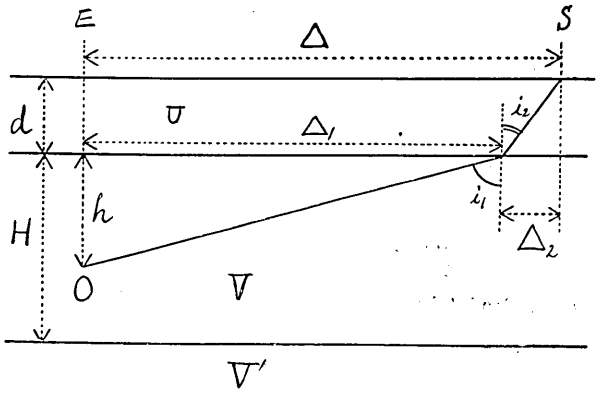

Fig. 1. Model of the earth-crust.
O: Hypocentre; E: Epicentre; S: Station.

tion velocities of seismic waves in the respective layers, while h denotes the part of focal depth in the granitic layer. Epicentral distance Δ is divided into the two parts Δ_1 and Δ_2 as shown in Fig. (1). Then the travel-time of $\overline{P}$- (or $\overline{S}$-) wave is written as follows;

$$\overline{T}=\frac{\sqrt{\Delta_1^2+h^2}}{V}+\frac{d}{U}\cdot\frac{1}{\sqrt{1-r^2\sin^2 i_1}}$$

$$=\frac{\sqrt{\Delta_1^2+h^2}}{V}+\frac{d}{U}\cdot\frac{\sqrt{\Delta_1^2+h^2}}{\sqrt{\Delta_1^2+h^2-r^2\Delta_1^2}},$$

where $$r=U/V=\frac{\sin i_2}{\sin i_1}.$$

$$\therefore\ \overline{T}\fallingdotseq\frac{\sqrt{\Delta_1^2+h^2}}{V}\left\{1+\frac{d}{r}\cdot\frac{1}{\Delta_1}\left(1+\frac{r^2}{2}-\frac{h^2}{2\Delta_1^2}\right)\right\}.$$

Now expanding this formula in terms of h/Δ_1 and neglecting its terms of higher order, we obtain

$$\overline{T}\fallingdotseq\frac{1}{V}\left\{\Delta_1+\frac{d}{r}+\frac{rd}{2}+\frac{1}{2}\frac{h^2}{\Delta_1}\right\}.$$

Since, $\Delta_1=\Delta-\Delta_2$ and $\Delta_2\fallingdotseq rd\left(1+\frac{r^2}{2}-\frac{h^2}{2\Delta_1^2}\right)$,

we have $$\overline{T}\fallingdotseq\frac{1}{V}\left\{\Delta+\frac{2-r^2}{2r}d+\frac{1}{2}\frac{h^2}{\Delta_1}\right\}\quad\cdots\cdots\cdots(1)$$

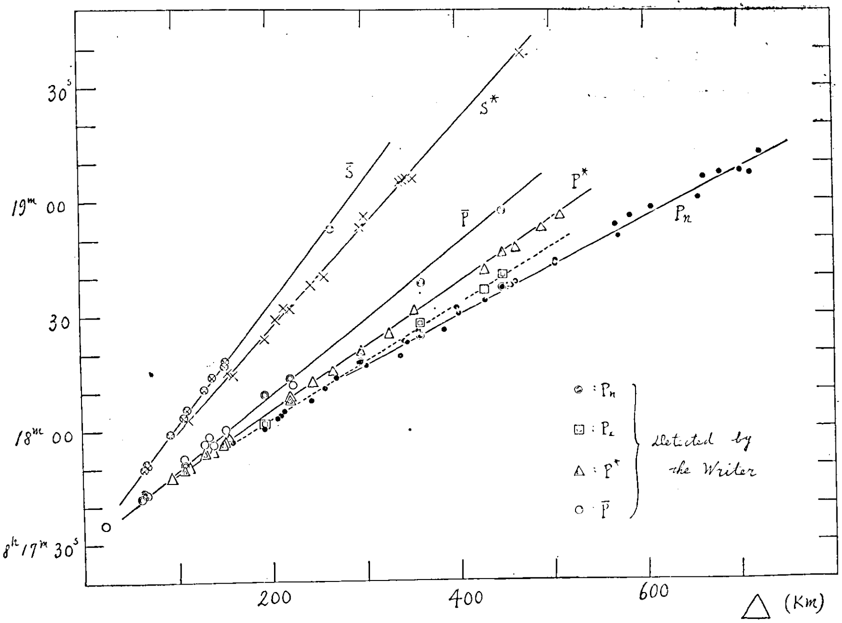

Fig. 2. Travel-time curves of the first shock.

