Earthquake Interpretations at Syowa Station, Antarctica

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1. Introduction

The progress of electronic computers and instrumentation for observation of surface waves of earthquakes has much contributed to the study of the earth's interior. Various kinds of the earth models have been proposed by many researchers using the travel times of *P* and/or *S* waves and the dispersion curves of surface waves. To obtain more accurate models, it is very important to use the travel times of later phases, both reflected and refracted waves.

Much information on the earth's interior may be provided by the seismograms between *P* and *S* phases or between *P* phase and surface waves. The later phases *pP*, *PcP*, etc. have also contributed to the study of earthquake mechanism.

Features of seismograms can be seen generally at a glance. Experienced readers of seismograms would realize immediately whether the location of an earthquake is nearby or far way and whether the shock is deep-earthquake or a shallow one. In seismograms there are some phases that can not be identified by theoretical travel time curves (for example; GUTENBERG, 1949). As these phases may contain useful information about the earth, detailed study and analysis of these phases are obviously necessary.

The purpose of this paper is to interpret seismograms recorded at the Japanese Antarctic Station, Syowa (SYO), for the researcher who has not the chance to see the original records and to help the observer interpret the seismograms.

Jefferys-Bullen (1958) and Gutenberg-Richter (1953) travel time tables were used in this study. The earthquakes treated in this paper occurred during the period from 1967 to 1969, and the seismograms are mainly the contact copies of HES seismograms. For the explanation of the phases following the initial *P* and *S* phases, the seismograms of *P* and *S* waves are partially enlarged and arranged with the contact copies. As denoted in the next section, the long-period seismograph was operated well only in 1968. The contact copies of long-period seismograms in 1968 are also arranged. The seismograms in this collection are arranged in some regions in Section 3. Earthquakes located in the shadow zone and the region of the minor activity are collected in Section 4. Seismograms of an icequake, a micro-earthquake and other shock types recorded at SYO are shown in Section 5.

2. Seismological Observation at Syowa Station

2.1. Observation by HES seismograph

The seismological observation at Syowa Station in Antarctica was started with a HES seismograph of Z component by the 3rd Japanese Antarctic Research Expedition (JARE) in 1959. HES seismographs with two horizontal components

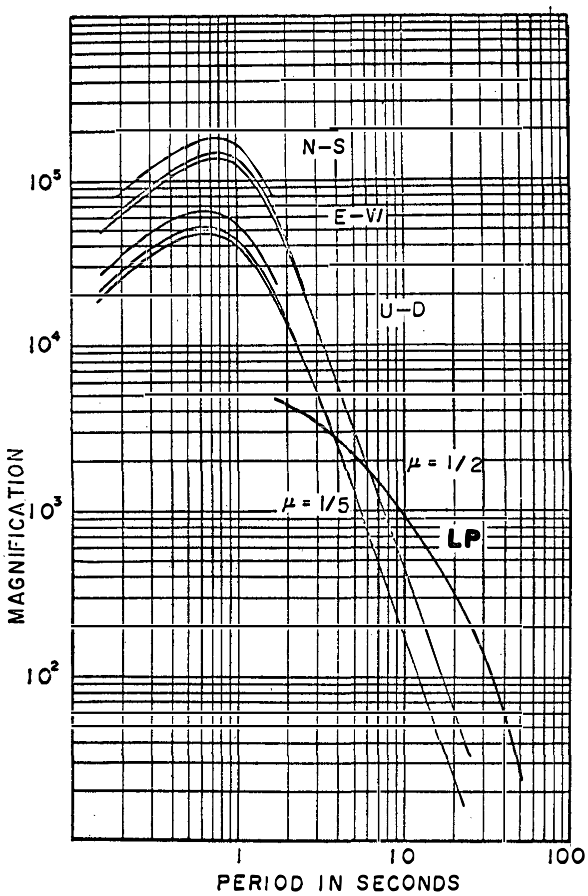

Fig. 1. Magnification curves of HES and LP seismographs. The LP seismograph was operated only in 1968.

were added in 1961 and a three-component seismological observation was begun. The period of pendulum and the galvanometer is about 1 second. When Syowa Station was closed in January 1962, all observations and scientific works were discontinued. Station coordinates for the seismological observation during these three years were lat. = 69°00′18″ S and long. = 39°35′12″ E. The elevation was h = 23 m above MSL.

In February 1966 Syowa Station was reopened. Since this time the seismological observation has been continued by JARE using three-component HES seismographs at the same place. Since 1967, seismographs have been set in the

Table 1. Instrumental constants of HES and LP seismographs.

Component	Z	N-S	E-W
HES			
T_1 (s)	1.0	1.0	1.0
S_1 (A/mm)	2.80×10^{-5}	2.03×10^{-5}	2.03×10^{-5}
R_1 (Ω)	940	920	930
Ω_1 (Ω)	820	1160	920
h_1	1.0	1.0	1.0
T_2 (s)	1.06	1.04	1.04
S_2 (A/mm)	1.47×10^{-9}	1.20×10^{-9}	1.35×10^{-9}
R_2 (Ω)	600	650	630
Ω_2 (Ω)	1200	1200	1200
h_2	1.0	1.0	1.0
LP (1968)			
T_1 (s)	18.7	18.1	16.4
S_1 (A/mm)	2450	3240	2820
R_1 (Ω)	3100	3200	2900
Ω_1 (Ω)	45	156	38
h_1	1.0	1.0	1.0
T_2 (s)	0.91	0.98	0.97
S_2 (A/mm)	0.906×10^{-9}	0.812×10^{-9}	0.790×10^{-9}
R_2 (Ω)	520	530	540
Ω_2 (Ω)	1702	1868	1960
h_2	1.0	1.0	1.0

T_1: Period of the pendulum.
T_2: Period of the galvanometer.
S_1: Sensitivity of the transducer.
S_2: Sensitivity of the galvanometer.
R_1: Resistance of the pendulum coil.
R_2: Resistance of the galvanometer coil.
Ω_1: External damping resistance of the transducer.
Ω_2: External damping resistance of the galvanometer.
h_1: Damping constant of the pendulum.
h_2: Damping constant of the galvanometer.

new room on the Precambrian gneiss about 350 m east of the old one. New coordinates and height are lat.=69°00′27″ S, long.=39°35′40″ E and h=21 m.

The period of pendulum is 1.0 second and that of galvanometer is also 1.0 second. The constants of the HES seismographs and galvanometers used for these four years are tabulated in Table 1 and the frequency characteristics of seismograph magnification are shown in Fig. 1.

Because of extreme seismic tremor activity in the summer season, the seismographs are usually operated with the attenuation factor $\mu=1/5$ (HAGIWARA, 1958) during the summer months (from January to May) and $\mu=1/2$ during the winter months (from May to December).

The HES recorder is designed for a continuous recording for 24 hours with a optical system. Positive film of 35 mm width is used as the recording film. The rotational speed and the leading speed of the recording drum are 20mm/min and 1 mm/hour respectively. The magnification in Fig. 1 is the value on the film reader with 8 times magnification.

2.2. Observation by long-period seismograph

A three-component long-period seismograph was installed at Syowa Station in 1967. The period of pendulum was 15.0 seconds and that of the galvanometer was about 1.0 second. Using an amplifier and an integrator between the pendulum and the galvanometer, the characteristics of the amplitude and the phase were designed to be the same as those of the long-period seismograph operated by USCGS. However, there were many defects in the system, and satisfactory records were not obtained. Then the long-period seismograph was operated without an amplifier and an integrator during 1968. The constants of the seismograph and the galvanometer are also tabulated in Table 1 and the magnification curve is also given in Fig. 1. It was operated with a long-period galvanometer of 20 seconds in 1969 but unfortunately satisfactory data could not be obtained due to the trouble of galvanometers.

The recorder of long-period seismographs is the same as the HES recorder, but the rotational speed of the recording drum is 4 mm/min.

3. Seismograms of Earthquakes in Each Region

Arranged in this section are the seismograms of earthquakes that occurred in the following regions; A (30°–60°S, 0°–60°E), B (50°–65°S, 20°–30°W), C (15°–45°S. 60°–75°W), D (15°–45°S, 178°E–180°–165°W), E (15°N–0°–15°S, 90°–160°E), G (45°–60°N, 150°E–180°–150°W). These regions are shown in Figs. 2–4. The earthquake detection capability at SYO for each region was obtained by KAMINUMA (1969).

Table 2. List of earthquakes.

Plate No.	Date	Origin time	Latitude	Longitude	Depth (km)	Magnitude	SYO distance
1	1969 08 23	$19^h 05^m 11.8^s$	53.48°S	25.87°E	N*	5.2	16.8°
2	1967 08 09	22 49 11.9	52.03 S	28.39 E	N	4.8	17.8
3	1967 08 13	16 33 04.0	50.88 S	29.07 E	N	5.4	18.9
4	1969 04 09	11 43 47.6	49.09 S	30.78 E	23	5.8	20.5
5	1968 06 16	19 14 05.3	53.92 S	8.70 E	33	5.7	20.7
6	1968 06 08	23 24 05.2	48.75 S	31.54 E	N	5.6	20.7
7	1969 09 29	20 03 32.8	32.91 S	19.66 E	N	5.9	37.9
8	1969 11 26	18 26 08.9	58.84 S	24.71 W	N	5.4	28.6
9	1969 10 23	01 39 22.1	56.15 S	27.35 W	95	5.3	31.5
10	1967 09 13	19 57 47.9	56.05 S	27.38 W	148	5.3	31.7
11	1967 09 26	16 11 23.9	30.04 S	71.53 W	53	5.7	69.4
12	1967 08 20	15 03 36.2	25.20 S	69.02 W	109	5.6	73.1
13	1968 09 22	21 52 59.2	24.13 S	69.91 W	194	5.5	73.4
14	1967 09 09	10 06 44.1	22.70 S	63.14 W	578	5.8	73.5
15	1967 12 25	10 41 31.6	21.48 S	70.37 W	53	5.8	77.0
16	1969 10 03	01 33 19.8	32.85 S	178.03 W	26	5.7	74.7
17	1969 08 28	13 54 11.0	31.47 S	177.88 W	29	5.3	76.1
18	1969 09 30	17 51 41.8	31.93 S	178.02 W	N	5.4	75.7
19	1968 05 30	19 42 25.1	30.95 S	177.63 W	42	5.5	76.7
20	1968 07 25	07 23 07.8	30.77 S	178.35 W	60(R)**	6.4	76.7
21-A	1967 09 04	03 51 58.9	31.44 S	179.45 W	231	5.5	75.9
B	1967 09 03	21 07 30.8	10.58 S	79.75 W	38	6.5	90.2
22	1969 10 26	21 25 32.2	27.10 S	176.63 W	44	5.2	80.6
23	1967 08 12	09 39 44.3	24.71 S	177.47 W	134	5.8	82.7
24	1969 10 13	06 56 01.6	18.85 S	169.31 E	246	5.9	85.3
25	1968 09 12	22 44 06.5	21.55 S	179.36 W	635	5.9	85.4
26	1968 10 12	19 17 39.9	20.88 S	178.78 W	607	5.7	86.2

Plate No.	Date	Origin time	Latitude	Longitude	Depth (km)	Magnitude	SYO distance
		h m s					
27	1969 11 14	07 37 45.7	19.67°S	175.85°W	209	5.5	88.0°
28	1969 11 24	21 31 17.6	17.99 S	178.40 W	593	5.4	89.1
29	1969 10 26	06 38 03.4	16.17 S	173.95 W	127	5.8	91.8
30	1967 07 10	12 01 31.5	5.92 S	113.14 E	591	5.4	78.6
31	1967 08 21	07 33 00.6	3.64 N	95.76 E	N	5.9	81.9
32	1969 02 11	22 16 13.5	6.70 S	126.85 E	450	6.0	82.8
33	1968 08 04	17 19 19.6	5.65 S	125.35 E	521	6.2	83.3
34	1968 08 14	22 14 19.4	0.16 N	119.79 E	23	6.0	86.7
35	1968 08 10	02 07 04.4	1.42 N	126.22 E	N	6.3	87.5
36	1969 08 05	02 13 09.6	1.30 N	126.20 E	34	6.1	90.0
37	1969 08 11	23 52 56.9	1.73 N	126.47 E	34	6.1	90.5
38	1968 08 18	18 38 30.6	10.11 S	159.87 E	538	6.2	90.9
39	1968 09 16	13 55 36.1	6.07 S	148.68 E	59	5.8	91.9
40	1968 11 28	16 30 32.1	6.79 S	156.23 E	169	5.7	92.9
41-A	1969 10 18	08 44 00.0	52.49 N	173.48 E	24	5.6	153.0
B	1969 10 21	20 53 47.5	51.31 N	179.24 W	48	5.9	154.5
42	1968 11 26	00 03 14.3	57.53 S	6.79 W	N	5.6	23.1
43	1968 10 14	02 58 47.8	31.52 S	116.97 E	0	6.0	56.5
44	1968 09 25	07 02 51.8	46.39 S	166.78 E	N	5.5	58.5
45	1969 08 19	17 26 07.4	56.67 S	142.05 W	N	4.4	70.7
46	1967 11 23	08 35 49.5	14.53 N	52.07 E	3	5.8	83.8
47	1969 11 07	18 33 59.9	27.85 N	60.06 E	35	6.1	97.7
48	1968 08 01	20 19 21.9	16.01 N	122.20 E	37	5.9	102.7
49	1967 07 22	16 56 53.3	40.66 N	30.77 E	4	6.0	109.5
50	1969 08 11	21 27 39.4	43.55 N	147.35 E	22	7.1	136.1
51	1967 10 18	01 11 44.8	79.80 N	2.37 E	N	5.7	150.1

(* N: Normal depth, the depth restrained at 33 km)
(** R: The depth restrained at any value indicated by evidence from available seismograms)

The earthquake magnitude treated in this paper is almost larger than 5.0.

Since no earthquake has been located instrumentaly in the area at latitudes higher than 65°S, the epicentral distance of the nearest earthquake observed at SYO was some 16 degrees.

Seismograms, earthquake data and comments are summarized in Plates together with the earthquake data quoted from the Earthquake Data Report of USCGS. Earthquakes treated in this section are tabulated in Table 2.

3.1. Earthquakes in Region A

Earthquakes located in the regions of "South of Africa" and "South Africa" are included and the nearest earthquake at SYO is located in this region. The detection capability for the earthquakes with magnitude larger than 4.0 is 100%, almost all the earthquakes which occurred in this region are recorded at SYO. These shocks in this region are arranged with distance in Plates 1–7. The epicenter locations of the earthquakes treated in this region are shown in Fig. 2. The magnitude of these shocks are around 5.5 and the epicentral distances are from 16° to 40°.

It is the special feature of seismograms, as shown in Plates 5 and 6, that the amplitude of the initial *P* wave is small and the following phases after several seconds of the first motion have large amplitudes.

