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61. Observation of Strong Earthquake Motions in Matsushiro Area. Part 1. (Empirical Formulae of Strong Earthquake Motions)

By

Kiyoshi KANAI, Kintaro HIRANO, Shizuyo YOSHIZAWA
and Tetsutaro ASADA,

Earthquake Research Institute.

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In the beginning of September 1965, the Strong Motion Seismograph Observation Center, Earthquake Research Institute, began the observation of strong earthquake motions in Matsushiro earthquake swarm* area.

The locations of the temporary stations where strong motion seismographs are installed are shown in Fig. 6, details of the location of the stations (in Japanese) as well as the period of observation at each station are tabulated in Table 2.

The characteristics of the strong motion seismographs used in the

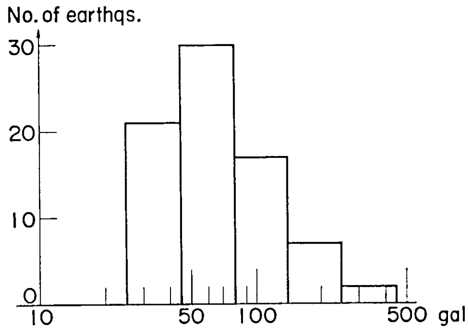


Fig. 1a. Hoshina. Number of earthquakes versus maximum recorded accelerations.

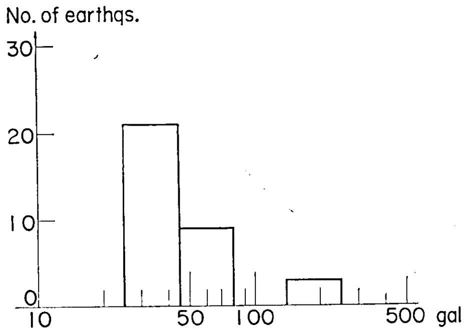


Fig. 1b. Wakaho. Number of earthquakes versus maximum recorded accelerations.

*) According to an announcement from the Matsushiro Seism. Obs., J. M. A., the total number of earthquakes recorded by a sensitive seismograph and of felt earthquakes were 400,714 and 39,433, respectively, during the period from Aug. 3, 1965 to June 14, 1966. Moreover, the earthquake swarm is still active.

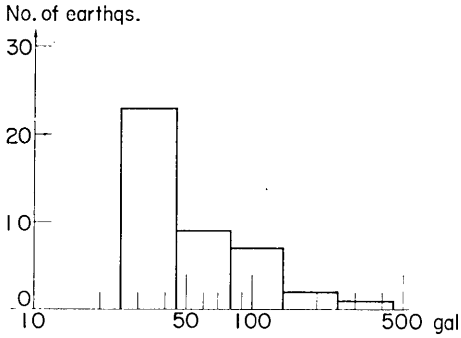


Fig. 1c. Matsushiro C. Number of earthquakes versus maximum recorded accelerations.

present investigations are shown in Table 3. The results of the strong earthquake motions recorded at the stations up to June 11, 1966 are tabulated in Table 4. Number of eathquakes versus maximum recorded accelerations obtained at Hoshina, Wakaho and Matsushiro C are shown in Fig. 1. As seen in Table 4 as well as Fig. 1, the value of the largest acceleration was more than 500 gals[+] and the number of earthquake motions in which the maximum accelerations were more than 200 gals was 9. Nevertheless, the damage to wooden houses caused by all the earthquakes has been very slight as shown in Table 1.

One of the important conclusions from the facts mentioned above, that is, the maximum accelerations of the earthquakes were very large and the earthquake damage to wooden houses very slight, is considered as forming the basis for calculating the necessary conditions of earthquake motions for causing the complete collapse of old Japanese-style wooden houses, this being the estimated displacement amplitudes of ground movement of about 1 cm$-$3 cm[1)]. However, the values of the large actual

+) The value should become reduced with regard to the vibration characteristics of the seismograph, because the apparent period of the waves is nearly equal to the proper period of pendulum.

1) T. SAITA, "Studies on the Seismic Vibrations of Wooden Houses," *Rep. No. 14 Sub-Committee, Japan Soc. Prom. Sci. Res.*, No. 1 (1934-1937), 60-76, (in Japanese).

T. SAITA, "Experiments in the Vibration and Destruction of Wooden Dwelling Houses," *Bull. Earthq. Res. Inst.*, **17** (1939), 152-167, (in Japanese).

M. SUZUKI, "Studies on the Earthquake Proofing of Wooden Structures," Feb., 1961, (in Japanese).

Teable 1. Earthquake damage to dwelling houses.

Earthquake	1965	1966					
	Nov. 22	Jan. 23, Feb. 7, Apr. 1	Apr. 5	Apr. 11	Apr. 17	May 6, May 20	May 28
Partially destroyed houses	0		4	0	0	0	0
Slightly damaged sections of houses	744		1,345	823	191	59	961

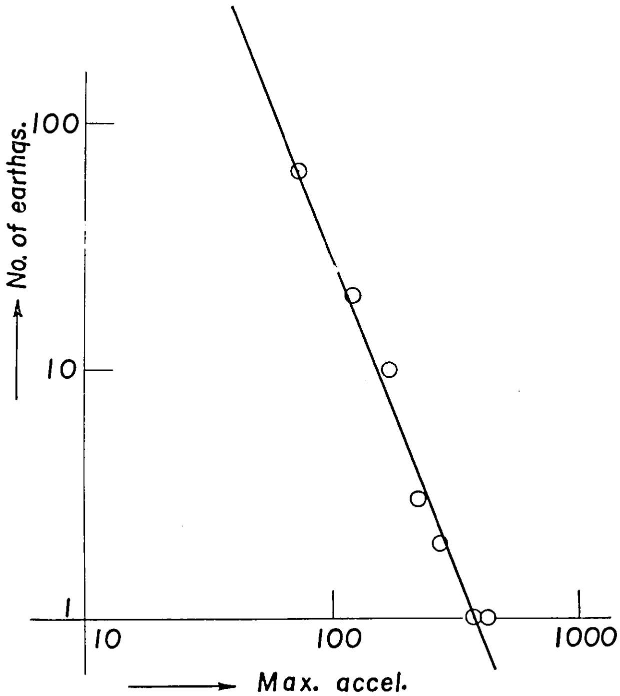


Fig. 2. Total number of earthquakes versus maximum recorded accelerations in gal obtained at six stations.

earthquake motions estimated roughly after the records of the strong motion seismographs were about 0.1 cm – 0.5 cm.

Anyway, the reason of the relation between the large acceleration and the slight damage to property remains to be treated as one of the most important problems on earthquake engineering in future.

Typical records of four destructive earthquakes are represented in Figs. 7–10. The fact in which the horizontal amplitudes of earthquake motions recorded at the environs of epicenters are about ten times the vertical ones, as seen in Figs. 7–10, is an interesting problem to be thoroughly investigated.

Next, total number of earthquake motions versus maximum recorded accelerations obtained at six stations, namely, Matsushiro C, Hoshina A and B, Wakaho, Kawanakajima, Sakaki and Mashima, are shown in Fig. 2. Using Fig. 2, we obtain the following relation, that is, $N(a)=150{,}000\ a^{-2.5}$, in which $N(a)$ is the number of earthquakes per month with maximum acceleration between a gals and $a+50$ gals.

Empirical formulae for the spectra of strong earthquake motions

An empirical formula for the maximum acceleration of strong earthquake motions in the cases of moderate distant earthquakes has been obtained as follows[2]:

$$a_{max}=\frac{5}{\sqrt{T_G}}\cdot 10^{0.61M-1.73\log_{10}x+0.13} \qquad (1)$$

in which, T_G, M and x represent predominant period of ground in sec, Richter magnitude and hypocentral distance in km.

In order to get the same kind of empirical formula in the cases of very near earthquakes by using the present data, Eq. (1) will be rewritten as follows:

$$\log_{10}\left(\frac{a_{max}\sqrt{T_G}}{5}\right)=0.61M-P\log_{10}x+Q\,. \qquad (1')$$

By applying the data of a_{max}, T_G, x and M at Hoshina A and Wakaho

2) K. KANAI, "A Study of Strong Earthquake Motions," *Bull. Earthq. Res. Inst.*, **36** (1958), 295–310.

ditto, "An Empirical Formula for the Spectrum of Strong Earthquake Motions," *ditto*, **39** (1961), 85–95.

in the cases of Apr. 5 and Apr. 1 earthquakes in Eq. (1′), we get

$$a_{max}=\frac{5}{\sqrt{T_G}}\cdot 10^{0.61M-2.35\log_{10}x-0.186}\,. \qquad (2)$$

Combining Eq. (1) with (2) yeilds the following empirical formula for the maximum acceleration of strong earthquake motions in the range of distance from epicenter to a few hundreds kilometers:

$$a_{max}=\frac{5}{\sqrt{T_G}}\cdot 10^{0.61M-P\log_{10}x+Q} \qquad (3)$$

in which

$$P=1.66+\frac{3.60}{x}\,, \qquad Q=0.167-\frac{1.83}{x}\,. \qquad (4)$$

Fig. 3 shows the values of P and Q calculated by Eq. (4). In this figure, the terms of Eq. (1) and Eq. (2) represent the values of P and Q calculated by Eq. (1) and Eq. (2), respectively.