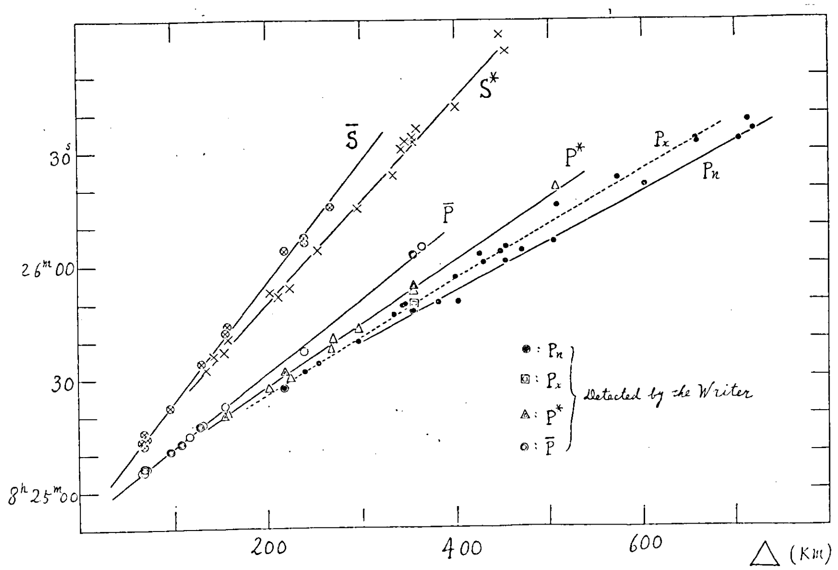

Fig. 3. Travel-time curves of the second shock.

According to Prof. T. Matuzawa,1) U_P=1.94 km/s, U_S=1.14 km/s, V_P=5.0 km/s, V_S=3.15 km/s and d=3.83 km in the Kwantô Plain. Here, suffixes

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1) T. MATUZAWA and T. FUKUTOMI, *Bull. Earthq.Res. Inst.*, 10 (1932), 511.

P and S denote the longitudinal and distortional waves respectively. Then, $r_P=0.384$ and $r_S=0.368$, their mean value being about 0.37. Assuming here $r=0.37$ and $d=4$ km for simplicity's sake, we have

$$\frac{2-r^2}{2r}\,d=10.1\,(km),$$

whereas $\frac{1}{2}\,\frac{h^2}{\Delta_1}=1\,(km)$,

provided $h=10$ km, even at the distance $\Delta_1=50$ km. From this we know that the effect of the superficial layer is greater than the effect of the focal depth, and the necessity to consider the former effect in the determination of the hypocentre will now be apparent.

3. Location of epicentre.

For the location of epicentre ,we may calculate those values of φ (latitude), λ (longitude), V (velocity) and T_0 (origin time); the effect of the superficial layer $\frac{2-r^2}{2r}\,d$ is included in T_0 as a constant term.

If we denote the deviation of φ, λ, V and T_0 as $\delta\varphi$, $\delta\lambda$, δV and δT, observation equation is written as follows;

$$\frac{1}{V}\,\frac{\partial\Delta}{\partial\varphi}\,\delta\varphi+\frac{1}{V}\,\frac{\partial\Delta}{\partial\lambda}\,\delta\lambda-\delta T-\frac{t}{V}\,\delta V=m\,, \quad\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where t and m are substituted for $T-T_0$ and $t-\frac{\Delta}{V}$ respectively.