The *S* phase onset of some earthquakes (Plates 1, 2, 3, 5, etc.) is not identified clearly. Most of *O–C* residuals are negative.

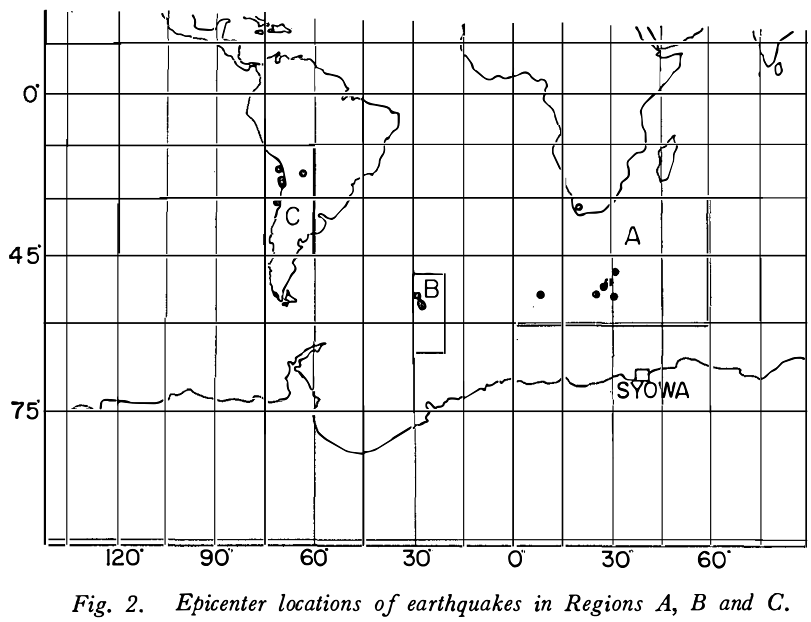

Fig. 2. Epicenter locations of earthquakes in Regions A, B and C.

3.2. Earthquakes in Region B

Earthquakes located in the South Sandwich Islands region are included and the epicentral distance at SYO is about 30°. The detection capability for the earthquakes with magnitude larger than 5.5 is 100% and that with magnitude 5.0 to 5.4 is 30%. The epicenter locations are shown in Fig. 2.

The initial *P* phase of the shallow shock (normal depth: Plate 8) has a small amplitude and the following phases show large amplitudes.

S phases of the shock of which focal depth is some 150 km are not clearly recorded (Plate 10).

3.3. Earthquakes in Region C

The earthquakes which occurred in the regions of Chile and Argentina provinces are included and the epicentral distances are mostly from 70° to 80°. The earthquake locations are also shown in Fig. 2. The detection capability for earthquakes of magnitude 5.5–5.9 is 72%, and some 40% for those of magnitude 5.0–5.4.

Pairs of *P* and *pP*, *S* and *sS*, *ScS* and *sScS*, *sP* and *sPcP*, etc. are well recorded in this region. *P′P′* phase of Gutenberg-Richter travel time table is recognized as shown in Plate 12. The direct *P* phase and the *pP* phase can be seen clearly grouping in Plates 11, 12 and 14.

3.4. Earthquakes in Region D

The regions of Fiji, Tonga, Kermadec Is., etc. are included in this region. The

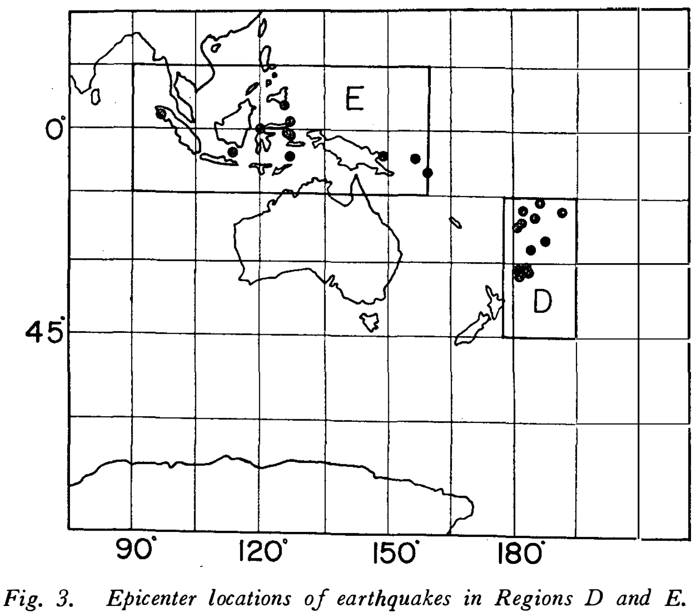

Fig. 3. Epicenter locations of earthquakes in Regions D and E.

epicentral distances are from 75° to 90°. The earthquake locations treated in this region are shown in Fig. 3. The detection capability for earthquakes of magnitude larger than 5.5 is 100%, but 30% for those of magnitude 5.0~5.4.

The shocks in the Kermadec Is. region are arranged with depth in Plates 16–21. The first *P* wave motion shows a small amplitude and the succeeding phases have large amplitudes (Plates 16, 17 and 18). The records of long period seismographs are shown in Plate 20.

The shocks located in the northern part of this region are shown in Plates 22–29. Some unexplained phases of Gutenberg-Richter travel time table shown with an arrow can be recognized. The phases of *S*, *ScS* and *SKS* can be seen to arrive nearly at the same time.

3.5. Earthquakes in Region E

The regions of Java Sea, Banda Sea, Solomon Is., New Britain, etc. are included in this region and the earthquake location are shown in Fig. 3. The detection capability for earthquakes of magnitude 5.5–5.9 is 50% and that of magnitude 5.0–5.4 is about 15%. The epicentral distances are from 80°~90° mainly.

The phases of *S*, *SKS* and *ScS* are well recorded as *S* group (Plate 31, 32, 33, etc.). Small initial *P* phases are observed (Plate 35, 36, etc.). The unexplained phases of *P* wave groups of Gutenberg-Richter travel time table are well identified as shown with an arrow in Plates 34 and 36.

The core phases of $P''P''$, $pP''P''$ and $sP''P''$ can be recognized on the long-period seismogram of *Z* component (Plate 38) and the group of initial *P* waves, *pP* phase, *SKS* phase and the group of reflected *S* waves have large amplitudes.

3.6. Earthquakes in Region G

The regions of Aleutian Is., Kamchatka, etc. are included and the epicentral distance is from 137°–177°. The detection capability for earthquakes of magnitude larger than 5.5 is 60% and that of magnitude 5.0–5.4 is about 10%.

As the region is located beyond the shadow zone, the initial phases are the core phases and the first motion can be detected very clearly.

The epicenter locations are shown in Fig. 4 and the seismograms are also given in Plate 41.

4. Earthquakes in Other Areas

Seismograms of earthquakes located in the shadow zone from SYO and in the other area discussed in the previous section. The earthquake location in this section is shown in Fig. 4. The earthquake data, comments and seismograms are also arranged with the epicentral distance as shown in the plate, and the earthquake data are tabulated in Table 2. The earthquakes in and near the Japanese Is. are located in the shadow zone from SYO.

The seismograms of a large earthquake in Western Australia, one of the minor seismic activity regions, are shown in Plate 43. High frequency *P* wave group can be recognized to compare with the case of Plate 42, which shows a seismogram at a shorter distance.

In Plate 45, a sample of small magnitude earthquake is shown. In spite of its small magnitude and the large epicentral distance, the amplitude of P wave is not so small but the initial motion is not identified clearly for the small amplitude. The surface wave magnitude determined from the data of two stations is 5.5. The paths of waves in Plates 46 and 47 are almost along the meridian line. The initial *P* phases are also small.

The earthquake in Plate 48 is located nearly at the beginning of the shadow zone and the earthquakes in Plates 49 and 50 are also locatad in the shadow zone. The initial phases of these shocks are very small.

In Plate 50, the core phases proposed by BOLT (1959; 1964) and othars can be

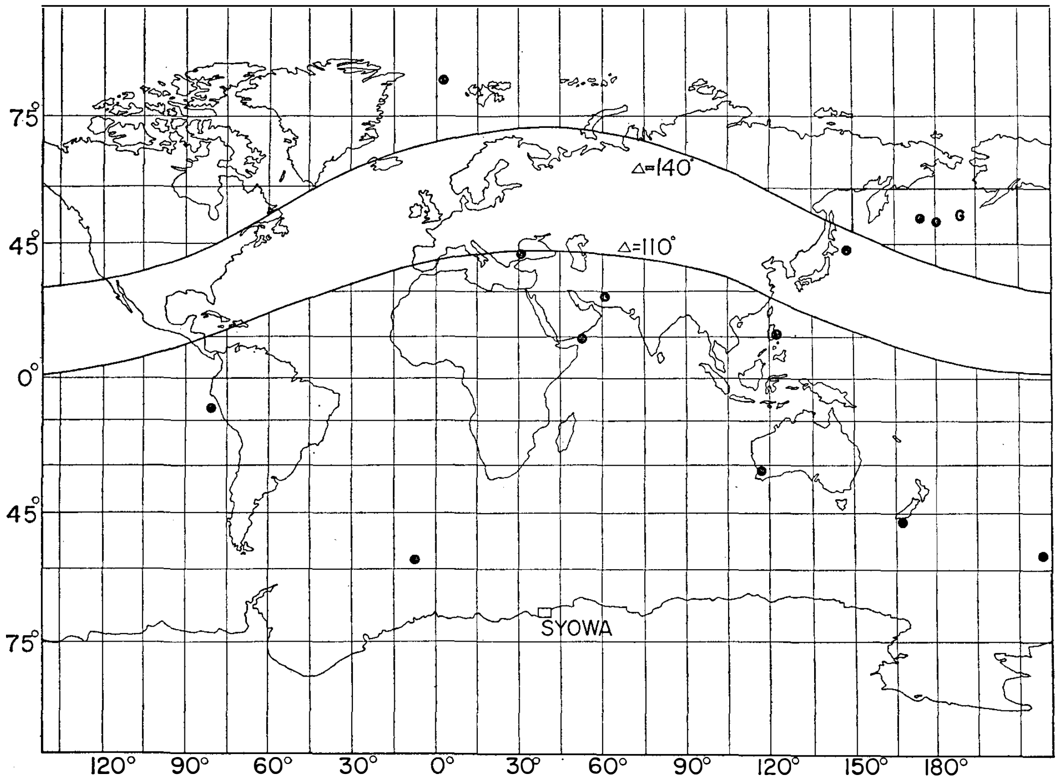

Fig. 4. Epicenter locations of earthquakes in Region G and the other area.

recognized. According to BOLT's formula, the arrival times of *PKP* and *PKIKP* of this shock, at the distance of 136.1° are as follows:

	Travel time	Arrival time
PKP	19 min 14.3 s	$21^{h}\ 46^{m}\ 53.7^{s}$
PKIKP	19 min 25.0 s	$21^{h}\ 47^{m}\ 04.4^{s}$

The estimated arrival times of both phases are shown with a dotted arrow. The seismograms at this time need the time correction of −5.9 seconds. These arrows are drawn on the records after the correction is made. Before *PKP*, unexplained small initial phases are recognized. The shock in the Greenland Sea is shown in Plate 51. The core phases are detected clearly.

5. Other Shock Type

Seismograms of which earthquake data were determined by USCGS are shown in the previous two sections. Seismograms in this section are collected from the shocks of which locations and origin times are unknown. There are much reports of phase readings from many seismological stations in Antarctica and these data are published in the Antarctic Seismological Bulletin. A part of the bulletin is shown in Fig. 5. The epicenters shown in this bulletin are computed by USCGS using the phase readings from many stations in addition to the Antarctic readings. On the other hand, there are some reports of phase readings from a single or a few stations and the epicenters cannot be computed due to insufficient data. For example the phase readings of *P* from five stations are reported as shown with an asterisk in Fig. 5, but the epicenter of this event can not be determined. The seismogram of this event is shown in Plate 52. The amplitude of the initial phase is small but the phase can be identified clearly.

KAMINUMA and ISHIDA (1971) determined the location of this event using these phase readings of five stations in Fig. 5 as follows:

Date	October 20, 1968
Origin time	$05^{h}\ 44^{m}\ 20.7^{s}\ \pm 1.5^{s}$
Lat.	63.1°S ± 17.3 km
Long.	165.8°W ± 9.4 km
Depth	30 km (restrained)

The events which were recorded at several stations but not located like the one mentioned above are reported in the bulletin more than ten times a year and also recorded at SYO several times a year.

10 COAST AND GEODETIC SURVEY

Date and Station	Phase (GCT)
	h m s
BY2 IP	01 33 34.0
OCT 20	
SBA EP	02 16 09.0
* OCT 20	
SBA P	05 48 20.0
BY2 IP	05 49 05.1
DRV EP	05 49 24.0
SPA EP	05 50 01.5
SYO EP	05 52 49.6
OCT 20	
H-07 08 17.1	
25.0N 122.5E	
h ABOUT 15KM	
MIR E(P)	07 21 42.0
SBA EP'	07 26 52.0
SPA EP'	07 26 56.8
BY2 EP'	07 27 05.9
E	28 20.7
OCT 20	
DRV EP	07 24 08.0
OCT 20	
MIR EP	11 02 51.0
OCT 20	
H-13 37 36.4	
55.8S 25.8W	
h ABOUT 33KM	
SYO EP	13 43 54.8
SPA EP	13 44 22.0
BY2 EP	13 44 36.6
I	44 49.8
SBA EP	13 46 01.0
OCT 20	
SPA EP	16 05 31.7
OCT 20	
H-17 03 58.7	
35.4S 15.9W	
h ABOUT 33KM	
SYO EP	17 12 13.9
SPA EP	17 13 28.4
BY2 EP	17 13 48.2
SBA P	17 14 51.0
OCT 20	
BY2 EP	18 21 56.3
SPA EP	18 22 25.8
OCT 20	
SBA EP	19 36 57.0

Date and Station	Phase (GCT)
	h m s
OCT 20	
BY2 EP	19 58 42.2
SPA EP	19 59 13.5
OCT 20	
SBA EP	22 14 42.0
OCT 20	
SBA EP	22 34 23.0
OCT 20	
H-23 15 04.0	
45.7N 26.6E	
h ABOUT 123KM	
BY2 EP'	23 34 22.0
OCT 21	
H-00 28 43.4	
19.1S 177.7W	
h ABOUT 575KM	
SPA EP	00 39 04.3
OCT 21	
SBA EP	00 43 43.0
OCT 21	
H-01 13 28.4	
7.9S 120.4E	
h ABOUT 33KM	
SPA EP	01 25 46.4
BY3 IP	01 26 14.5
OCT 21	
SPA EP	02 42 56.6
OCT 21	
SPA EP	05 21 54.5
BY3 IP	05 22 10.1
OCT 21	
H-06 46 19.7	
5.4S 146.5E	
h ABOUT 170KM	
SPA EP	06 58 35.8
BY3 I(P)	06 58 50.3
OCT 21	
SPA EP	07 51 27.2
OCT 21	
H-07 54 38.4	
59.4S 25.3W	
h ABOUT 33KM	
SPA EP	08 00 52.8
BY3 IP	08 01 12.0
SBA P	08 02 31.0
OCT 21	
SBA EP	09 29 07.0
OCT 21	
BY3 EP	09 41 33.7