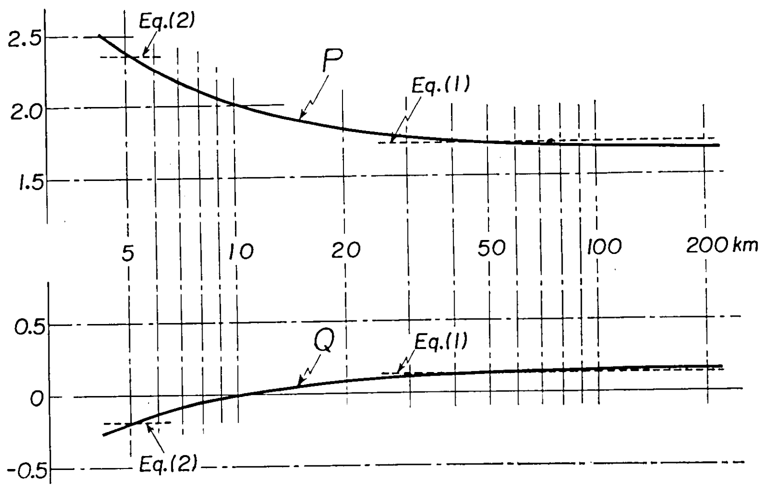
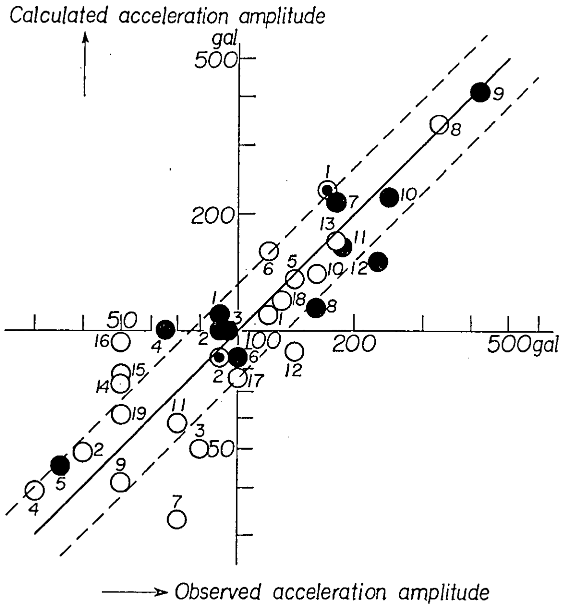


Fig. 3. Values of P and Q calculated by Eq. (4).

The comparison of the values of observed maximum acceleration with the values calculated by Eqs. (3) and (4) is shown in Fig. 4. In Fig. 4,



●

1:	XI	13, '65	Hoshina		2:	XI	21, '65	Hoshina
3:	I	3 '66	〃		4:	I	23, '66	〃
5:	I	23, '66	Wakaho		6:	II	7, '66	〃
7:	IV	1, '66	Hoshina		8:	IV	1, '66	Wakaho
9:	IV	5, '66	〃		10:	IV	5, '66	〃
11:	IV	17, '66-1	〃		12:	IV	17, '66-2	Hoshina

⊙

1:	VI	16, '64	Niigata	2:	VI	16, '64	Akita

○

1:	III	10, '33	Vernon	2:	III	10, '33	Los Angeles
3:	X	2, '33	〃	4:	X	2, '33	〃
5:	XII	30, '34	El Centro	6:	X	31, '35	Helena
7:	IX	11, '38	Ferndale	8:	V	18, '40	El Centro
9:	II	9, '41	〃	10:	VI	30, '41	Santa Barbara
11:	X	3, '41	〃	12:	III	9, '49	Hollister
13:	IV	13, '49	Olympia	14:	IV	13, '49	Seattle
15:	III	22, '57	Alexander	16:	III	22, '57	S. Pacific
17:		〃	State Bldg.	18:		〃	Golden Gate
19:		〃	Oakland				

Fig. 4. Observed maximum accelerations versus the values calculated by Eqs. (3) and (4).

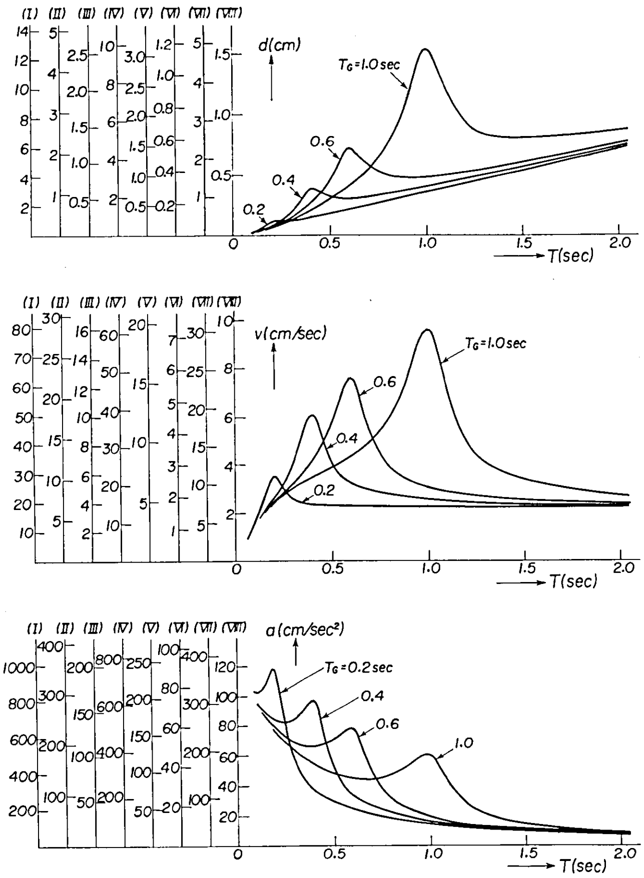


Fig. 5. Calculated acceleration spectra at ground surface.
(I): M=8, x=50 km, (II): M=8, x=100 km, (III): M=8, x=150 km,
(IV): M=7, x=20 km, (V): M=7, x=50 km, (VI): M=7, x=100 km,
(VII): M=6.5, x=20 km, (VIII): M=6.5, x=50 km.

broken lines represent the range of the average error of M, ± 0.2. It can be said from Fig. 4 that, the coincidence of the observed and the calculated values is very good.

Thus, utilizing the results of the previous paper[3] we can easily get the displacement (d_0 and d), the velocity (v_0 and v) and the acceleration

3) *loc. cit.*, 2).

(a_0 and a) spectra of earthquake motions at bed rock and ground surface as follows:

$$d_0=\frac{T}{(2\pi)^2}\cdot 10^{0.61M-P\log_{10}x+Q}\,, \tag{5}$$

$$v_0=\frac{1}{2\pi}\cdot 10^{0.61M-P\log_{10}x+Q}\,, \tag{6}$$

$$a_0=\frac{1}{T}\cdot 10^{0.61M-P\log_{10}x+Q}\,, \tag{7}$$

$$d=G(T)\cdot d_0\,,\quad v=G(T)\cdot v_0\,,\quad a=G(T)\cdot a_0\,, \qquad (8)\ (9),\ (10)$$

in which

$$G(T)=\frac{1}{\sqrt{\left\{1-\left(\frac{T}{T_G}\right)^2\right\}^2+\left\{\frac{0.2}{\sqrt{T_G}}\cdot\frac{T}{T_G}\right\}^2}} \tag{11}$$

or

$$G(T)=1+\frac{1}{\sqrt{\left[\frac{1+\alpha}{1-\alpha}\left\{1-\left(\frac{T}{T_G}\right)^2\right\}\right]^2+\left\{\frac{0.3}{\sqrt{T_G}}\cdot\frac{T}{T_G}\right\}^2}} \tag{11'}$$

P, Q being the same as Eq. (4) and α is the impedance ratio of surface layer to lower medium.

In order to serve as a reference, the displacement, the velocity and the acceleration spectra at ground surface in the cases where $T_G=0.2$, 0.4, 0.6, 1.0 sec, $x=20$, 50, 100 km and $M=6.5$, 7, 8 besides the condition where $\alpha=1/5$ (in this case, the value of α has a slight influence upon the amplitude of the resonance condition) are calculated by using Eqs. (8)-(10) and (11′). The results are shown in Fig. 5.

In conclusion, we wish to express our sincere thanks to Dr. T. Hagiwara, Director of ERI, and Akashi Seisakusho Ltd. for their contributions in making two strong-motion seismographs available to us. Our thanks are also due to the occupiers of the temporary stations and Messers. S. Saito, M. Shibano and I. Karakama for their cooperation in the present investigations.