In the case of the first shock, it was difficult to identify the arrival time of $\overline{P}$, whereas $\overline{S}$ was very clear to the near stations. Assuming $\varphi=36^\circ\ 41.'9$, $\lambda=139^\circ\ 39.'5$, $V_S=3.15$ km/s, $T_0=17$ m28.7s, the method of least squares was applied to obtain the most probable values of φ, λ, V_S and T_0. P^*-wave, also, appeared clearly. As to the second shock, $\overline{P}$-wave was distinct, but P^* and $\overline{S}$ were not so clear. The bands of time variation of P_n-wave were rather broad in both the first shock and the second. Owing to the feebleness of P_n-wave, many stations seem to have overlooked it and reported P_x as P_n. For example, the seismograms of Morioka as examined by the writer, show P_x-phase distinctly, especially in the vertical movements, 2.0 sec. later than the very feeble movement of P_n.

The epicentre of the first shock was located independently from P^* as well as from $\overline{S}$ and obtained the fairly concordant results as shown in Table

Table 1. Data used to locate the epicentre.

Tentative epicentre $\begin{cases} 36^\circ\ 41.'9 \text{ N lat.} \\ 139^\circ\ 39.'5 \text{ E long.} \end{cases}$

Station	Δ	$\frac{\partial\Delta}{\partial\phi}$	$\frac{\partial\Delta}{\partial\lambda}$	1st shock		2nd shock
				P^*	$\bar{S}$	$\bar{P}$
Maebashi	km 62.4	0.5290	0.6804	m s 17 41.9	——	——
Kumagaya	65.7	0.9315	0.3026	——	——	m s 25 06.4
Tsukuba	66.6	0.8010	−0.4771	42.4	m s 17 49.7	05.2
Shirakawa	68.0	−0.6860	−0.5835	——	50.9	05.3
Kakioka	69.8	0.7388	−0.5409	42.9	51.3	06.1
Chichibu	94.7	0.8377	0.4379	47.2	59.1	10.9
Oiwake	106.9	0.3742	0.7444	——	——	12.8
Tokyo (E.R.I.)	110.1	0.9963	−0.0714	49.2	18 03.7	——
Tokyo (C.M.O.)	113.0	0.9970	−0.0643	50.5	05.4	15.0
Onahama	113.6	−0.2363	−0.7790	49.9	——	——
Nagano	130.1	0.0195	0.8016	53.5	10.6	17.6
Takada	133.0	−0.3426	0.7526	——	——	17.8
Fukushima	137.1	−0.8551	−0.4155	53.9	13.8	——
Chôshi	152.5	0.6991	−0.5734	56.6	16.9	22.9
Kofu	153.7	0.7666	0.0514	——	18.2	——

(2). The epicentre of the second shock which were located from the arrival time of $\bar{P}$ coincided with the macroseismic data. It was situated in the western outskirts of Imaichi where the largest acceleration in this earthquake was experienced.

To evaluate the focal depth, the differences of intercept time between the direct waves ($\bar{P}$ or $\bar{S}$) and the refracted waves (P^* or S^*) were used.

The travel-time of the refracted wave T^* is written in the form,

$$T^* = \frac{\Delta}{V'} + \frac{(2H-h)\cos i}{V} + \frac{d}{r}\frac{\sqrt{1-r^2R^2}}{V}, \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where V' means the velocity in the intermediate (basaltic) layer, and $R = \sin i = V/V'$. Taking the difference of the values of the equations (1) and (3), at $\Delta = 0$, we have

$$T^* - \bar{T} = \frac{(2H-h)\cos i}{V} + \left(\sqrt{1-r^2R^2} - \frac{2-r^2}{2}\right)\frac{d}{rV}.$$

Now that $\sqrt{1-r^2R^2} - \frac{2-r^2}{2} = 0.02$, and therefore may be neglected, when $r=0.37$ and $R=0.85$.

$$\therefore \quad T^* - \overline{T} \doteqdot \frac{(2H-h)\cos i}{V}.$$

Table 2. Results obtained by the method of least squares.