Date and Station	Phase (GCT)
	h m s
OCT 21	
SBA EP	09 58 22.0
OCT 21	
SPA EP	14 44 25.7
OCT 21	
SPA EP	15 42 55.4
BY3 EP	15 43 36.2
OCT 21	
H-18 16 41.6	
35.2N 23.4E	
h ABOUT 5KM	
SPA EP'	18 35 43.3
BY3 EP'	18 35 58.9
OCT 21	
MIR EP	20 23 01.0
OCT 21	
MIR EP	21 11 24.0
OCT 21	
SBA EP	23 01 20.0
OCT 21	
H-23 13 37.0	
7.7S 120.4E	
h ABOUT 33KM	
SPA EP	23 25 56.7
OCT 21	
BY3 IP	23 21 23.7
OCT 21	
MIR EP	23 38 20.0
OCT 21	
SPA EP	23 56 34.2
OCT 22	
SBA EP	00 56 52.0
OCT 22	
MIR EP	01 50 55.0
OCT 22	
MIR EP	02 02 49.0
OCT 22	
MIR EP	02 11 02.0
OCT 22	
BY1 EP	04 55 08.2
OCT 22	
H-05 30 20.0	
32.9S 72.0W	
h ABOUT 85KM	
BY1 E(P)	05 39 02.0
OCT 22	
MIR EP	07 42 05.0
OCT 22	
H-07 45 56.1	
4.4S 104.9W	
h ABOUT 33KM	

Date and Station	Phase (GCT)
	h m s
BY1 EP	07 57 41.5
OCT 22	
MIR EP	08 12 47.0
OCT 22	
MAW IP	10 29 50.8
OCT 22	
MIR EP	12 44 09.0
OCT 22	
MIR EP	14 15 32.0
[illegible] 22	
A E	16 32 02.0
OCT 22	
BY1 EP	18 22 16.0
OCT 22	
H-19 13 31.7	
18.3S 177.9W	
h ABOUT 612KM	
SPA EP	19 23 57.1
OCT 22	
MIR EP	20 14 19.0
OCT 22	
MIR EP	21 30 16.0
OCT 22	
MIR EP	23 04 02.0
OCT 22	
MIR EP	23 20 10.0
OCT 23	
MIR EP	00 17 19.0
OCT 23	
MIR EP	00 32 53.0
OCT 23	
MIR EP	00 44 55.0
OCT 23	
MIR IP	00 46 00.0
OCT 23	
SPA EP	01 00 58.9
OCT 23	
H-01 54 01.9	
53.5S 140.3E	
h ABOUT 33KM	
MIR E(P)	01 59 28.0
BY2 E(P)	02 01 22.2
BYR E(P)	02 01 23.2
SYO E(P)	02 02 05.6
OCT 23	
H-02 34 48.2	
4.2S 143.2E	
h ABOUT 33KM	
DRV EP	02 45 08.0

Fig. 5. A part of the Antarctic Seismological Bulletin by USCGS. An asterisk shows the event for which the phase readings from some stations are reported but its location cannot be determined.

A small shock like a micro-earthquake is also recorded frequently at SYO. The small shock is roughly classified into two types according to its first motion. One has a sharp initial motion and the other has a weak first motion as shown in Plates 53 and 54 respectively. Some types shown in Plate 53 have a clear S phase and S–P times can be read on the record. But most of the shocks of this type have a small S phase.

The type of a small first motion can be considered as an iceshock. The shock of Plate 54 is the largest of this type. An iceshock swarm is recorded once or twice a year. A kind of the iceshock swarm is shown in Plate 55. Four shocks were recorded in this seismogram as shown with arrows.

Acknowledgements

The authors wish to express their sincere thanks to Professor H. KANAMORI for kindly reading the manuscript and making many suggestions.

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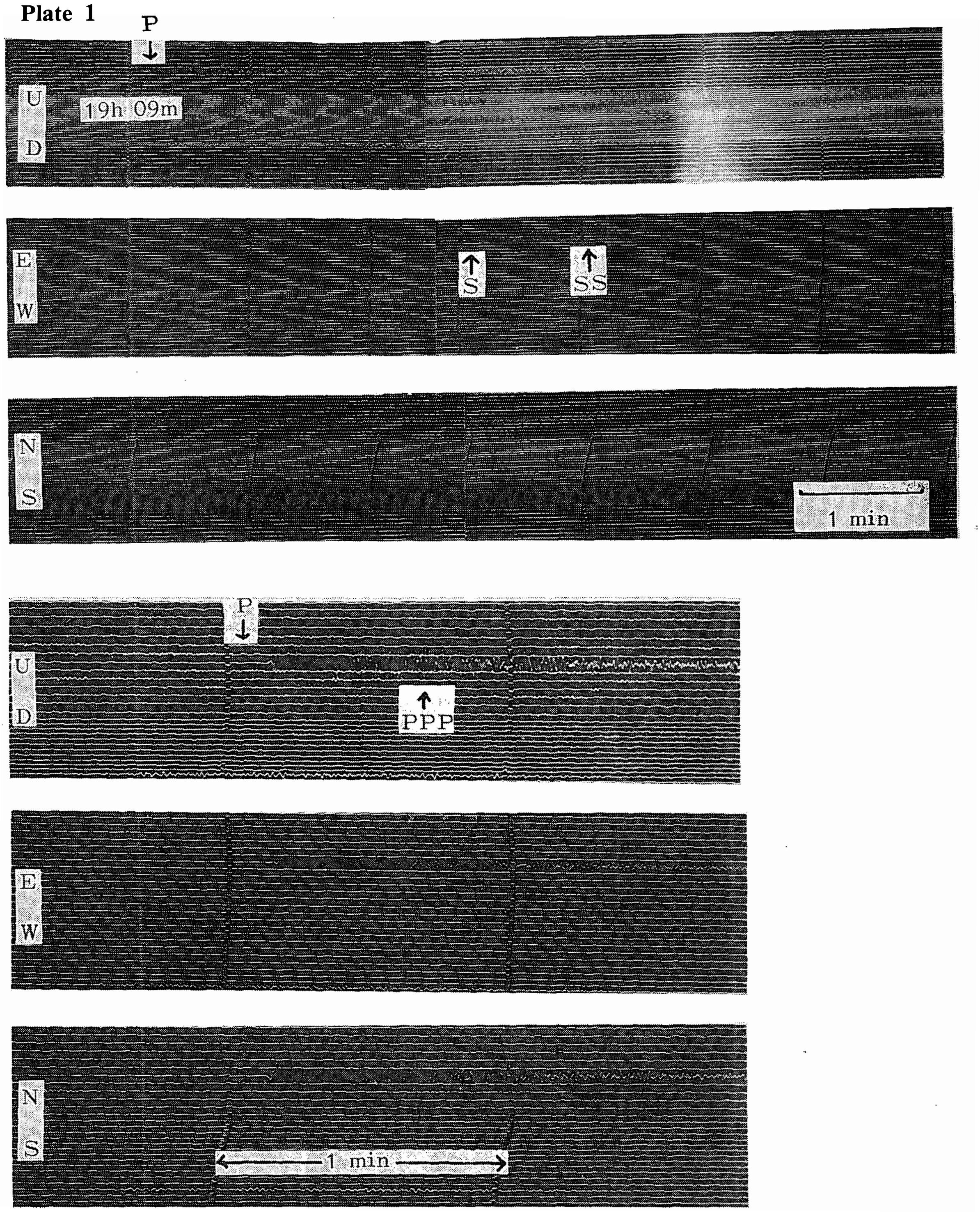
(*Manuscript received October 28, 1970*)

Plate 1



August 23, 1969

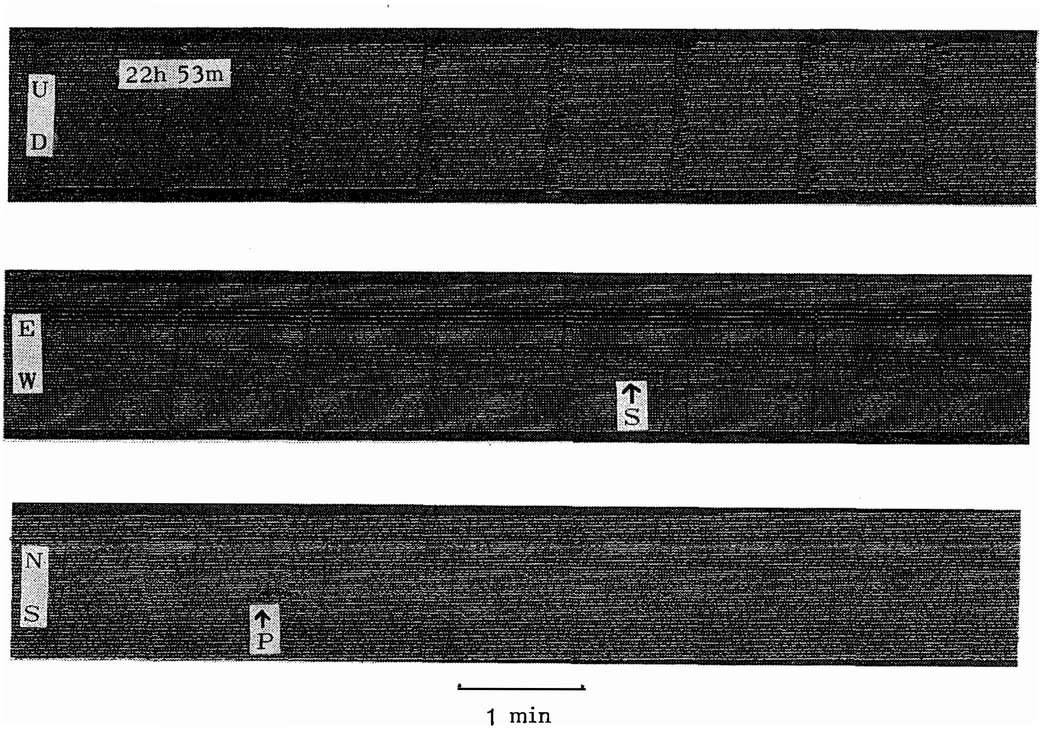
Origin time	19^h 05^m 11.8^s
Lat.	53.48°S
Long.	25.87°E
Depth	N
M	5.2

$\triangle = 16.8°$

South of Africa

Note: One of the nearest earthquakes whose hypocenters are determined by USCGS. The *S*-phases are not identified clearly. Small amplitude of first motion.