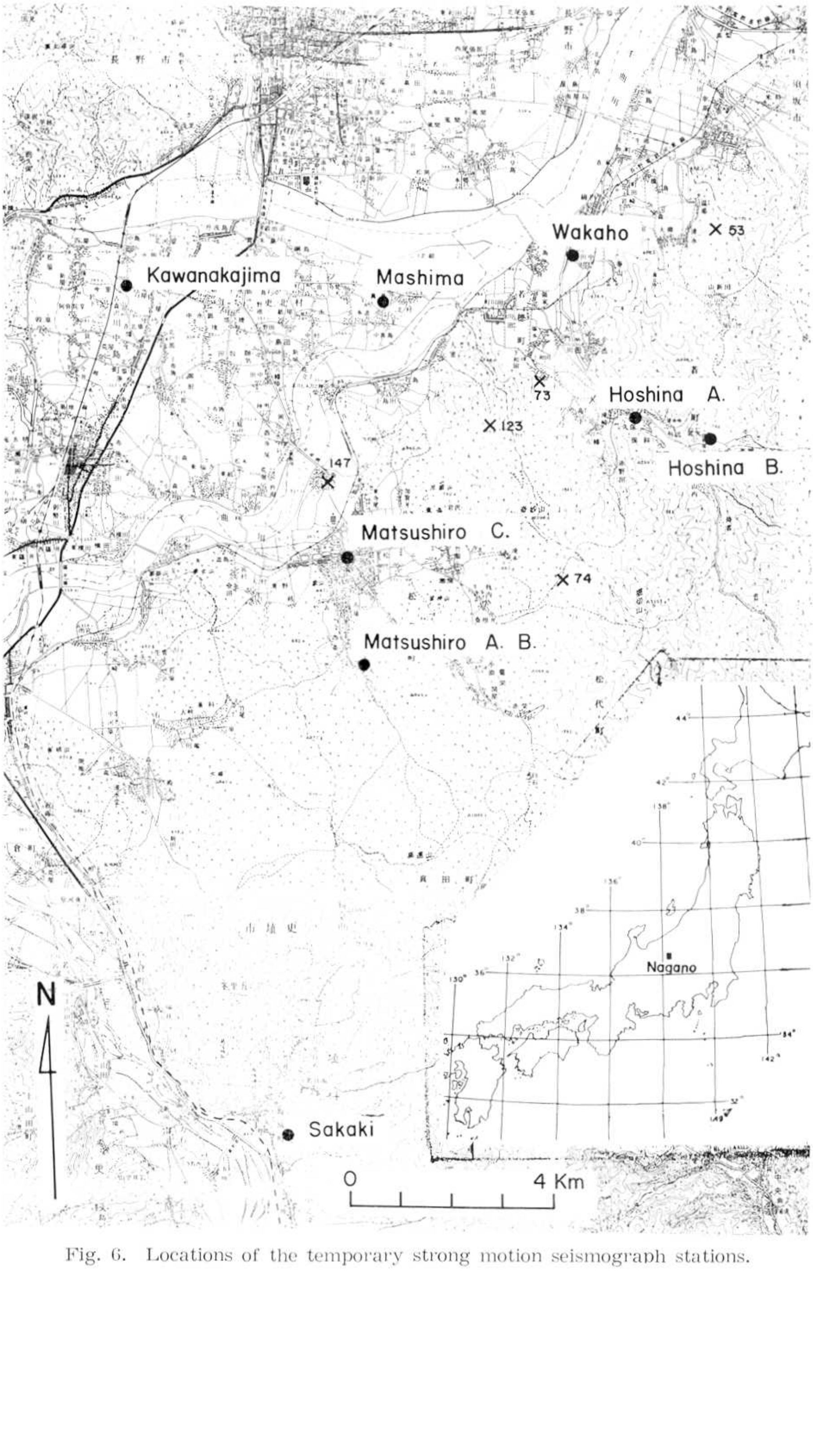


Fig. 6. Locations of the temporary strong motion seismograph stations.

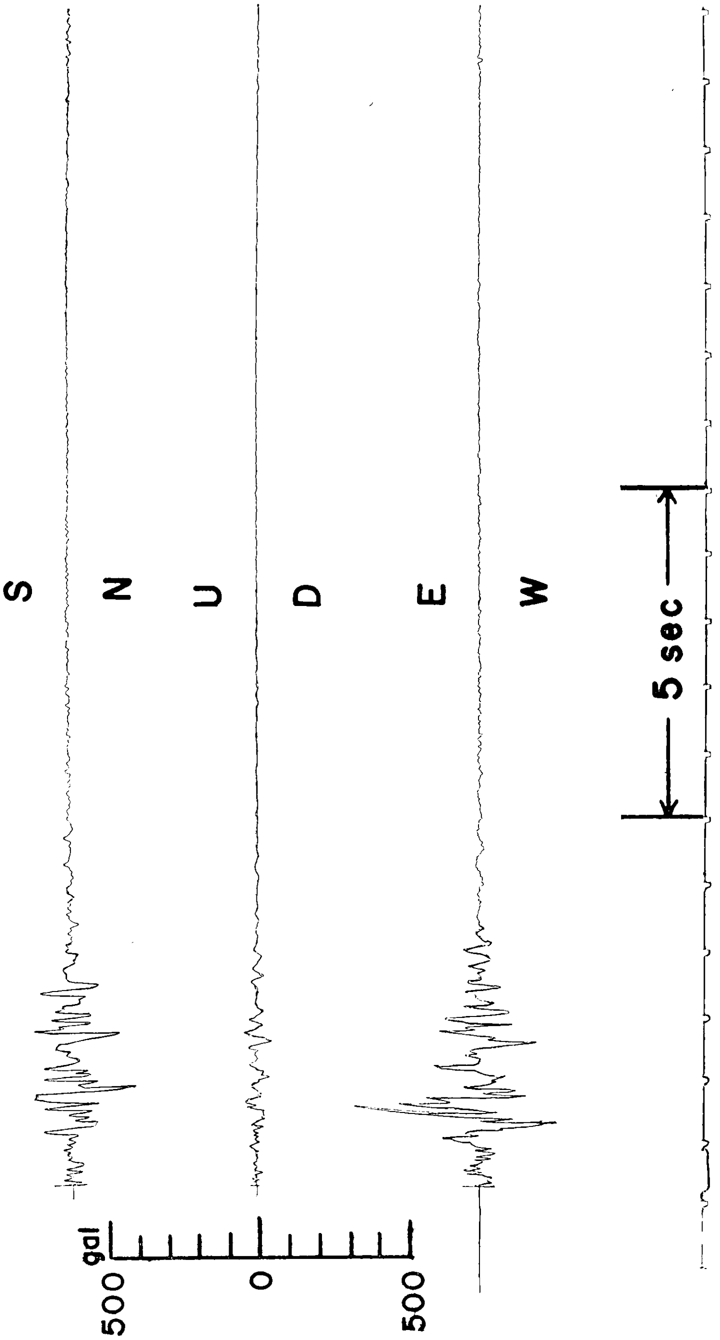


Fig. 7a. No. 53, Apr. 5, 1966. DC-3C, Hoshina A.

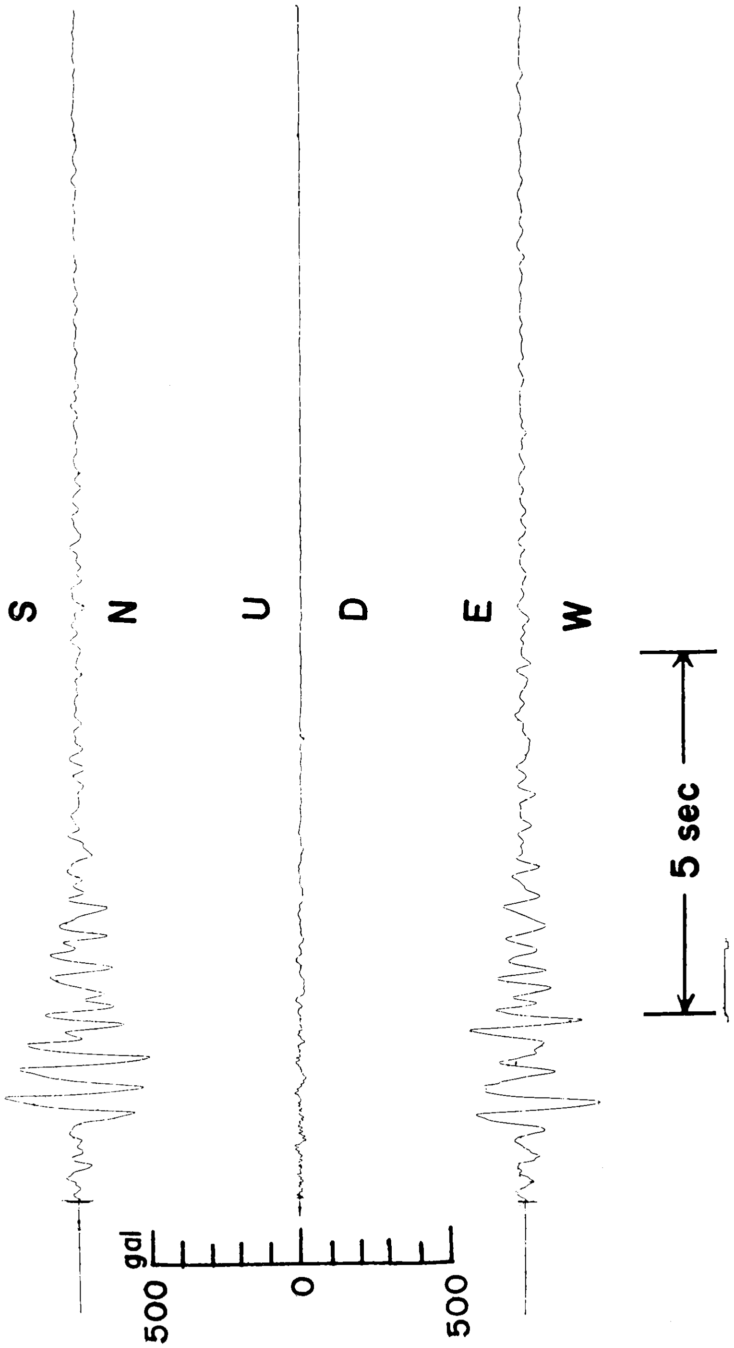


Fig. 7b. No. 53, Apr. 5, 1966. DC-3C Wakaho.