	The first shock		The second shock
	By the arrival times of		
	$\overline{S}$	P^*	$\overline{P}$
$\delta\varphi$	$-0'.837 \pm 0'.120$	$+0'.171 \pm 1'.095$	$+1'.743 \pm 0'.436$
$\delta\lambda$	$+0'.351 \pm 0'.226$	$+1'.503 \pm 1'.357$	$-0'.715 \pm 0'.557$
δV (km/s)	-0.334 ± 0.320	-0.103 ± 0.240	-0.0531 ± 0.0743
δT (sec.)	-0.0318 ± 0.0146	$+0.276 \pm 1.901$	$+0.578 \pm 0.858$
$\varphi \left(\begin{smallmatrix}N\\ \text{lat.}\end{smallmatrix}\right)$	$36°\ 41'.06 \pm 0'.12$	$36°\ 42'.1 \pm 1'.1$	$36°\ 43'.6 \pm 0'.4$
$\lambda \left(\begin{smallmatrix}E\\ \text{long.}\end{smallmatrix}\right)$	$139°\ 39'.85 \pm 0'.23$	$139°\ 41'.0 \pm 1'.4$	$139°\ 38'.8 \pm 0'.6$
V (km/s)	3.118 ± 0.015	6.00 ± 0.24	5.05 ± 0.074
T	17m $29.05\text{s} \pm 0.33\text{s}$	17m $31.32\text{s} \pm 1.90\text{s}$	24m $51.92\text{s} \pm 0.86\text{s}$

Intercept time (T_o) of

$\overline{P}$	P^*	S^*	P^*	S^*	$\overline{S}$
17m $29^{s}.31 \pm 0^{s}.92$	$31^{s}.33 \pm 0^{s}.29$	$32^{s}.25 \pm 0^{s}.64$	24m $54^{s}.33 \pm 0^{s}.71$	$55^{s}.58 \pm 0^{s}.62$	$51^{s}.48 \pm 0^{s}.59$

Velocity of S^*: 3.689 ± 0.016 (km/s)

For the longitudinal wave of the first shock,

$(T^*-\overline{T})_P = 17\text{ m } 31.32\text{ s} - 17\text{ m } 29.31\text{ s} = 2.01\text{s}$,

$\therefore \quad 2H-h=18.8$ (km).

For the distortional wave of the first shock,

$(T^*-\overline{T})_S = 17\text{ m } 32.25\text{ s} - 17\text{ m } 29.05\text{ s} = 3.20\text{ s}$,

$\therefore \quad 2H-h=18.7$ (km).

The mean value of $2H-h=18.8$ (km).

Similarly, for the second shock,

$(T^*-\overline{T})_P = 24\text{ m } 54.33\text{ s} - 24\text{ m } 51.92\text{ s} = 2.41\text{ s}$,

$\therefore \quad 2H-h'=22.6$ (km),

$(T^*-\overline{T})_S = 24\text{ m } 55.58\text{ s} - 24\text{ m } 51.48\text{ s} = 4.10\text{ s}$,

Table 3. Data used to determine the intercept time.

Station	1st shock				2nd shock			
	Δ	$\bar{P}$	P^*	S^*	Δ	P^*	S^*	$\bar{S}$
	km	m s	m s	m s	km	m s	m s	m s
Shirakawa	68.9	——			66.4			25 13.4
Maebashi	63.0	17 41.9			64.3			
Tsukubasan	64.7	42.4			69.3			
Kakioka	68.0	42.9			72.4			14.4
Kumagaya	65.0	43.5			68.9			
Chichibu	94.1		17 47.2		97.3			22.7
Tokyo (E.R.I.)	108.4	51.0	49.2		113.3			
Onahama	113.2		49.9		113.1			
Tokyo (C.M.O.)	111.4		50.5		117.2			
Nagano	129.0		53.5		127.6			
Fukushima	138.1		53.9		134.7		25 32.4	
Yokohama	139.4	56.-			144.2			
Niigata	149 2		55.8		144.3		36.1	
Chôshi	151.0		56.6		155.3			42.2
Kôfu	152.0	18 00.2			154.8	25 20.4	37.3	
Matsumoto	159.8			18 14.5	158.4	21.1		
Funatsu	154.7		57.8		158.1	20.7		
Takada	134.2	17 58.5			131.2			
Aikawa	193.8	18 09.5		24.-	189.3			
Sendai	206.8			29.2	203.4	27.4	52.8	
Ōshima	214.8			32.2	219.4			
Toyama	221.1	13.7	18 07.7		219.3	31.7		
Shizuoka	221.5		08.-	32.0	224.9	30.-		
Takayama	224.3	12.0			224.2			
Ishinomaki	243.7			38.1	240.6			
Sakata	245.0		12.5		240.3			26 07.2
Wajima	257.6			40.4	254.8		26 04.0	
Omaezaki	266.3		15.2		269.7	40.6		
Nagoya	296.0		20.7	53.2	297.5		15.0	
Mizusawa	301.1			56.-	297.3	43.-		
Irako	325.8		25.-		328.1			
Akita	339.3			19 04.9	334.7			
Tsuruga	343.0			05.4	344.1		30.7	
Hikone	345.7			05.8	346.6		32.6	