Plate 2



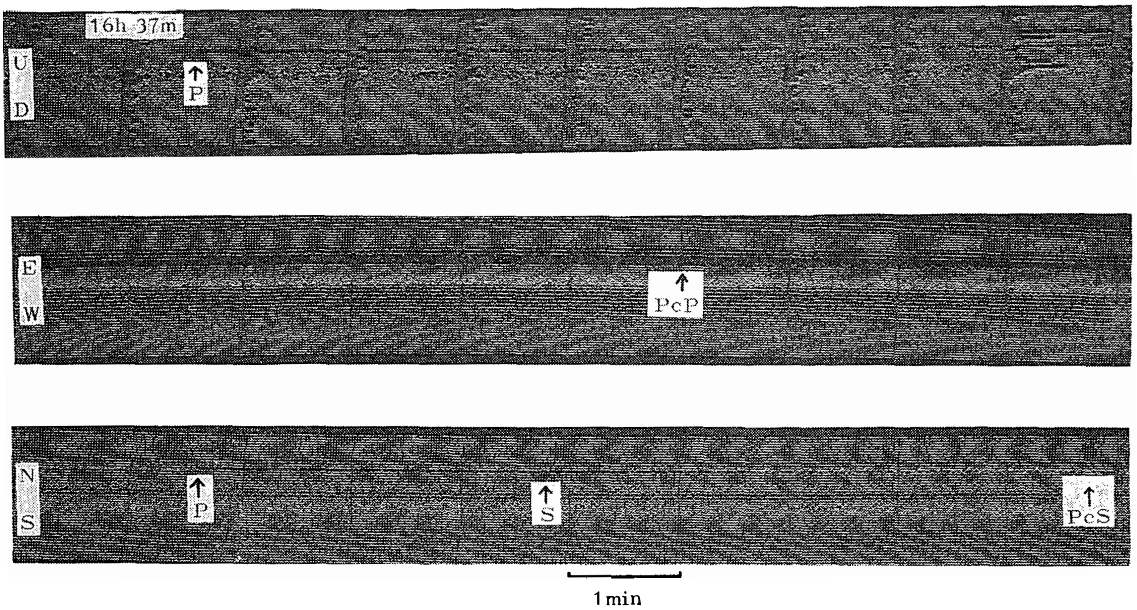
August 9, 1967

Origin time	22^h 49^m 11.9^s
Lat.	52.03°S
Long.	28.39°E
Depth	N
M	4.8

$\triangle = 17.8°$

South of Africa

Plate 3

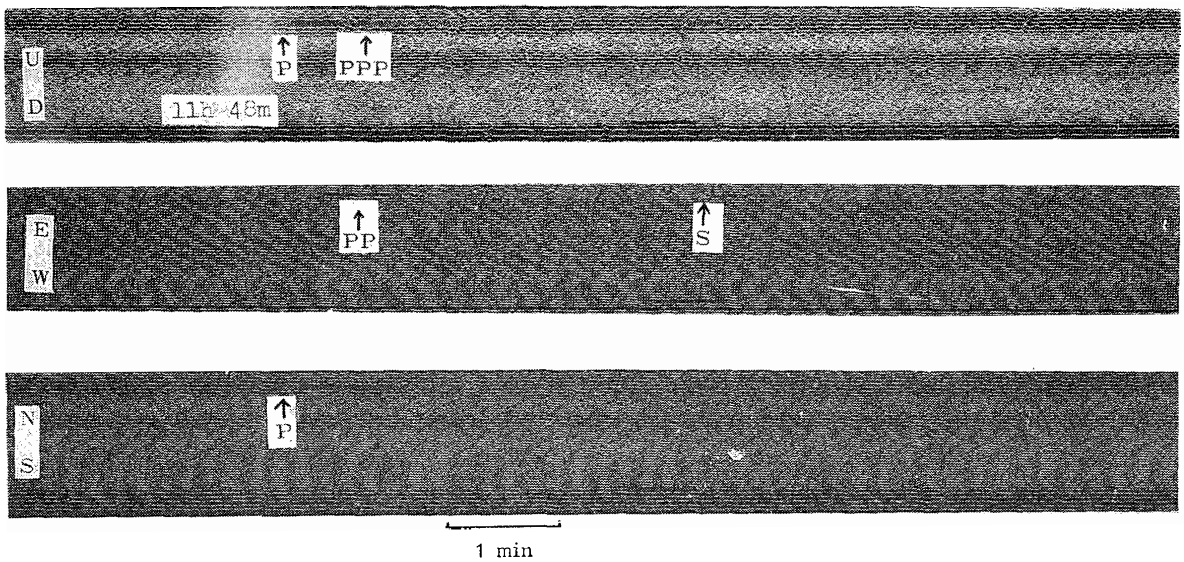


August 13, 1967

Origin time	16^h 33^m 04.0^s
Lat.	50.88°S
Long.	29.07°E
Depth	N
M	5.4

$\triangle = 18.9°$
South of Africa

Plate 4

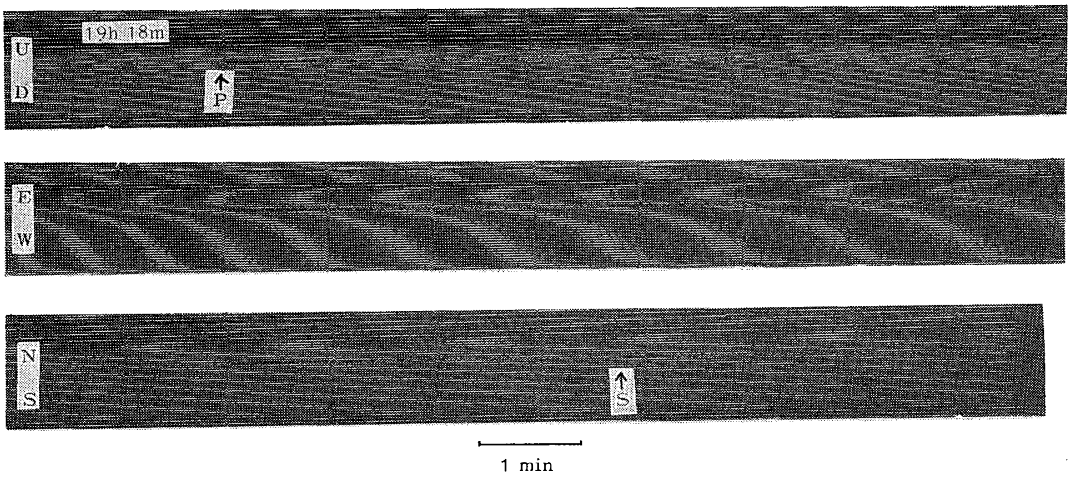


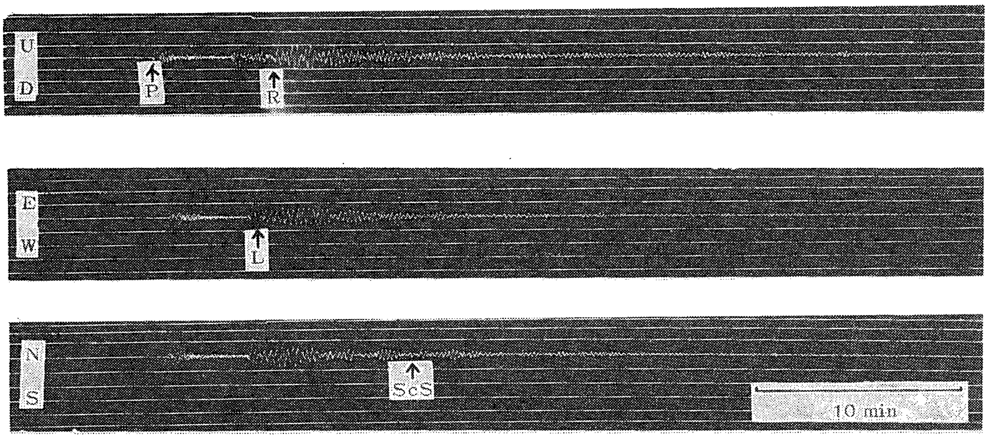
April 9, 1969

Origin time	11^h 43^m 47.6^s
Lat.	49.09°S
Long.	30.78°E
Depth	23 km
M	5.8

$\triangle = 20.5°$
South of Africa

Plate 5





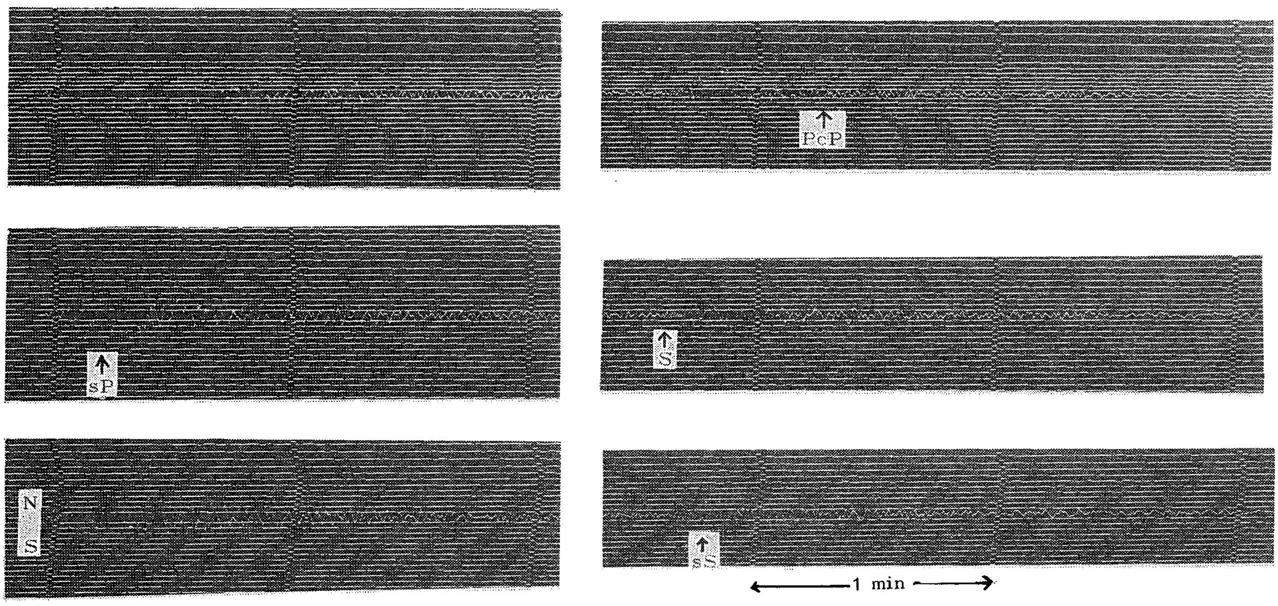


Plate 6

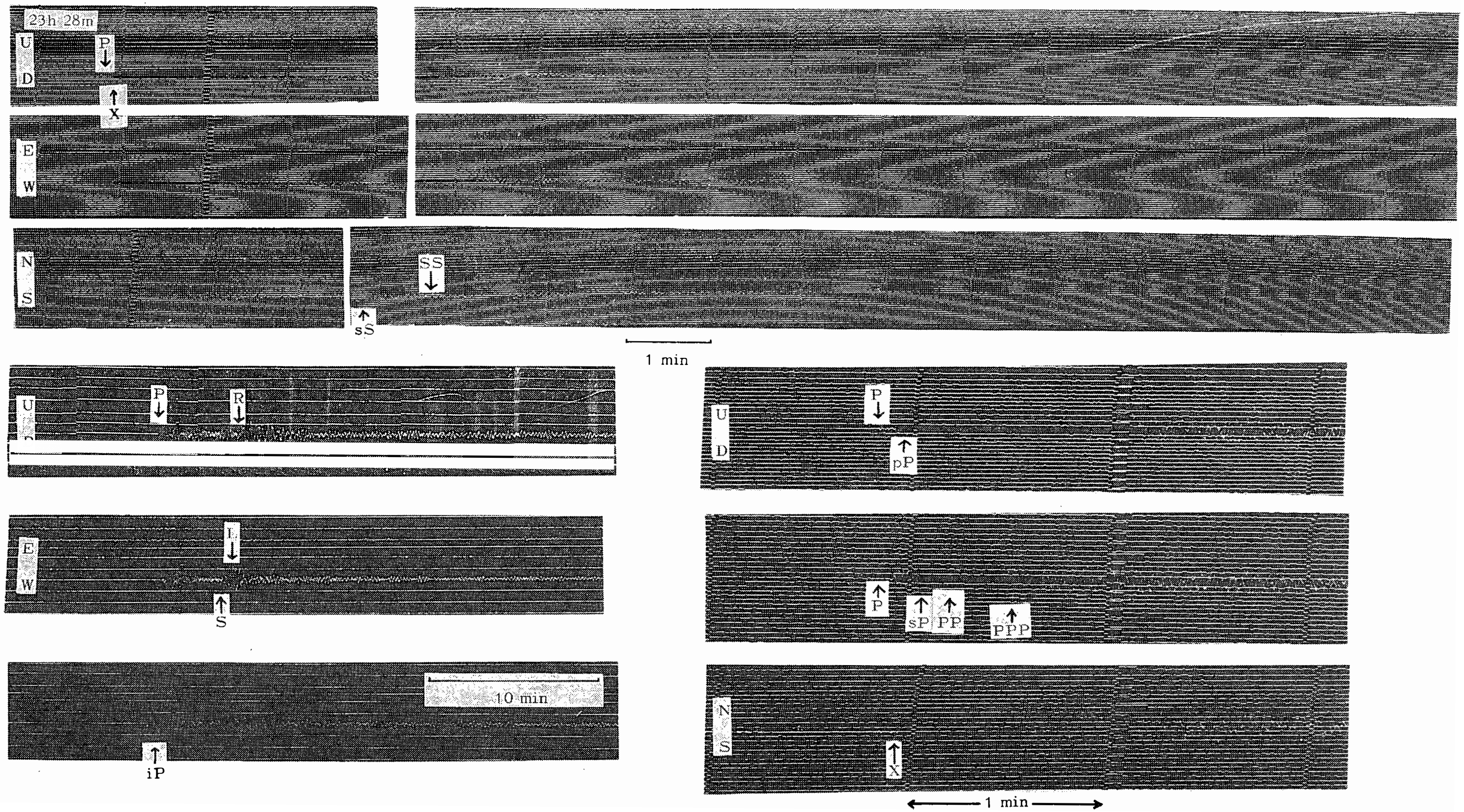
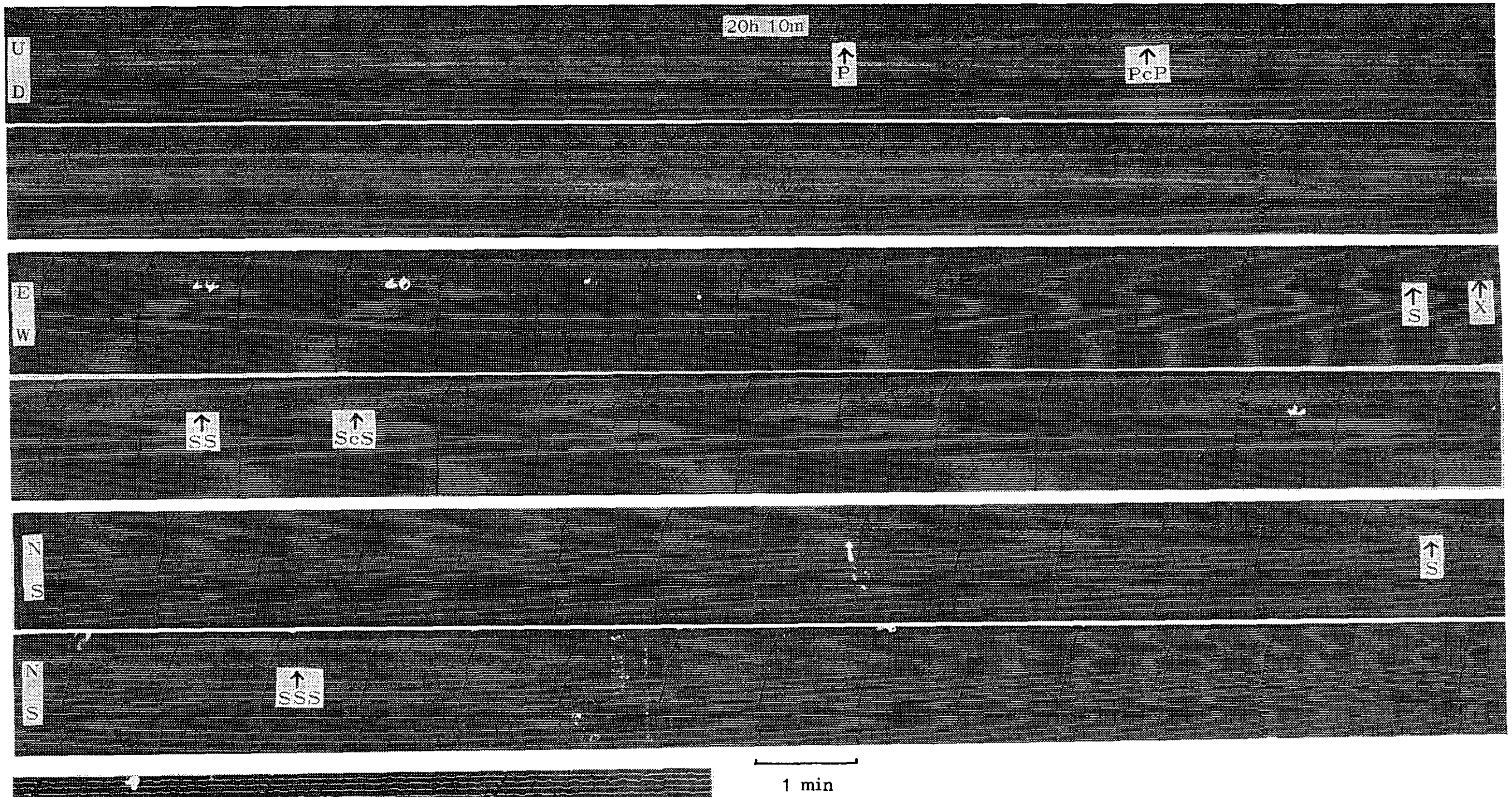


Plate 7


20h 10m
U
D
P
PcP
E
W
S
X
SS
ScS
N
S
S
N
S
SSS
1 min

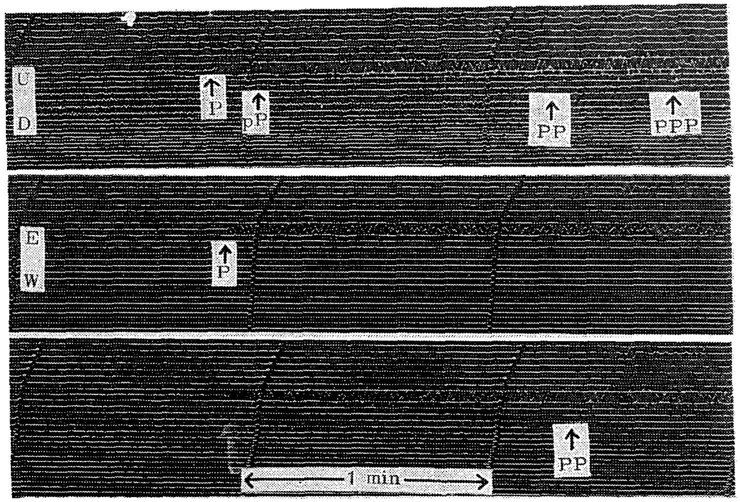

U
D
P
pP
PP
PPP
E
W
P
PP
1 min

Plate 5

June 16, 1968

Origin time	19^h 14^m 05.3^s
Lat.	53.92°S
Long.	8.70°E
Depth	33 km
M	5.7

△=20.7°

Bouvet Is. region

Note: Large amplitude *P* wave phases (*X*) arrived following the small initial *P* phase. Arrival time of *S* waves is some 15 seconds earlier than that of G–R tables.