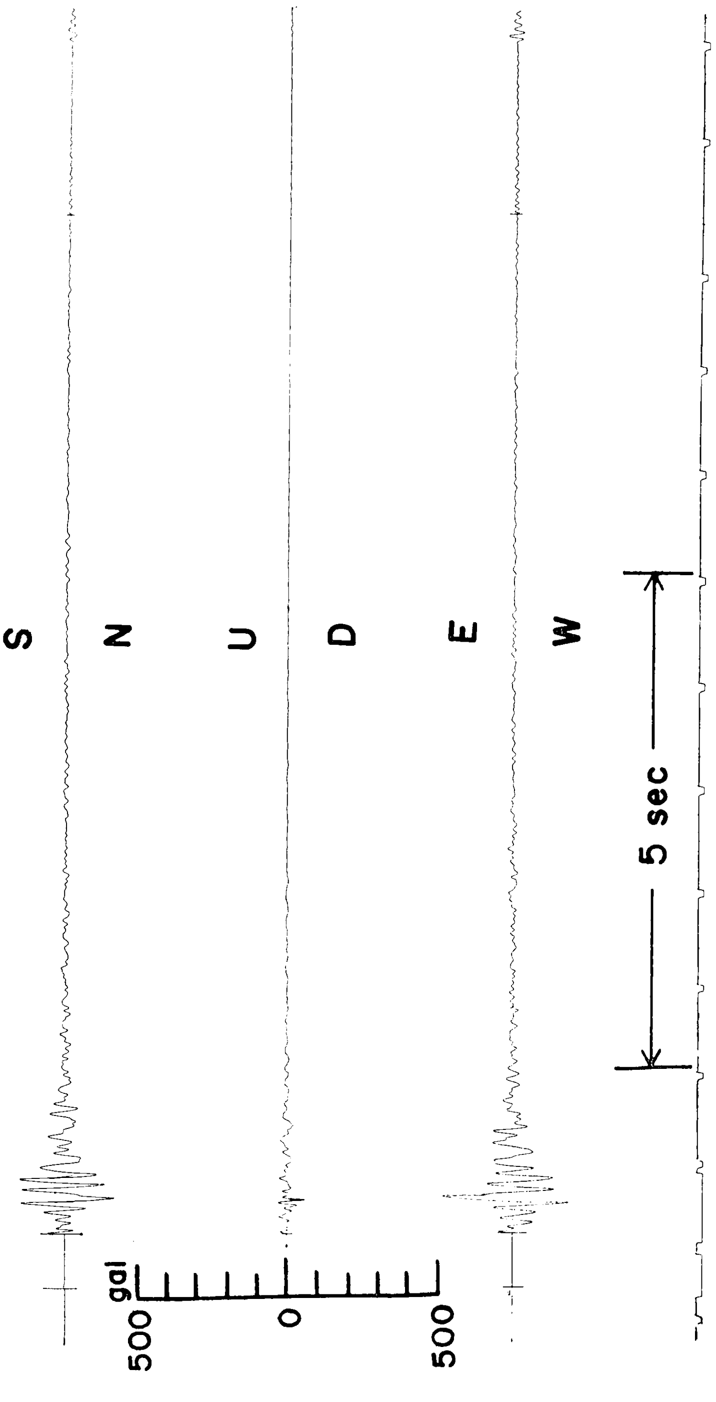


Fig. 9a. No. 123, May 20, 1966. DC-3C, Hoshina A.

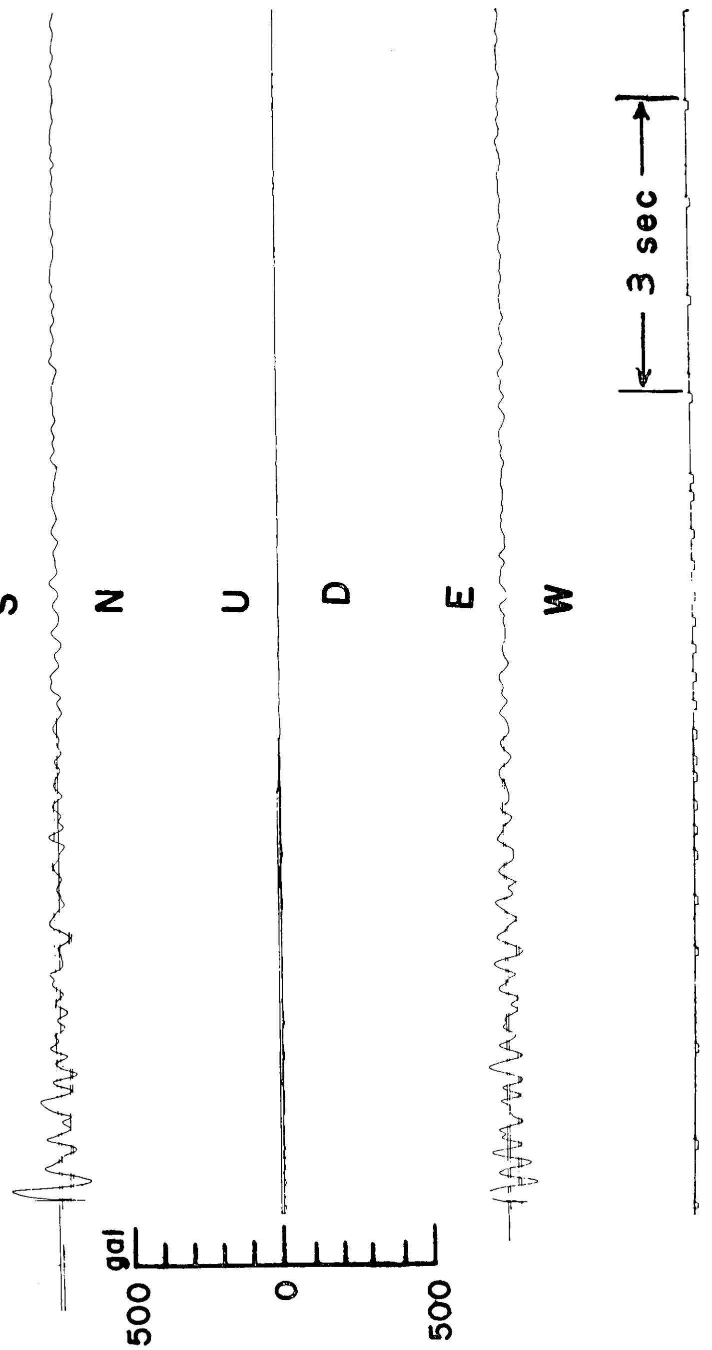


Fig. 9b. No. 123, May 20, 1966. DC-3C, Wakaho.