(to be cotinued)

Table 3. (continued)

Station	1st shock				2nd shock			
	Δ	$\overline{P}$	P^*	S^*	Δ	P^*	S^*	$\overline{S}$
	km	m s	m s	m s	km	m s	m s	m s
Kameyama	353.6			19 05.8	355.2	25 52.8	26 33.7	
Morioka	360.1	18 38.5			356.1	54.4	32.5	
Tsu	357.7				359.5			
Owase	428.5		18 41.5		430.7			
Osaka	448.-	57.5	46.2		449.-			
Kôbe	462.0		47.5		472.0			
Wakayama	490.4		52.7		491.8			
Tottori	509.5		56.0		509.2			
Shionomisaki	505.1				507.5	26 20.6		
Kanazawa	269.7				268.1	25 38.0		

$$\therefore \quad 2H-h'=23.8\ (\text{km}).$$

The mean value of $2H-h'=23.2$ (km).

Then $h>h'$, and $h-h'=23.2-18.8=4.4$ (km). The values of H, h and h' which satisfy $2H-h=18.8$ and $2H-h'=23.2$ are listed in Table (4). The accurate values of h and h' could not be determined, but h may be about 15 km and h' may perhaps be 10 km.

Table 4.

h'	h	H
km	km	km
0	4.4	11.6
2	6.4	12.6
4	8.4	13.6
6	10.4	14.6
8	12.4	15.6
10	14.4	16.6
12	16.4	17.6
14.4	18.8	18.8

Discussions concerning P_n and P_x will be held at some future date.

Summary.

Considering the effect of the superficial layer, the location of epicentres was executed by means of the method of least squares, using the arrival times of $\overline{S}$ and P^* of the first shock and of $\overline{P}$ of the second. The epicentre of the first shock was obtained at a situation about 4.5 km southwards Imaichi. The second epicentre was located at a position in the western outskirts of Imaichi, about 5 km NNW from the first epicentre.

The focal depth of the former may be 15 km or so, and the latter's depth may be a few kilometers shallower than the former.

In conculsion, the writer wishes to express his sincere thanks to Professor

H. Kawasumi who gave him kind advices and Dr. W. Inouye, the head of the Seismometrical Section of C. M. O. and the other members of the section who offered him every facility for analysing the seismograms.

26. 今市地震の計測

地震研究所　越川善明

淺い地震を稍々遠い所で觀測した結果に基いて震源の深さを求めようとする場合，表面の低速度層の影響が大きいということを考察した．次に發震時を用いて最小自乘法によつて震央の決定を行つた．第一の地震については P^* 波と $\overline{S}$ 波との發震時を用いて別々に震央を定めたが，よく一致する結果が得られた．その震央位置は落合村長畑附近となつた．第二震はこれより北北西約 5km で，今市町の西端の邊りになる．深さは正確には定め得ないが第一震は 15km 位，第二震はそれより 4～5km 淺いということを，走時曲線の震央における時間差から求めた．所謂花崗岩層の厚さは 17 km 前後と考えられる．

花崗岩層及び玄武岩層における縦波，横波の傳播速度は次の樣に求められた．(單位は km/s).

$\overline{P}$: 5.05；　$\overline{S}$: 3.12；　P^*: 6.00；　S^*: 3.69．