Plate 6

June 8, 1968

Origin time	23^h 24^m 05.2^s
Lat.	48.75°S
Long.	31.54°E
Depth	N
M	5.6

△=20.7°

South of Africa

Note: Large amplitude *P* phases (*X*) following the small initial *P*.

Plate 7

September 29, 1969

Origin time	20^h 03^m 32.8^s
Lat.	32.91°S
Long.	19.66°E
Depth	N
M	5.9

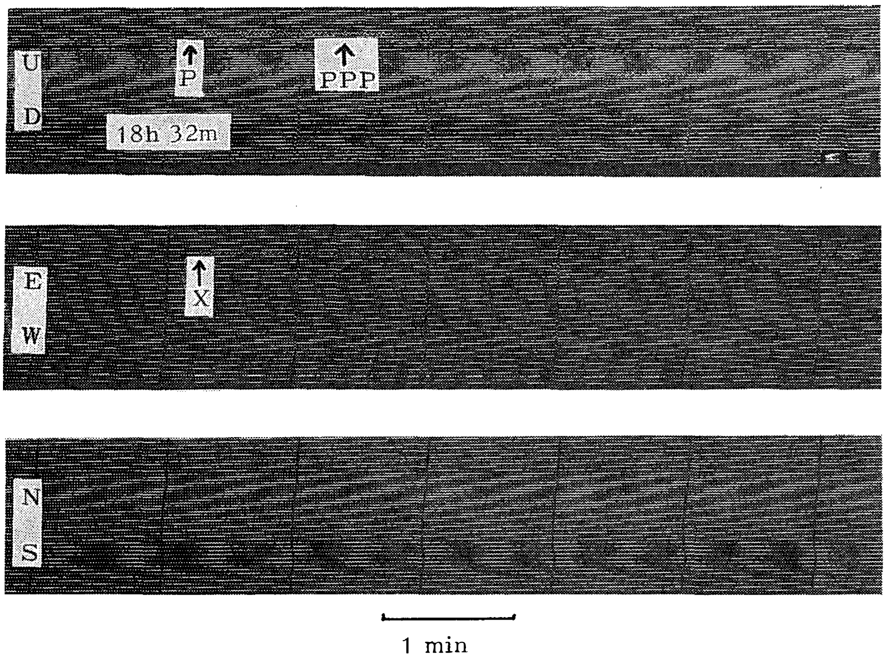
△=37.9°

Republic of South Africa

12 dead, dozens injured, hundreds homeless at Tulbrogh and Walseley. Felt widely throughout Cape Province. Foreshock preceded computed origin time by approximately 5 seconds.

Note: Arrival time of *S* waves is some 20 seconds earlier than that of G–R tables.

Plate 8



November 26, 1969

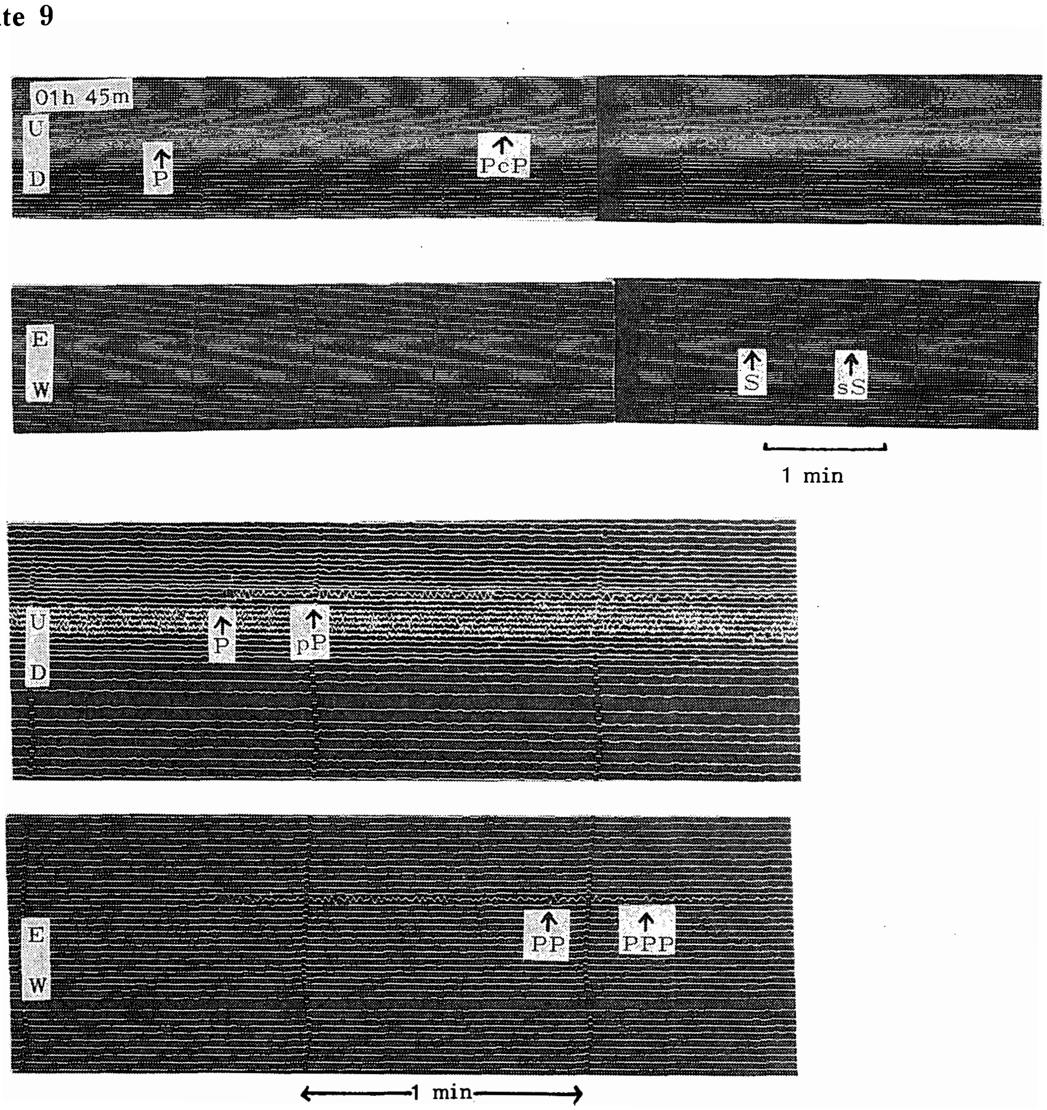
Origin time	$18^h\ 26^m\ 08.9^s$
Lat.	58.84°S
Long.	24.71°W
Depth	N
M	5.4

$\triangle = 28.6°$

South Sandwich Is. region

Note: Small initial *P* phase and following large *P* wave group. Small *S* phase.

Plate 9



October 23, 1969

Origin time	01^{h} 39^{m} 22.1^{s}
Lat.	56.15°S
Long.	27.35°W
Depth	95 km
M	5.3

$\triangle = 31.5°$

South Sandwich Is. region

Note: Compare the amplitude of *P* with before Plate, the shallow shock. The pulse like first motion.

Plate 10

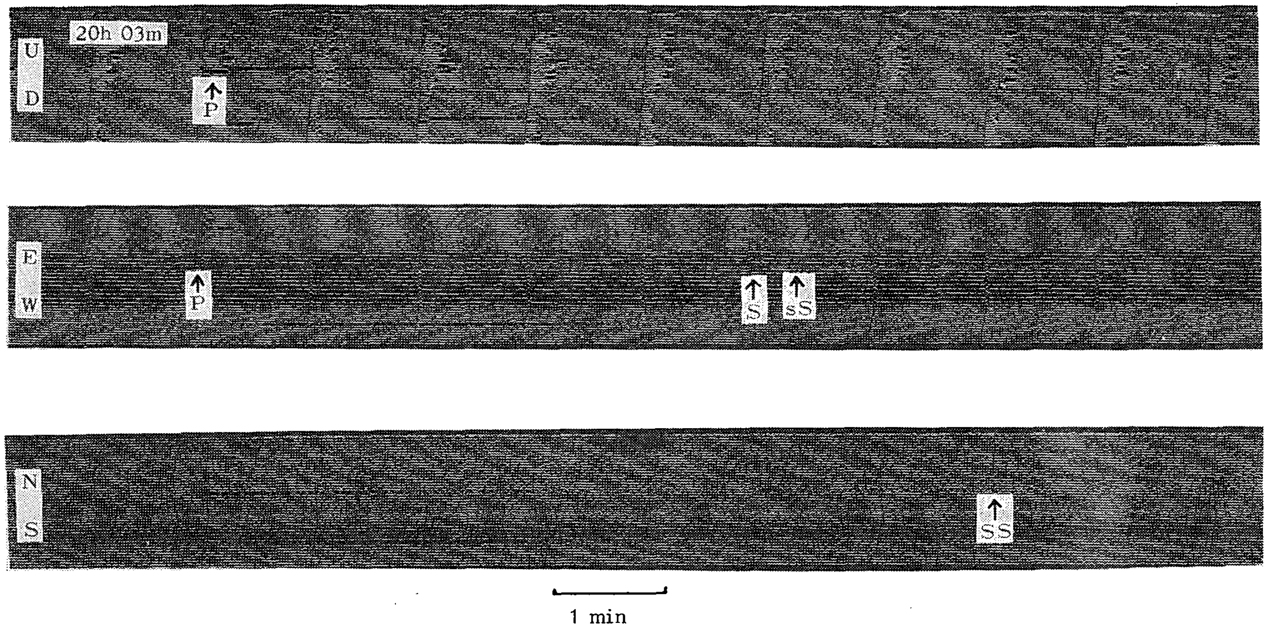


Plate 11

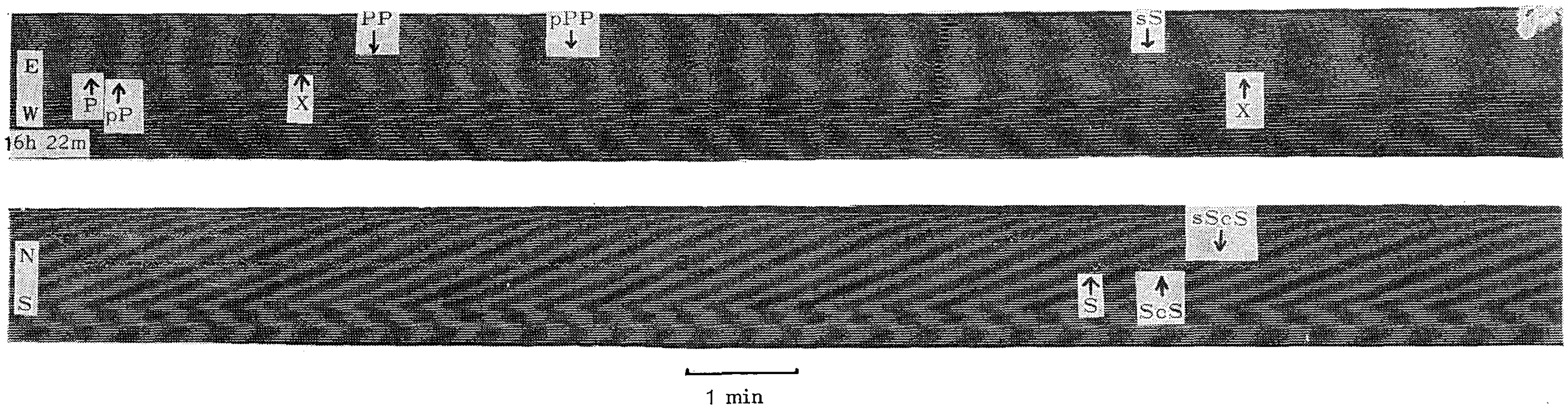


Plate 10

September 13, 1967

Origin time	$19^h\ 57^m\ 47.9^s$
Lat.	56.05°S
Long.	27.38°W
Depth	148 km
M	5.3

$\triangle = 31.7°$

South Sandwich Is. region

Plate 11

September 26, 1967

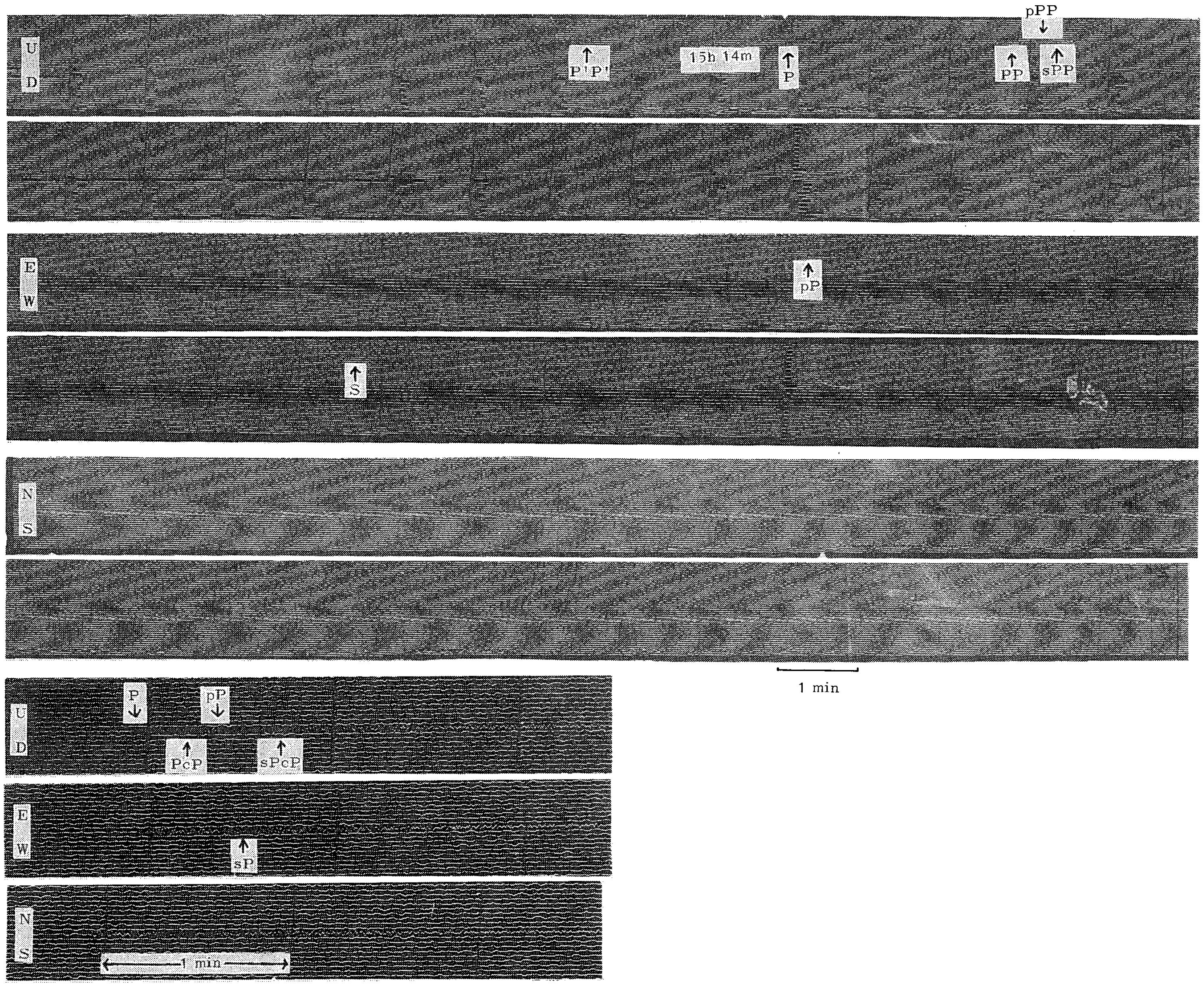
Origin time	$16^h\ 11^m\ 23.9^s$
Lat.	30.04°S
Long.	71.53°W
Depth	53 km
M	5.7