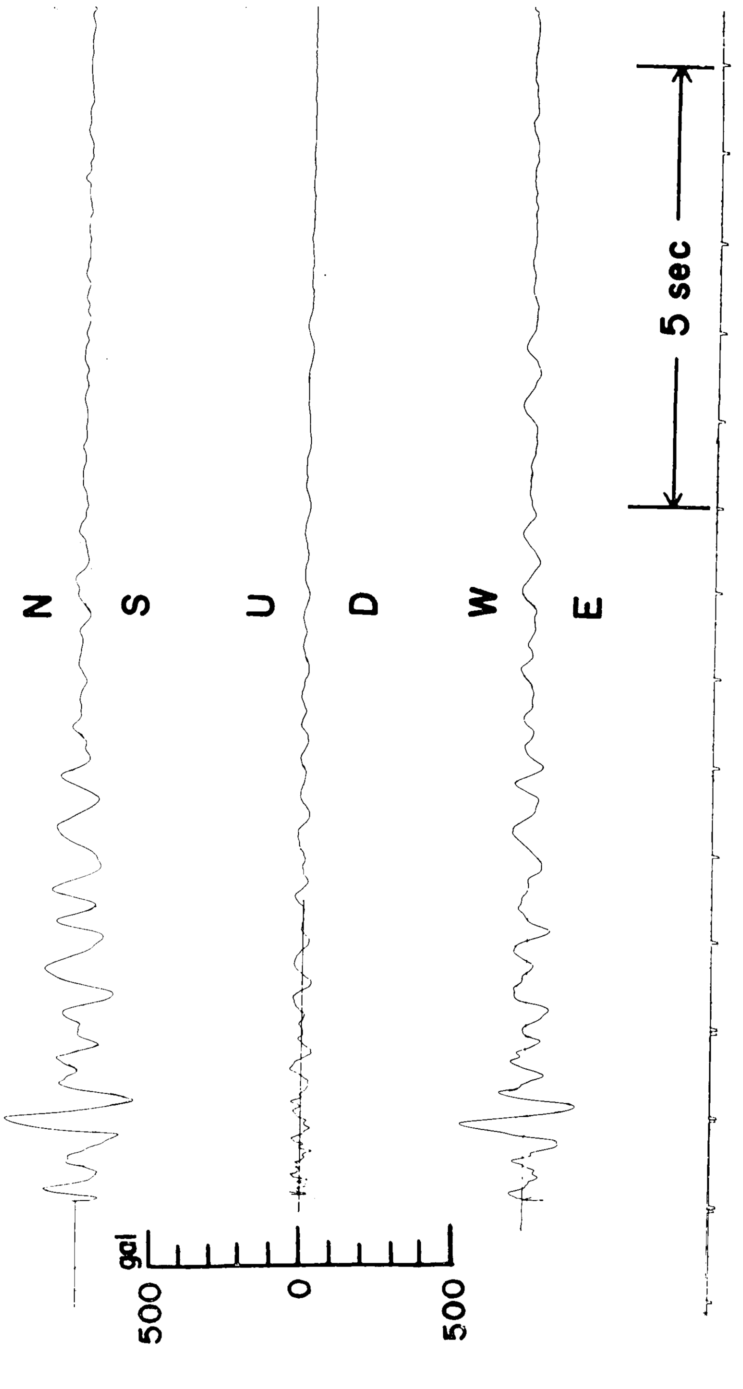


Fig. 9c. No. 123, May 20, 1966. DC-3C, Matsushiro C.

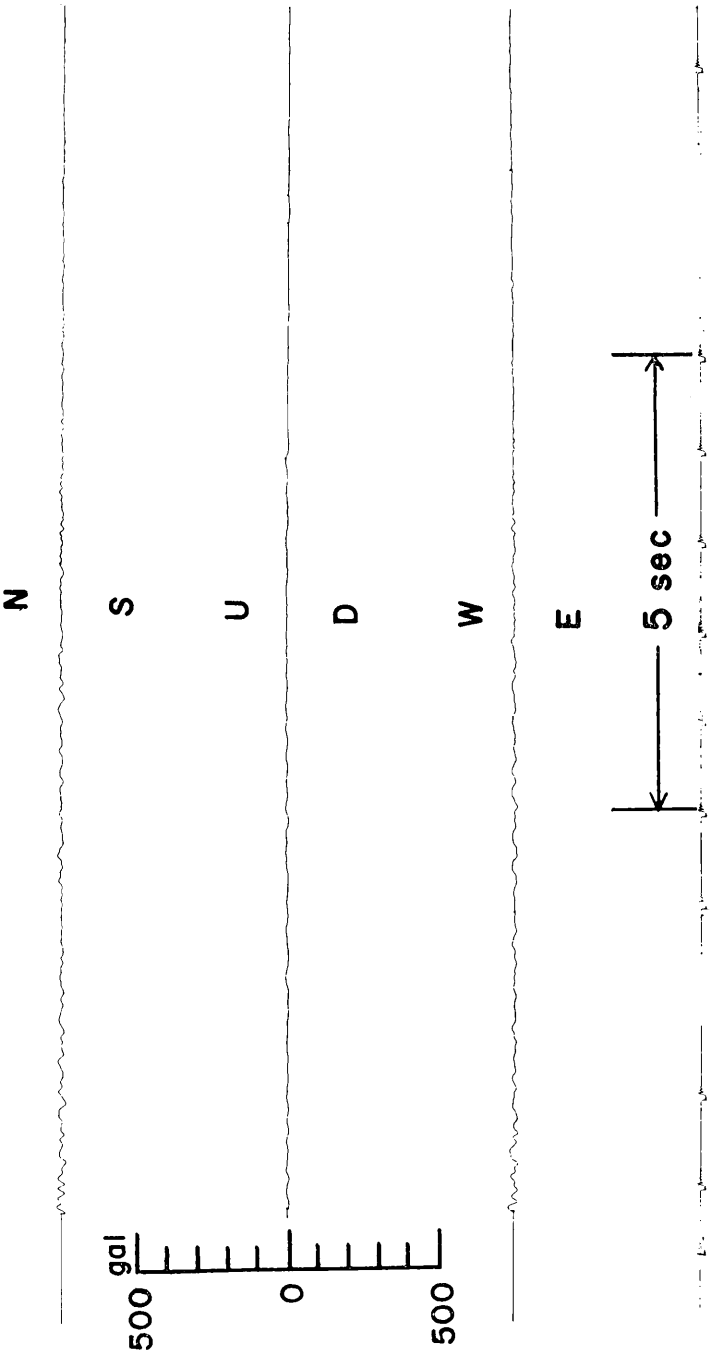


Fig. 9d. No. 123, May 20, 1966. DC-3C, Kawanakajima.

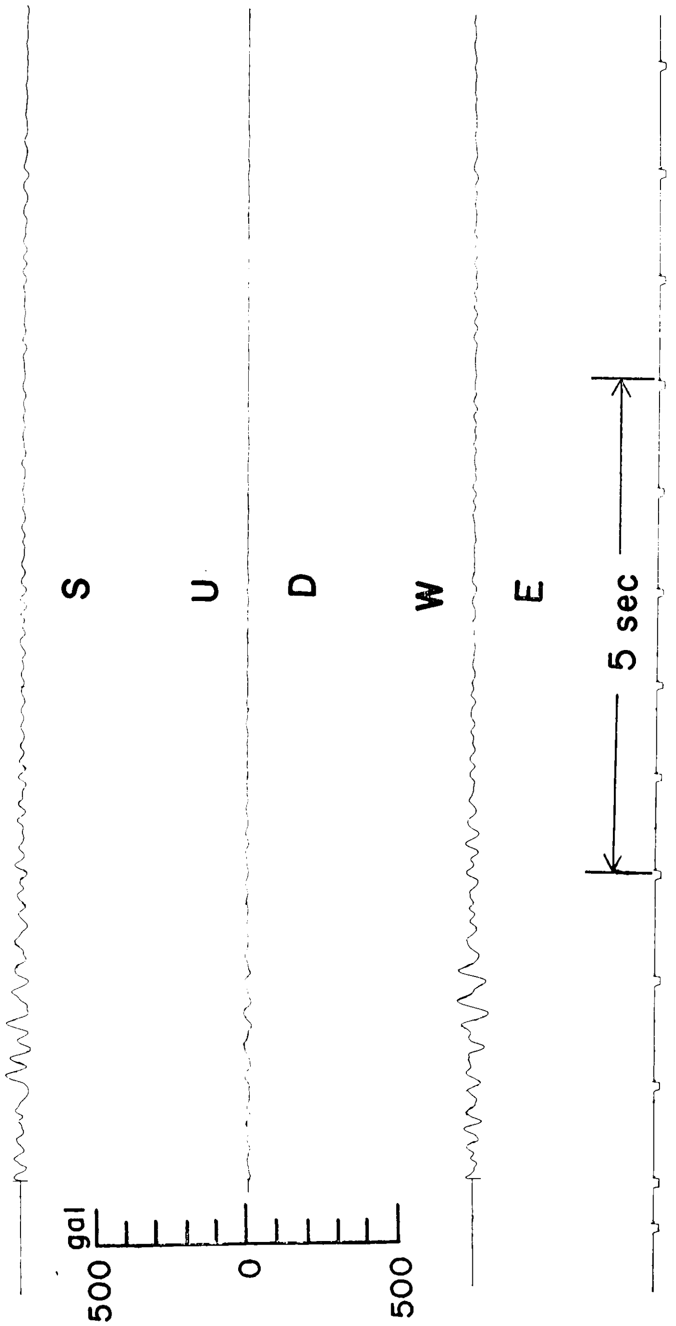


Fig. 10a. No. 147, May 28, 1966. DC-3C, Hoshina B.

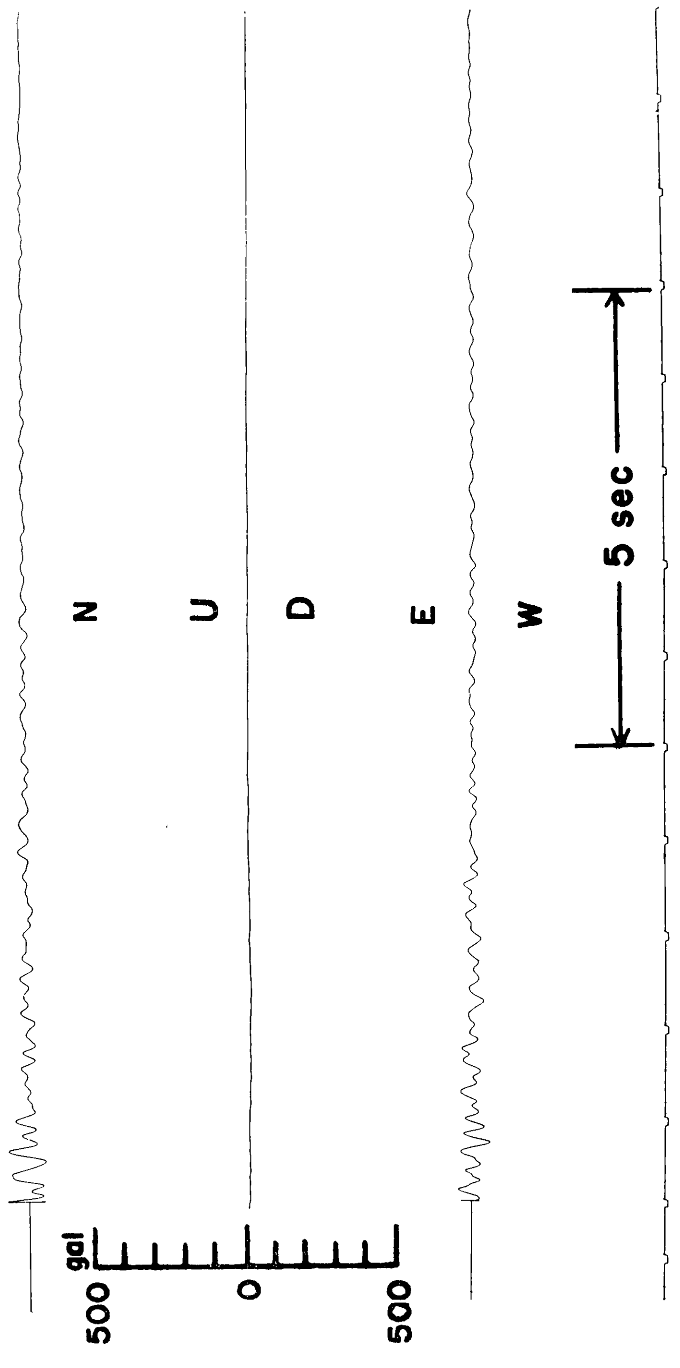


Fig. 10b. No. 147, May 28, 1966. DC-3C, Wakaho.

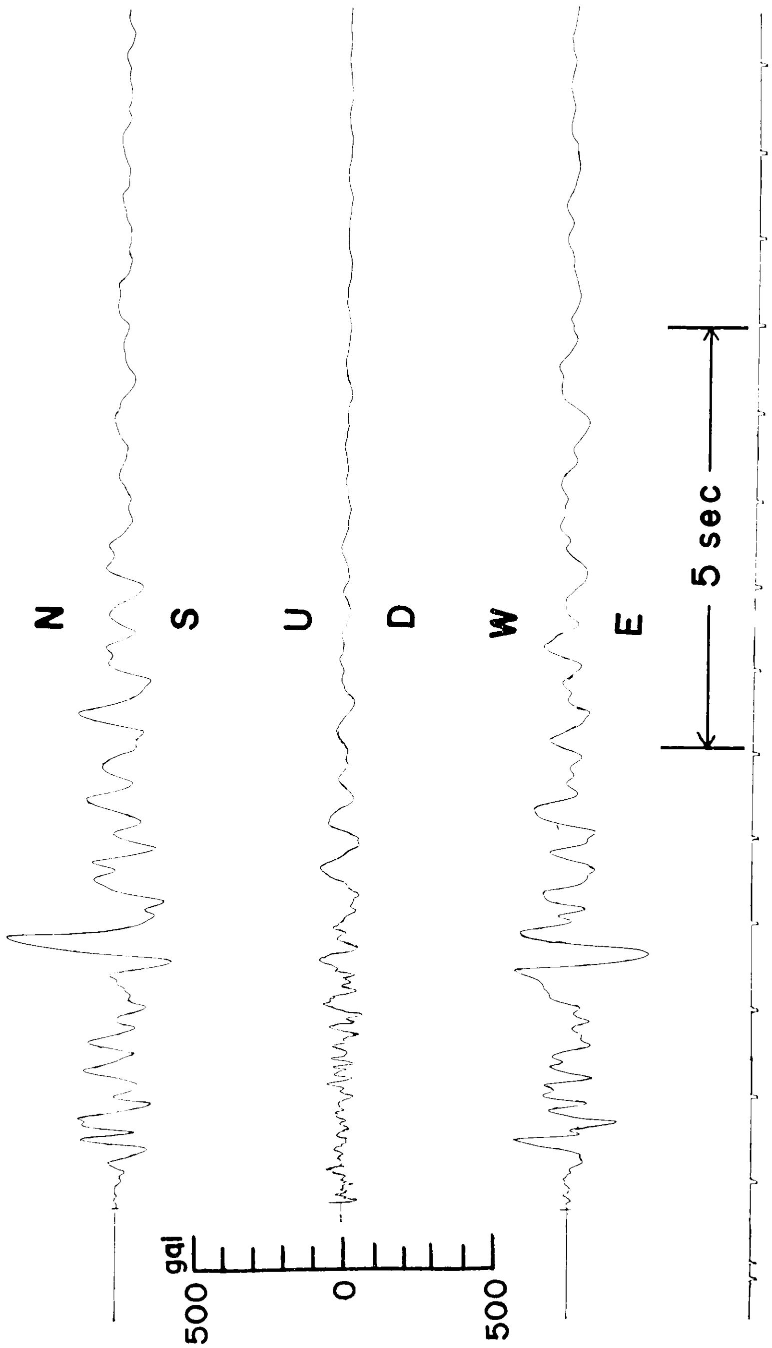


Fig. 10c. No. 147, May 28, 1966. DC-3C, Matsushiro C.

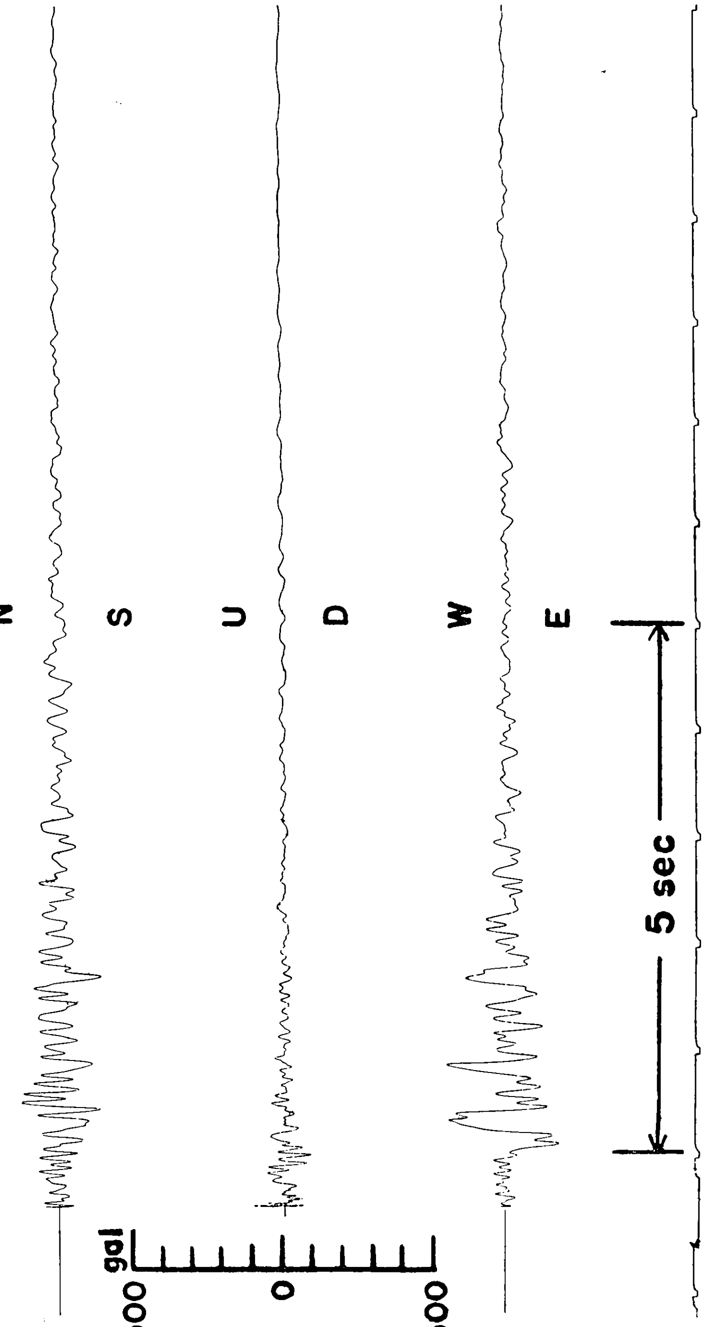


Fig. 10d. No. 147, May 28, 1966. DC-3C, Kawanakajima.