$\triangle = 69.4°$

Near coast of Central Chile

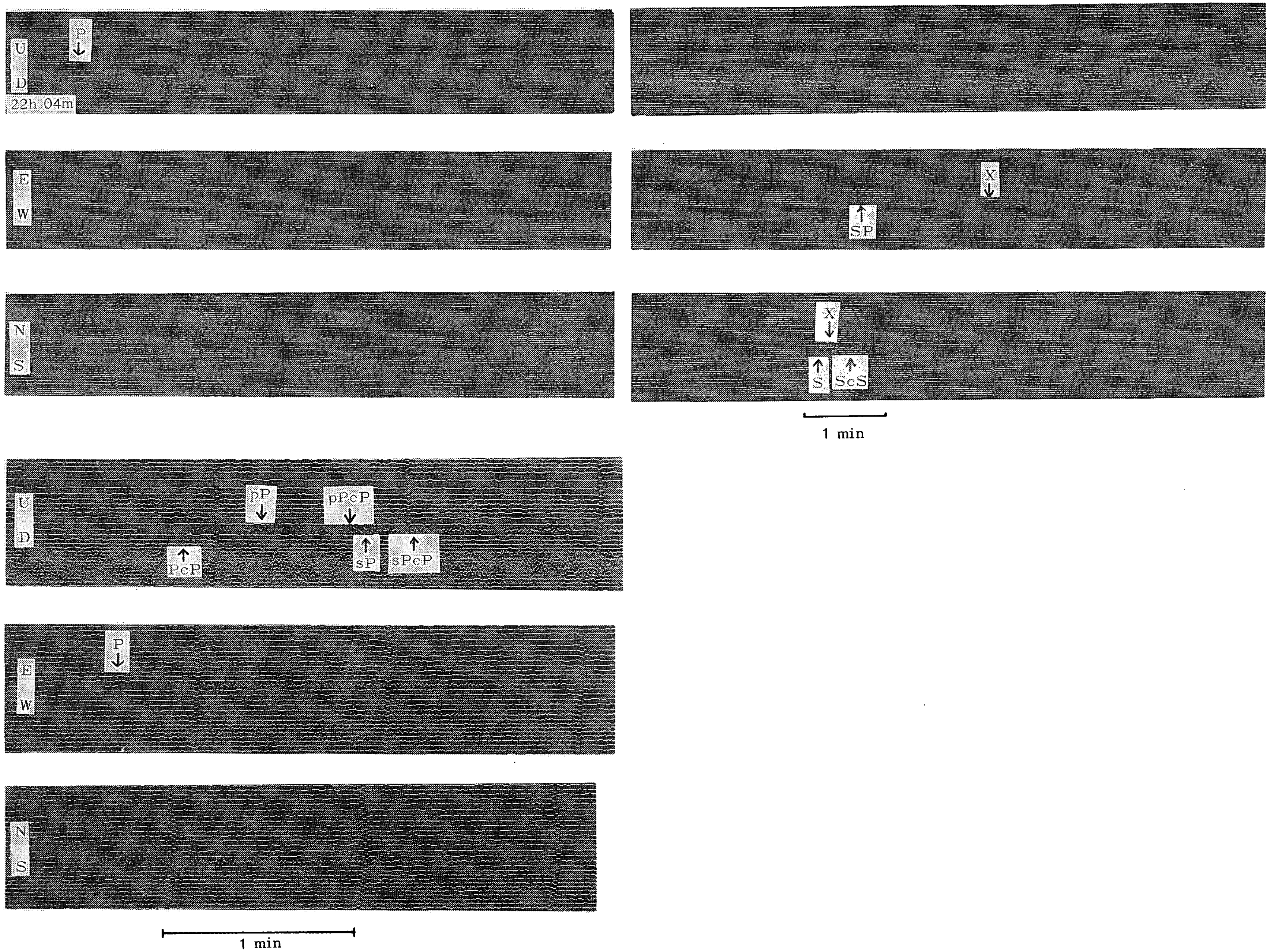
Note: Unexplained phases (X) are recorded. Large sS on Z component.

Plate 12



U
D
P'P'
15h 14m
P
PP
pPP
sPP
E
W
pP
S
N
S
1 min
U
D
P
pP
PcP
sPcP
E
W
sP
N
S
1 min

Plate 13


U
D
22h 04m
P
E
W
N
S
X
SP
X
S
ScS
1 min
U
D
pP
pPcP
PcP
sP
sPcP
E
W
P
N
S
1 min

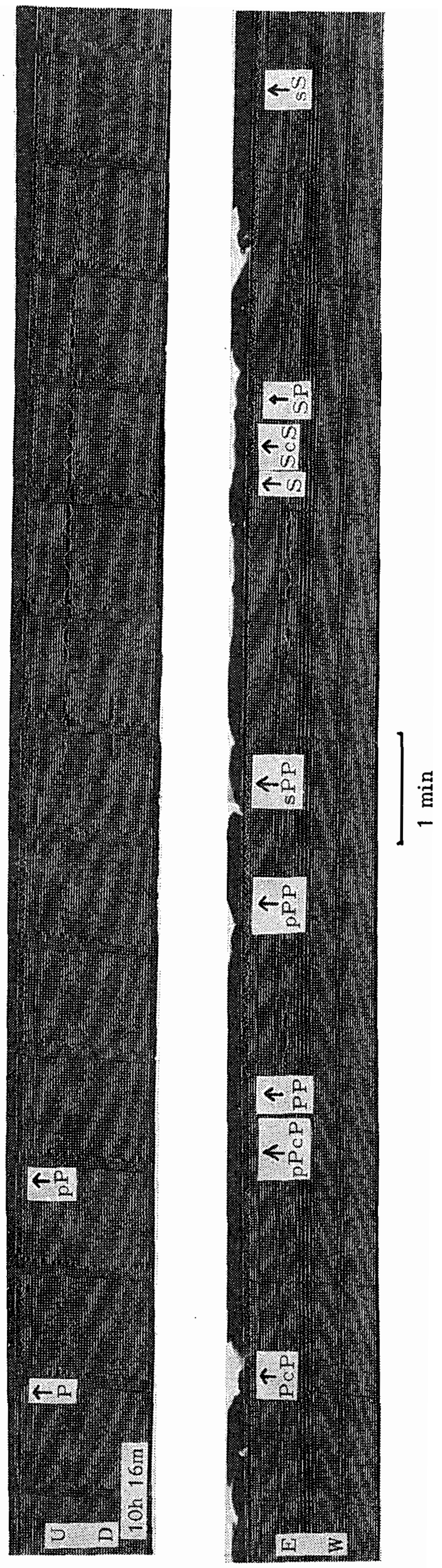


Plate 14

Plate 12

August 20, 1967

Origin time	15^{h} 03^{m} 36.2^{s}
Lat.	25.20°S
Long.	69.02°W
Depth	109 km
M	5.6

△=73.1°

Northern Chile

Note: The shock on the lower part of seismograms is treated in Region E (Plate 31).
Core phase of $P'P'$ can be interpreted.

Plate 13

September 22, 1968

Origin time	21^{h} 52^{m} 59.2^{s}
Lat.	24.13°S
Long.	69.91°W
Depth	194 km
M	5.5

△=73.4°

Salta province, Argentina

Note: Large phases (X) follwing the direct S wave.

Plate 14

September 9, 1967

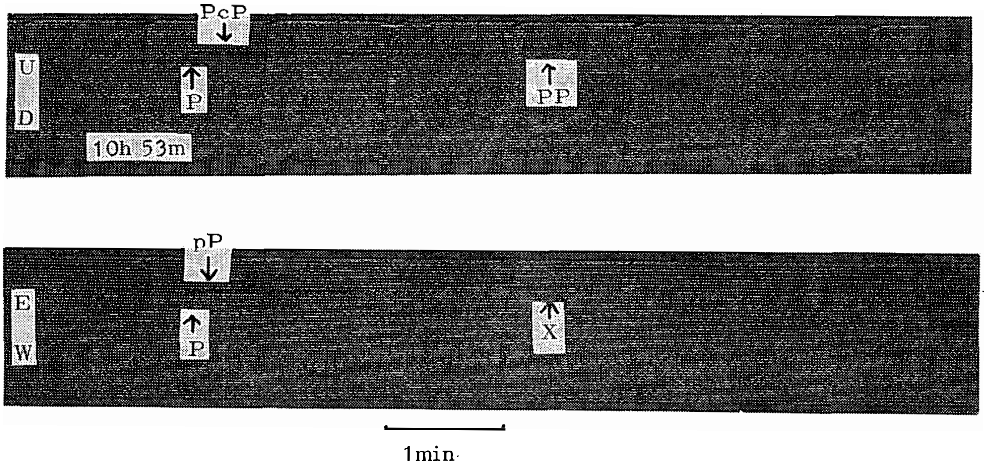
Origin time	10^{h} 06^{m} 44.1^{s}
Lat.	22.70°S
Long.	63.14°W
Depth	578 km
M	5.8

△=73.5°

Santiago del Estero prov., Argentina.

Note: Initial P wave cannot identified for the obscure records.

Plate 15



December 25, 1967

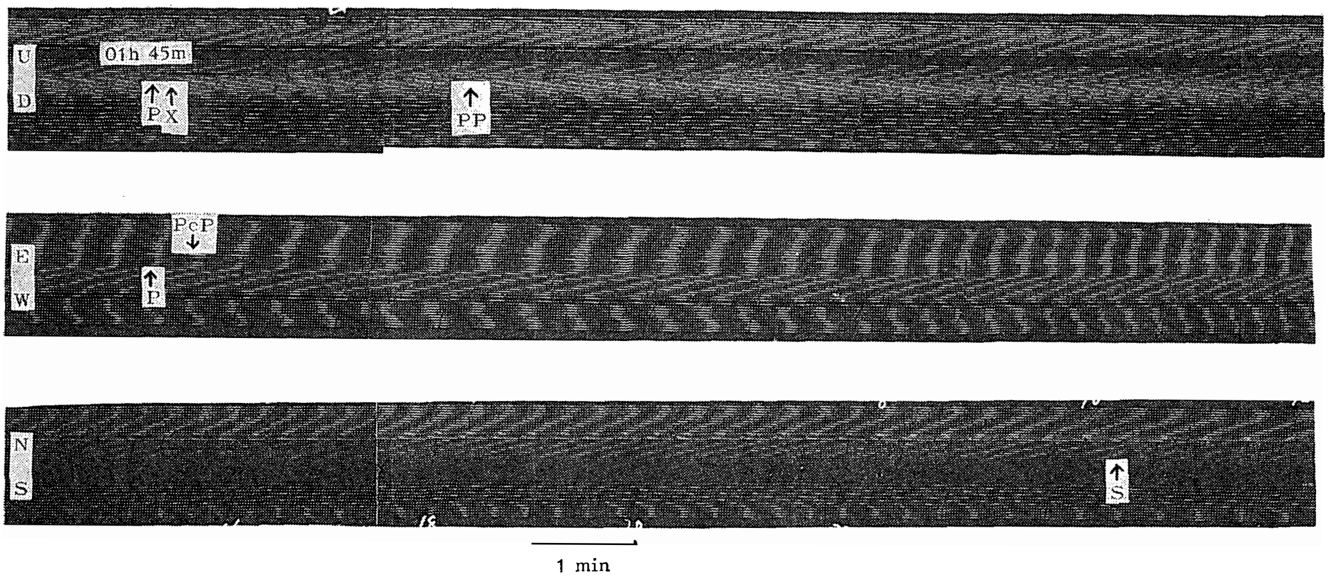
Origin time	$10^{h}\ 41^{m}\ 31.6^{s}$
Lat.	21.48°S
Long.	70.37°W
Depth	53 km
M	5.8

$\triangle = 77.0°$

Near coast of Northern Chile

Note: *S* phases are not identified for small amplitude.

Plate 16



October 3, 1969

Origin time	$01^{h}\ 33^{m}\ 19.8^{s}$
Lat.	32.85°S
Long.	178.03°W
Depth	26 km
M	5.7

$\triangle = 74.7°$

South of Kermadec Is.

Note: Small initial *P* phase and following large unexplained phases.