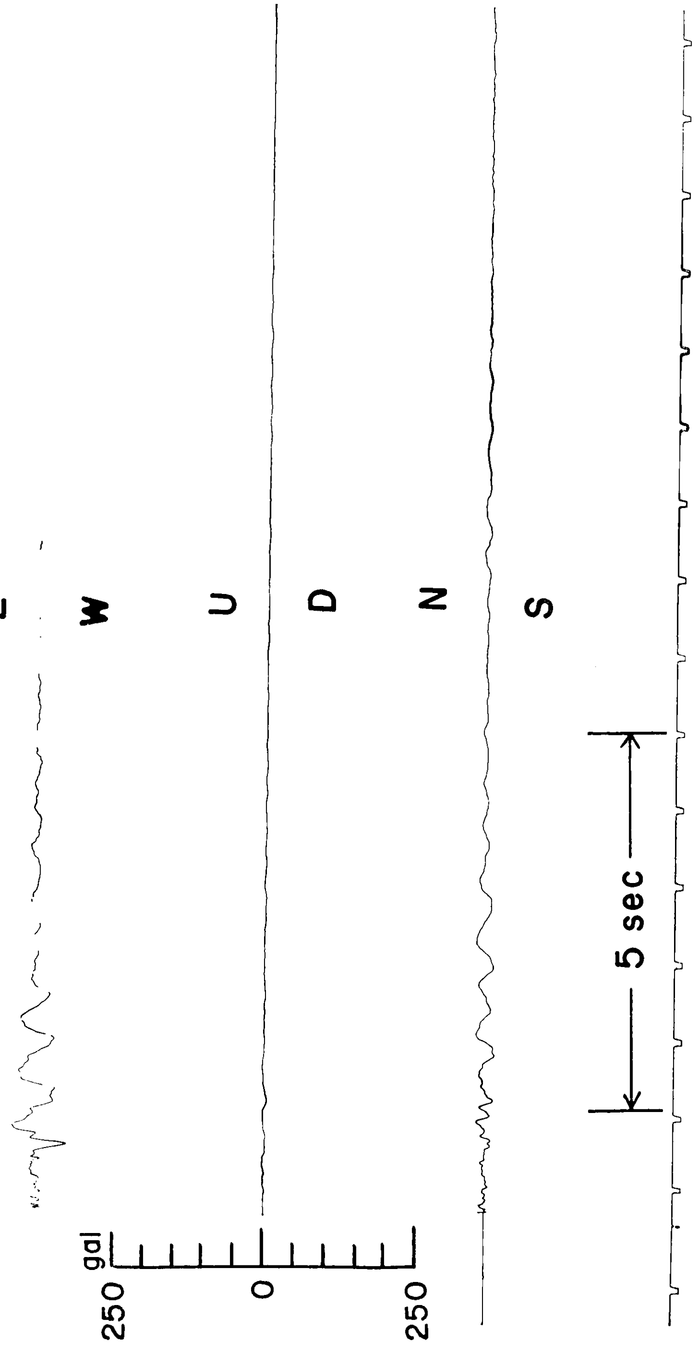


Fig. 10e. No. 147, May 28, 1966. SMAC-B2, Sakaki.

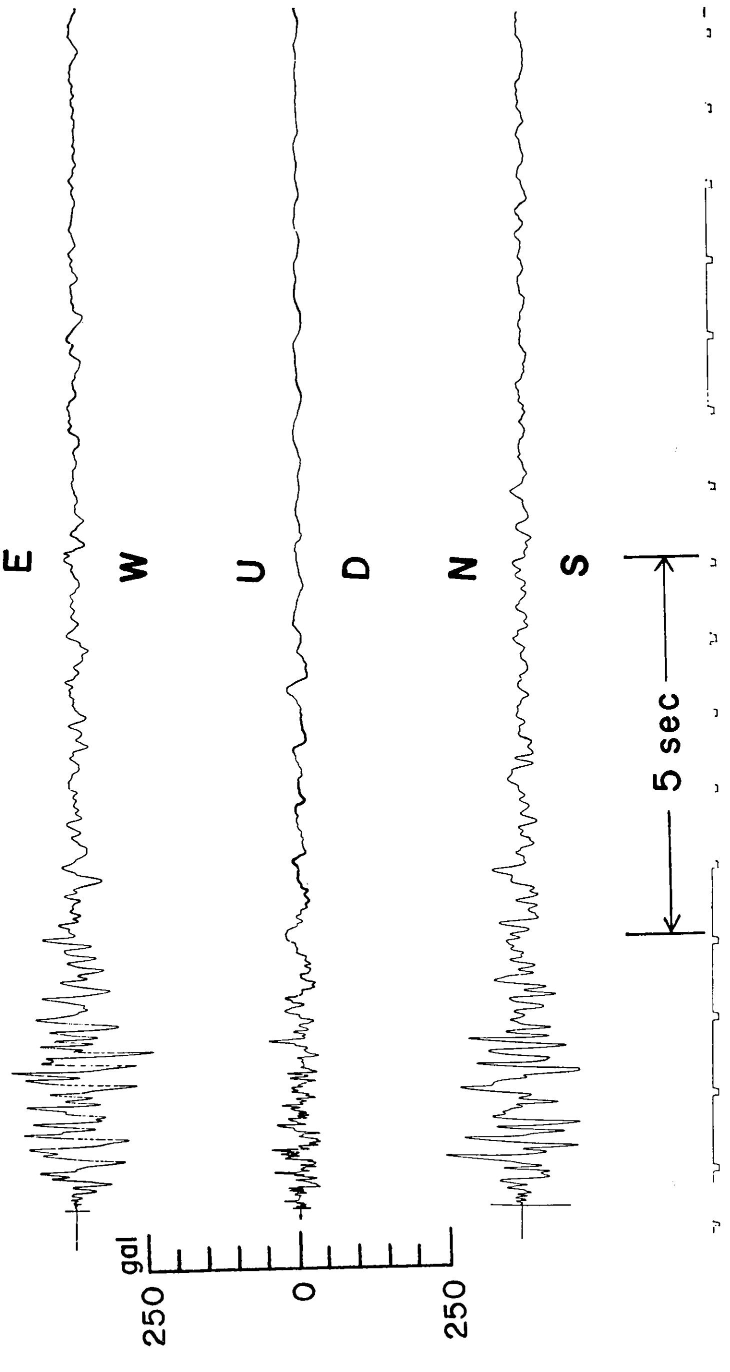


Fig. 10f. No. 147, May 28, 1966. SMAC-B2, Mashima.

Table 2. Stations of the strong motion seismographs in Matsushiro earthquake swarm area.

Station		Strong motion seismograph	
Name	Place	Type	Period of observation
Matsushiro A	長野県埴科郡松代町 気象庁松代地震観測所坑内	DC-3C	Sept. 4,～Nov. 7, 1965
Matsushiro B	同上　地上発電機室	DC-3C	〃
Matsushiro C	長野県埴科郡松代町 松代町役場内	DC-3C	April 23, 1966～
Hoshina A	長野県上高井郡若穂町 保科小学校更衣室	DC-3C	Nov. 7, 1965～May 26, 1966
Hoshina B	長野県上高井郡若穂町 保科温泉　元ボイラー室	DC-3C	May 26, 1966～
Wakaho	長野県上高井郡若穂町 若穂町役場内	DC-3C	Nov. 7, 1965～
Kawanakajima	長野県更級郡川中島町 川中島小学校内	DC-3C	April 22, 1966～
Sakaki	長野県埴科郡坂城町 坂城小学校内	SMAC-B2	May 25, 1966～
Mashima	長野県更級郡更北村 真島小学校内	SMAC-B2	May 26, 1966～

Table 3. Characteristics of the strong motion seismographs.

Characteristics \ Name	SMAC-B2	DC-3C
Component	2 horizontal 1 vertical	2 horizontal 1 vertical
Type	horizontal pendulum	inverted pendulum
Weight of bob (kg)	4.3	8.5
Natural peiod (sec)	0.14	0.1
Sensitivity (gals/mm)	12.5	25
Damping	critical	critical
Damping mechanism	air piston	oil piston
Recording range (gals)	10-500	10-1,000
Recording speed (mm/sec)	10	10
Recording medium	waxed paper	waxed paper
Recording time duration (min)	3	1, 2, 3
No. of repeat cycles	5	5-15
Starter	elect. contact made by vertical motion	elect. contact made by vertical motion
Period of starter pendulum (sec)	0.3	0.3
Starter threshold (gals)	10	10
Auxiliary starter	mechanical, works at 100 gals	——
Time marking (sec)	1	1, 1/2, 1/5
Power supply	4 dry cells	4 dry cells
Size, overall (cm)	54×54×37	79×57×36