Plate 17

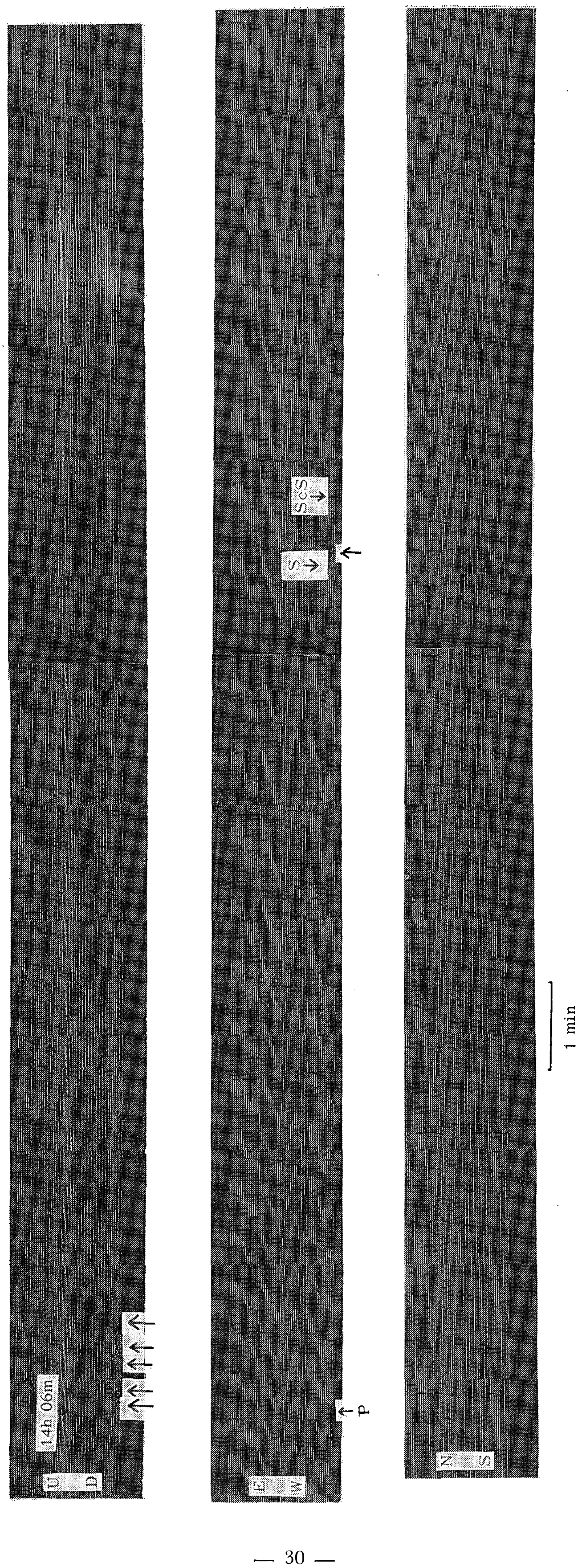


Plate 18

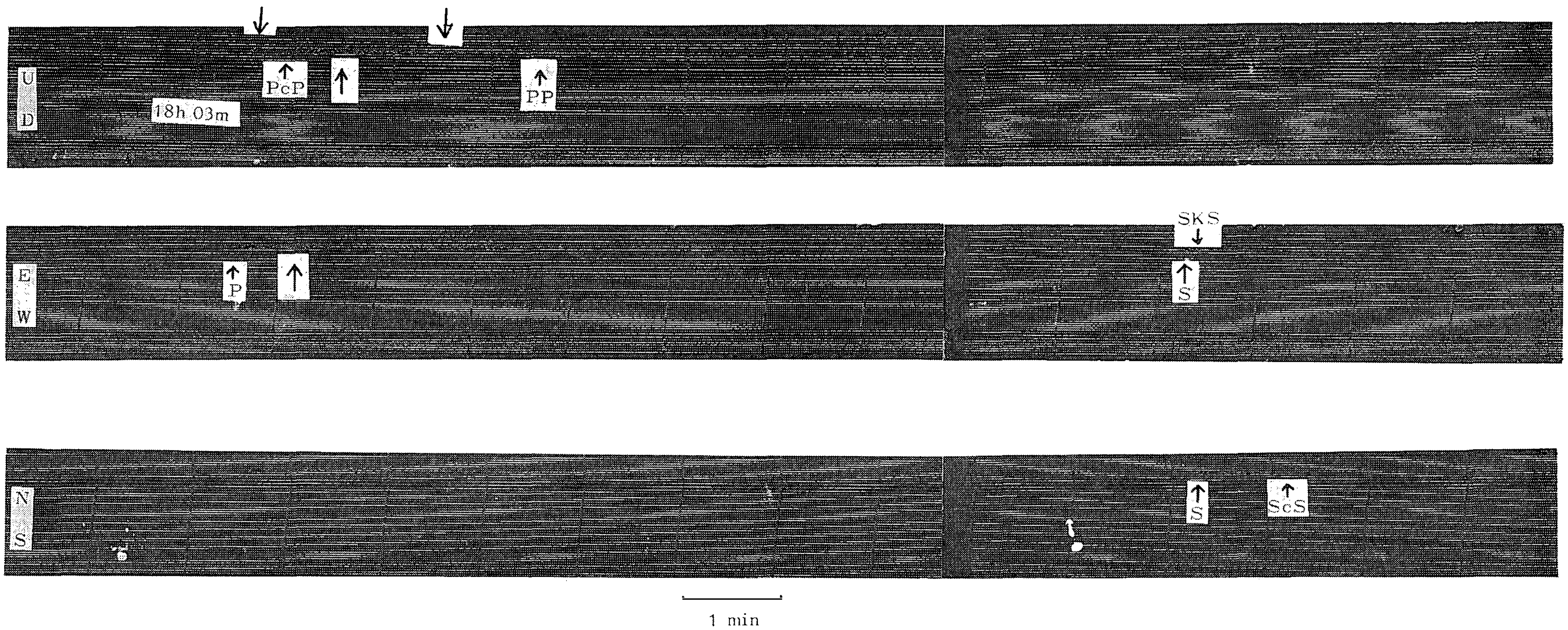


Plate 19

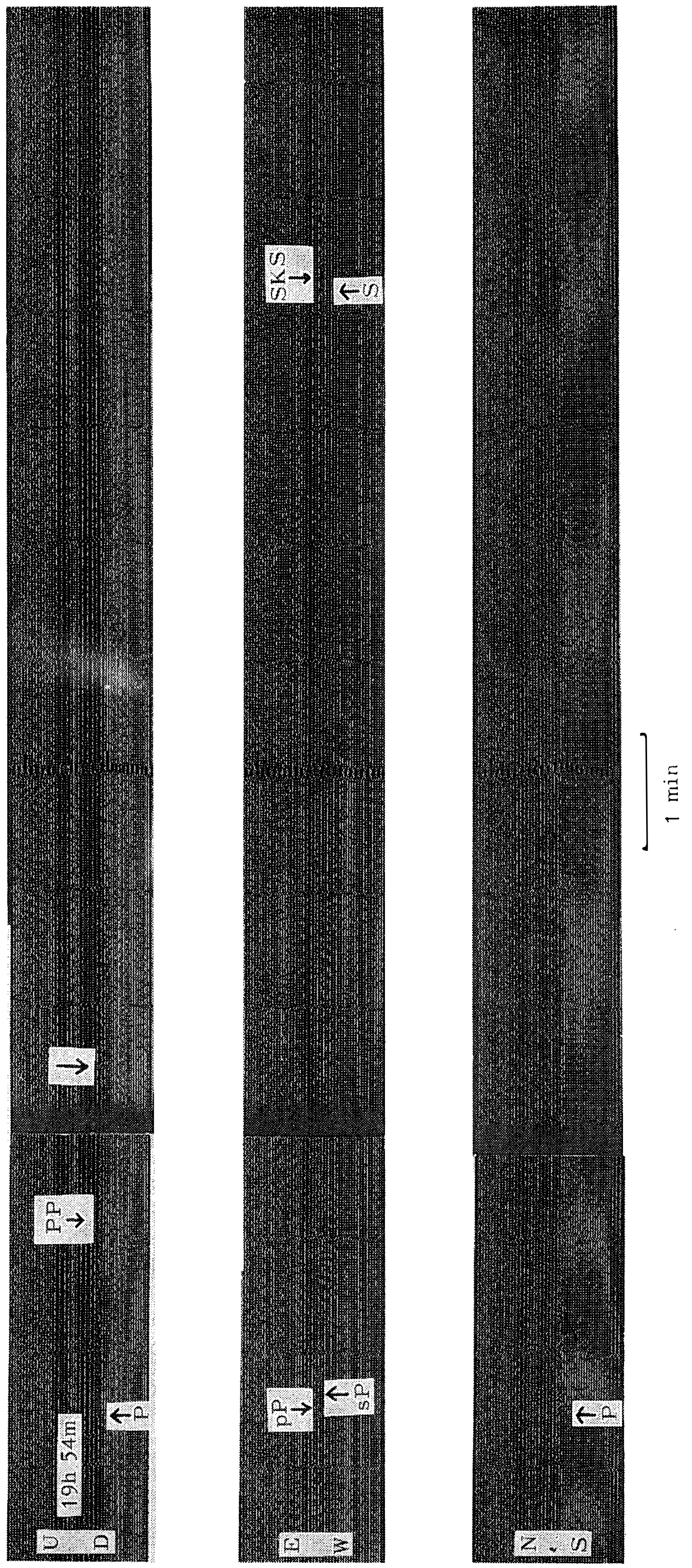


Plate 17

August 28, 1969

Origin time	13^{h} 54^{m} 11.0^{s}
Lat.	31.47°S
Long.	177.88°W
Depth	29 km
M	5.3

△=76.1°

Kermadec Is.

Note: Unexplained phases of Gutenberg and Richter are shown with an arrow.

Plate 18

September 30, 1969

Origin time	17^{h} 51^{m} 41.8^{s}
Lat.	31.93°S
Long.	178.02°W
Depth	N
M	5.4

△=75.7°

Kermadec Is.

Note: A clear phase of *S* group following the direct *S* phase.

Plate 19

May 30, 1968

Origin time	19^{h} 42^{m} 25.1^{s}
Lat.	30.95°S
Long.	177.63°W
Depth	42 km
M	5.5

△=76.7°

Kermadec Is.

Note: A clear *S* phase following the direct *S* phase.

Plate 20

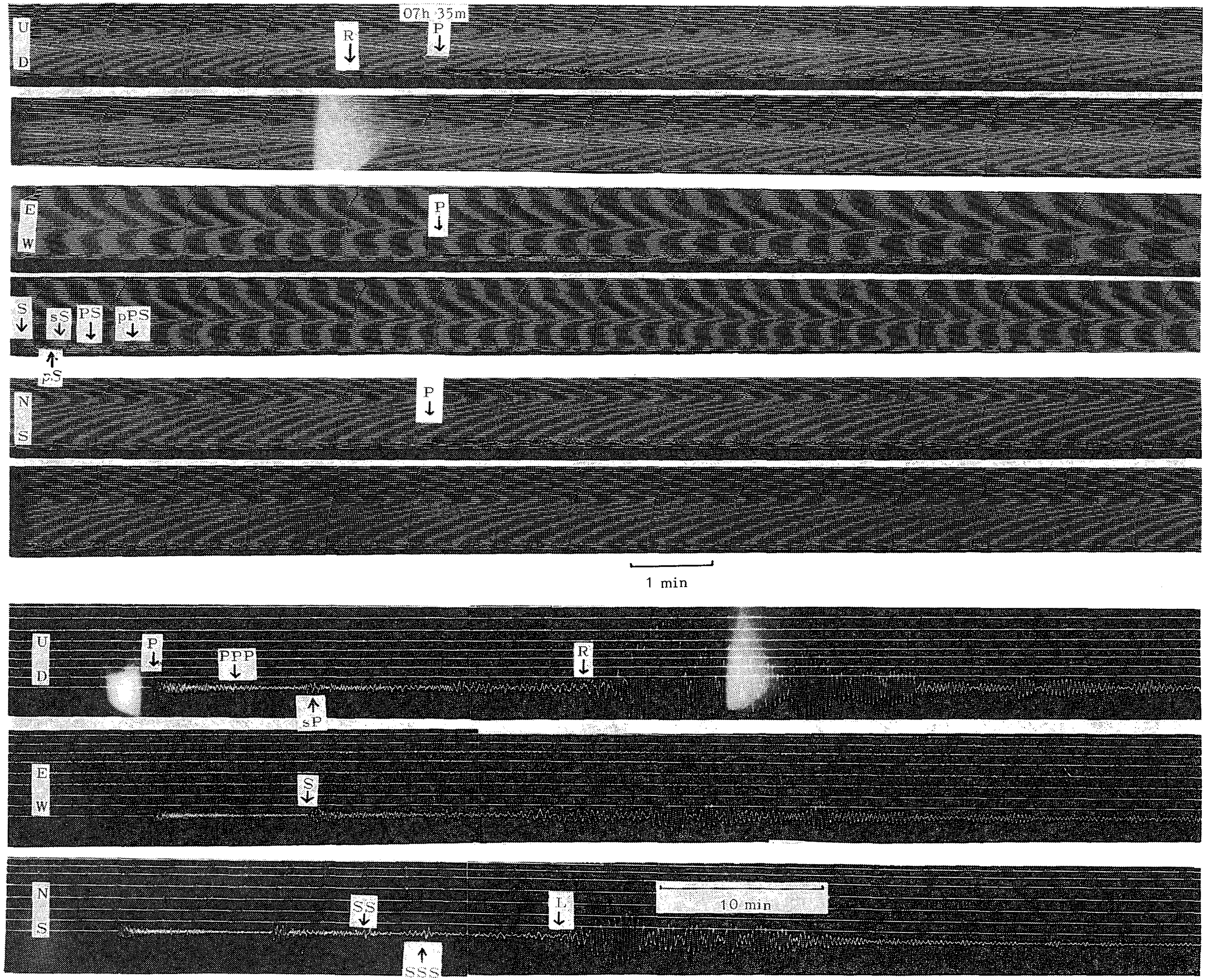

07h 35m
U
D
R
P
E
W
S
sS
PS
pPS
pS
N
S
1 min
U
D
P
PPP
sP
R
E
W
S
N
S
SS
SSS
L
10 min