Table 4. Data of the earthquake motions larger than 50 gals

No.	Date				M	Depth (km)	Maximum acceleration in gal						
	Year	Month	Day	Time			Hoshina A	Hoshina B	Wakaho	Matsushiro C	Kawana-kajima	Sakaki	Mashima
1	1965	XI	13	23 : 14	4.5	2.9	93						
4	〃	XI	21	03 : 30	4.7	2.7	90						
7	〃	XI	23	02 : 57	5.0	2.5	70						
12	1966	I	3	03 : 59	4.5	4.0	93						
13	〃	I	8	22 : 34	4.7	3.7	88						
14	〃	I	15	01 : 21	4.3	4.2	(175) 125		75				
16	〃	I	23	20 : 16	4.6	2.9	63						
17	〃	II	7	04 : 05	4.4	1.5	100						
18	〃	II	11	01 : 17	4.5		95						
19	〃	II	12	04 : 05	4.6	2.5	58						
20	〃	II	14	07 : 32	4.2	4.4	80						
28	〃	III	1	15 : 45	4.0	6.3	55						
31	〃	III	8	19 : 28	4.5	4.6	63						
32	〃	III	10	07 : 03	4.4	1.9	68						
40	〃	〃	26	17 : 51	4.2	3.8	50						
45	〃	〃	30	08 : 39	4.0	5.6	68						

(to be continued)

(continued)

No.	Date				M	Depth (km)	Maximum acceleration in gal						
	Year	Month	Day	Time			Hoshina A	Hoshina B	Wakaho	Matsushiro C	Kawana-kajima	Sakaki	Mashima
46	1966	III	30	14: 35	3.8	5.5	53						
47	〃	〃	30	16: 57	2.8	0.7	55						
49	〃	IV	1	05: 25	4.9	4.2	178		163				
51	〃	〃	3	14: 01			(245) 100						
52	〃	〃	4	00: 11	4.0	3.3	50						
53	〃	〃	5	17: 51	5.1	4.3	418		250				
54	〃	〃	5	17: 52	4.2		63						
55	〃	〃	5	18: 35	4.1	5.7	100						
56	〃	〃	5	18: 44	4.4	7.9	75		65				
57	〃	〃	5	23: 51	4.3	3.7	80						
63	〃	〃	11	04: 58	4.5	1.5			55				
65	〃	〃	11	06: 06	4.5	3.0			63				
67	〃	〃	12	07: 28	3.8		95						
72	〃	〃	16	15: 06	4.1	3.3	68						
73	〃	〃	17	10: 21	5.0	5.5	188						
74	〃	〃	17	10: 22	4.7	5.6	225						
76	〃	〃	19	07: 35	4.6	4.5	155						

(to be continued)

(continued)

No.	Date				M	Depth (km)	Maximum acceleration in gal						
	Year	Month	Day	Time			Hoshina A	Hoshina B	Wakaho	Matsushiro C	Kawana-kajima	Sakaki	Mashima
77	1966	IV	21	20: 25	4.4	3.5	60						
78	〃	〃	22	03: 00	3.9	7.0	75						
79	〃	〃	24	03: 25	3.8	4.0	68						
80	〃	〃	25	05: 45	3.8	4.4	55						
81	〃	〃	26	07: 50	4.0	4.8	50						
82	〃	〃	26	07: 51	4.3	4.6	90						
87	〃	〃	29	03: 49	4.2	5.7	50						
90	〃	〃	29	10: 17	3.9	3.7				70			
92	〃	〃	30	17: 42	4.6	5.1	103						
94	〃	V	2	00: 44	4.7	3.6	194			75			
95	〃	〃	2	00: 45	5.2	6.9	290			133			
96	〃	〃	2	01: 52	4.8		65						
97	〃	〃	2	13: 29	4.8	6.1	65						
99	〃	〃	4	10: 48	4.4	3.6	55			88			
101	〃	〃	5	12: 55	4.5	5.0	85						
102	〃	〃	6	04: 59	4.7	6.6	65						
103	〃	〃	6	11: 09	4.2	3.6	153						

(to be continued)

(continued)

No.	Date				M	Depth (km)	Maximum acceleration in gal						
	Year	Month	Day	Time			Hoshina A	Hoshina B	Wakaho	Matsushiro C	Kawana-kajima	Sakaki	Mashima
104	1966	V	6	19: 08	5.1	2.8	68		73				
113	〃	〃	13	12: 05	3.3					50			
115	〃	〃	14	19: 36			95						
116	〃	〃	14	22: 24	3.3	5.6				80			
123	〃	〃	20	09: 30	4.9	5.5	230		168	238	(120) 23		
128	〃	〃	21	06: 09	3.5	4.7	60			95			
132	〃	〃	22	14: 19	4.2	6.5	50						
138	〃	〃	25	05: 57	4.4	2.5	130			185			
141	〃	〃	25	11: 05	4.3	4.1	95						
142	〃	〃	25	20: 30	4.2	6.7	125						
145	〃	〃	27	22: 02	4.1	4.4		113		53			50
146	〃	〃	28	12: 28	4.2	6.8			55				
147	〃	〃	28	14: 21	4.7	3.2		55	70	367	198	52	125

61. 松代地域における強震計観測結果 第1報

地震研究所 金井 清
平能金太郎
吉沢静代
浅田鉄太郎

地震研究所強震計観測センターでは，1965年11月から地盤の性質のちがう保科と若穂で強震計観測を始め，その後，松代，川中島，更北，坂城に増設し，6ケ所での観測を続けている．

現在（6月11日）までに観測した最大加速度別地震数からは，次の関係が得られた．即ち

$$N(a)=150{,}000a^{-2.5}$$

こゝに，a は gal 単位の最大加速度，$N(a)$ は a と $a+50$ gals の間の地震回数である．

現在までに，最大加速度 200 gals 以上の地震動が9回もあり，特に，4月5日の保科の記録は 500 gals を越すものであったが，全体を通じて，倒潰家屋は1棟もなく，半壊程度のものも非常に少ない．いろいろ検討の結果，旧式日本家屋を倒潰させる地震動は，その変位振巾が 2～3 cm 以上でなければならず，これを加速度になおすと，0.3 sec で 900～1,300 gals, 0.6 sec で 200～300 gals になるから，こゝで倒潰家屋のないのは当然かも知れない．

次に，今回得られた震央附近の強震記録から，最大加速度 a_{max} (gal), マグニチュードM, 震源距離 x(km), 卓越周期 T_G (sec) の関係式を求めると

$$a_{max}=\frac{5}{\sqrt{T_G}}\cdot 10^{0.61M-2.35\log x-0.186}$$

となった．この式と以前に震央距離数十km 以上の資料から求めた実験式を組合せて，新たな実験式を作ったところ，現在までに，日本，アメリカで得られた強震記録の値と非常によく合うことがわかった．

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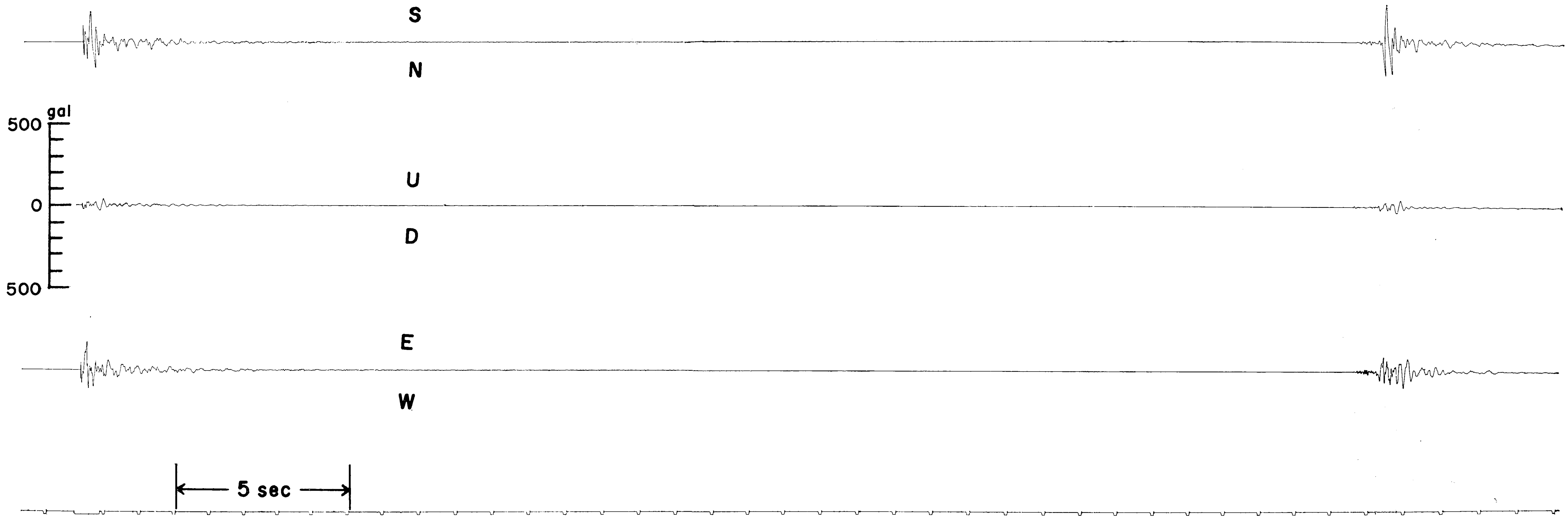

Fig. 8. Nos. 73, 74, Apr. 17, 1966. DC-3C, Hoshina A.