Plate 21

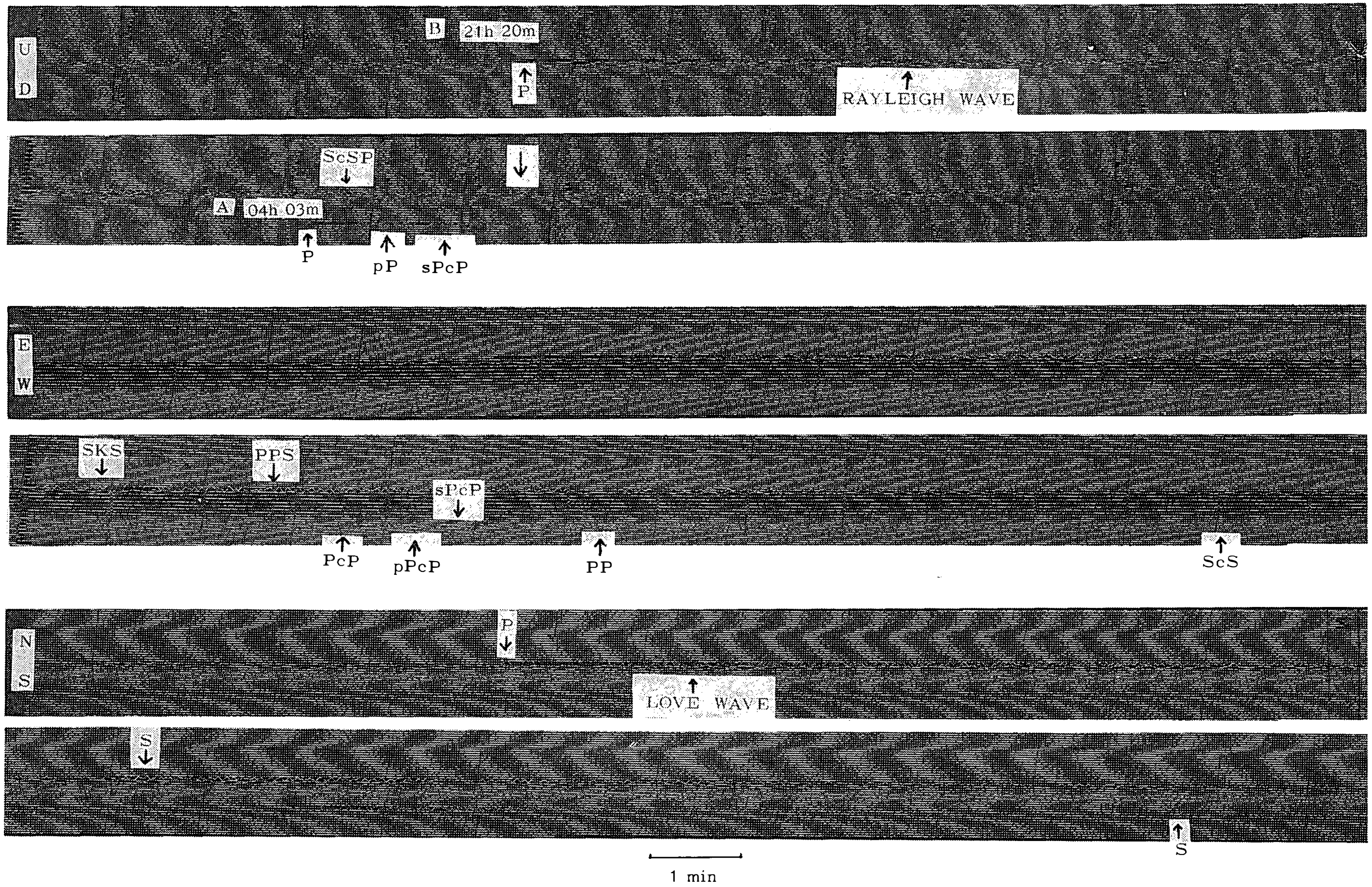

U
D
B
21h 20m
P
RAYLEIGH WAVE
ScSP
A
04h 03m
P
pP
sPcP
E
W
SKS
PPS
sPcP
PcP
pPcP
PP
ScS
N
S
P
LOVE WAVE
S
S
1 min

Plate 22

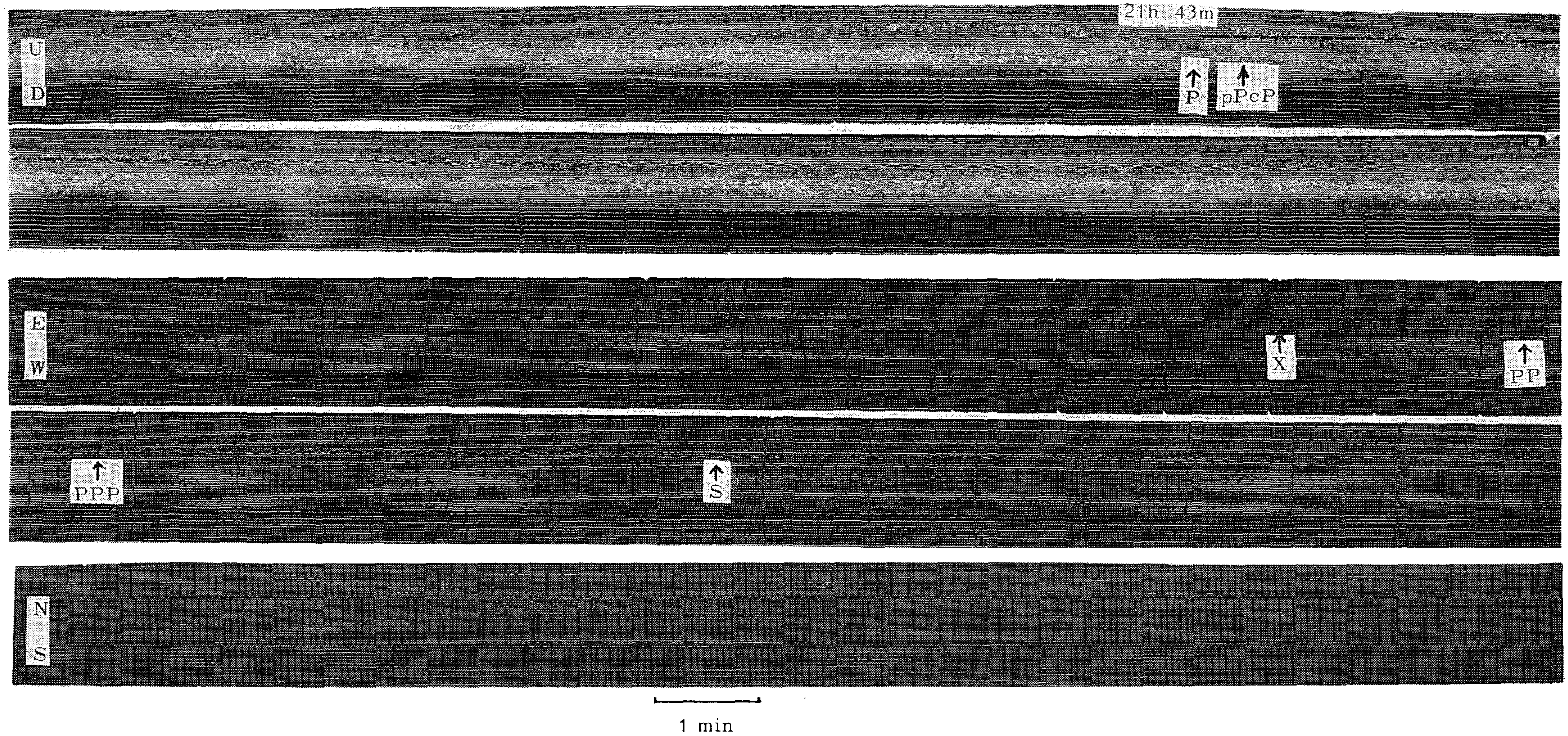


Plate 20

July 25, 1968	
Origin time	07^h 23^m 07.8^s
Lat.	30.77°S
Long.	178.35°W
Depth	60 (Restrained) km
M	6.4

$\triangle = 76.7°$

Kermadec Is. region

Note: Phases of *ScS*, *pS*, *sS sP*, *PS* and *pPS* following the direct *S* wave.

Plate 21

A	September 4, 1967	
	Origin time	03^h 51^m 58.9^s
	Lat.	31.44°S
	Long.	179.45°W
	M	5.5

$\triangle = 75.9°$

Kermadec Is.

B	September 3, 1967	
	Origin time	21^h 07^m 30.8^s
	Lat.	10.58°S
	Long.	79.75°W
	Depth	38 km
	M	6.5

$\triangle = 90.2°$

Off coast of Peru

Note: This shock enlarges the Region C.

Plate 22

October 26, 1969	
Origin time	21^h 25^m 32.2^s
Lat.	27.10°S
Long.	176.63°W
Depth	44 km
M	5.2

$\triangle = 80.6°$

Kermadec Is.

Note: Large amplitude of *PP* phases.

Plate 23

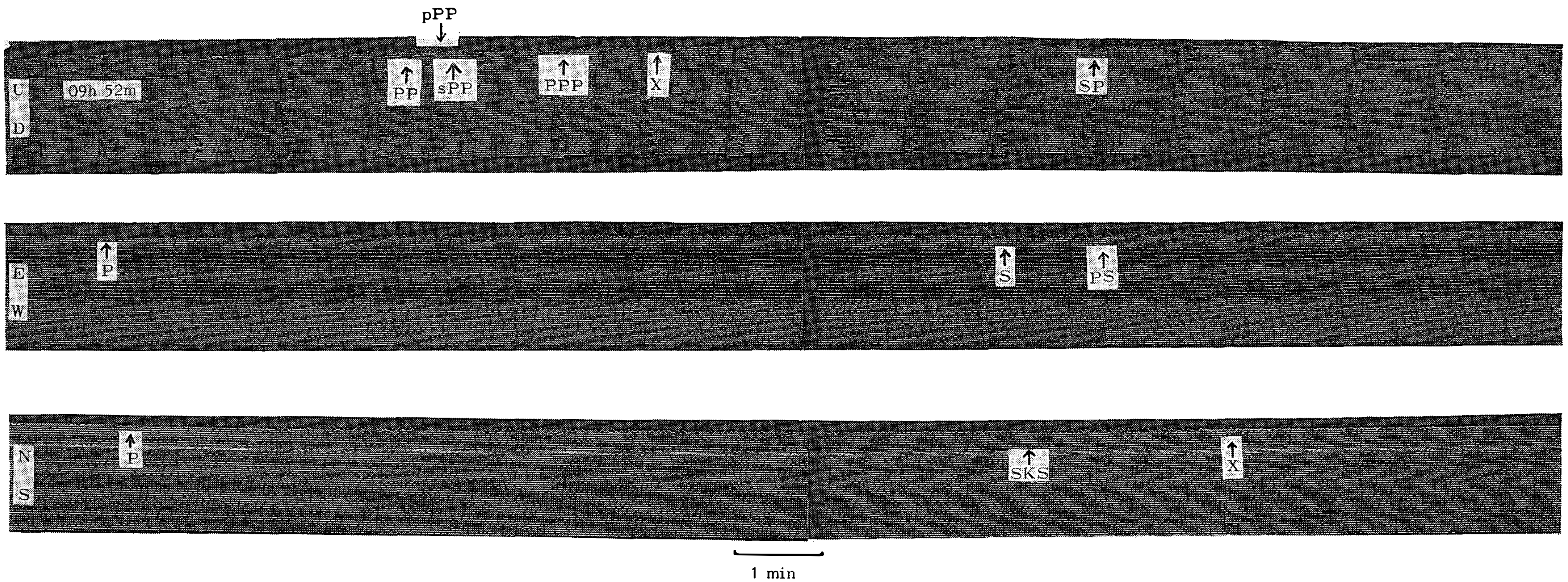
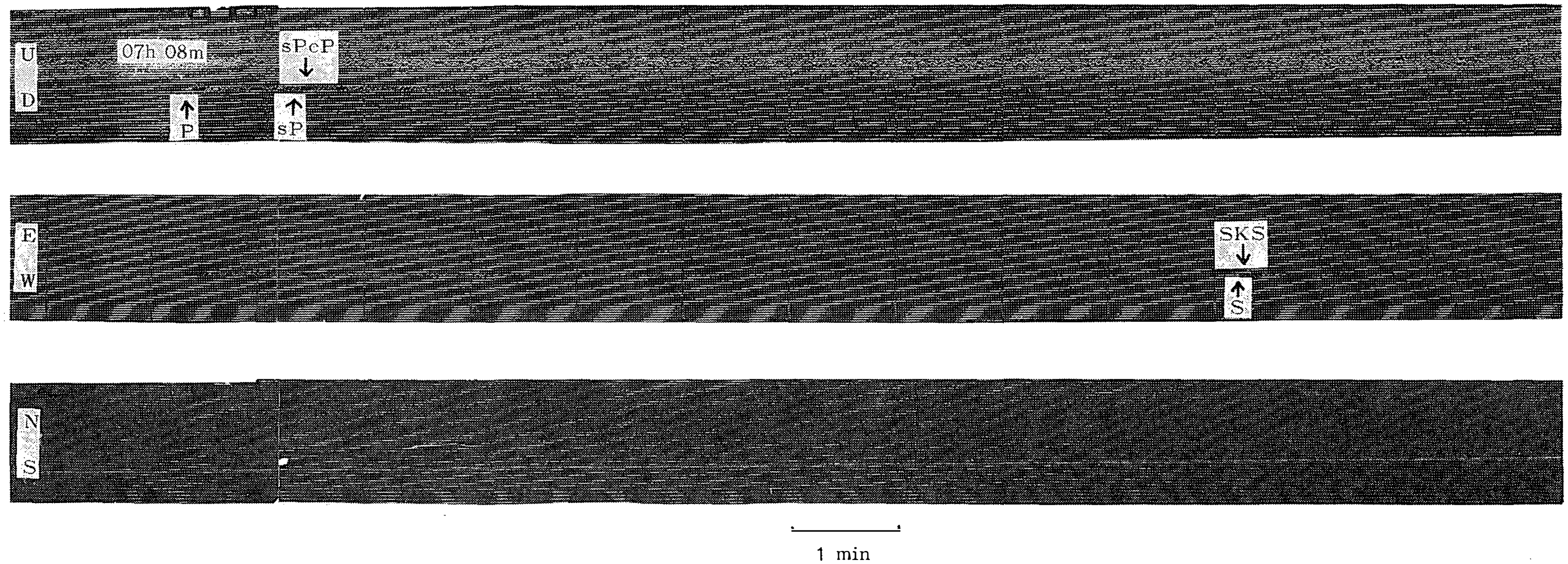


Plate 24



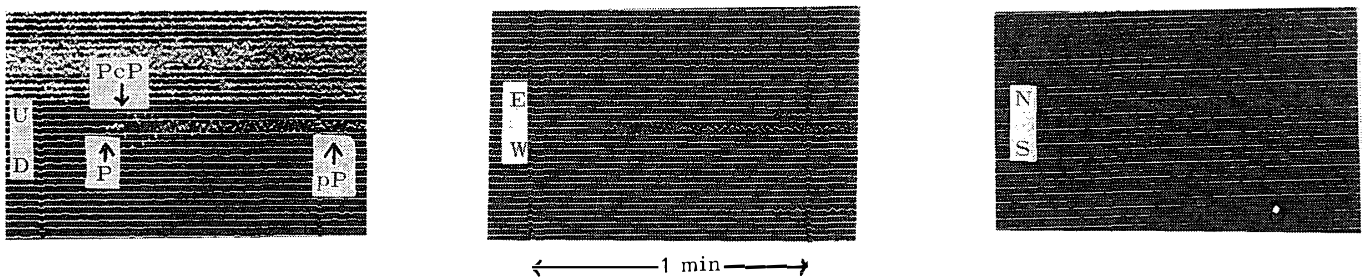


Plate 25

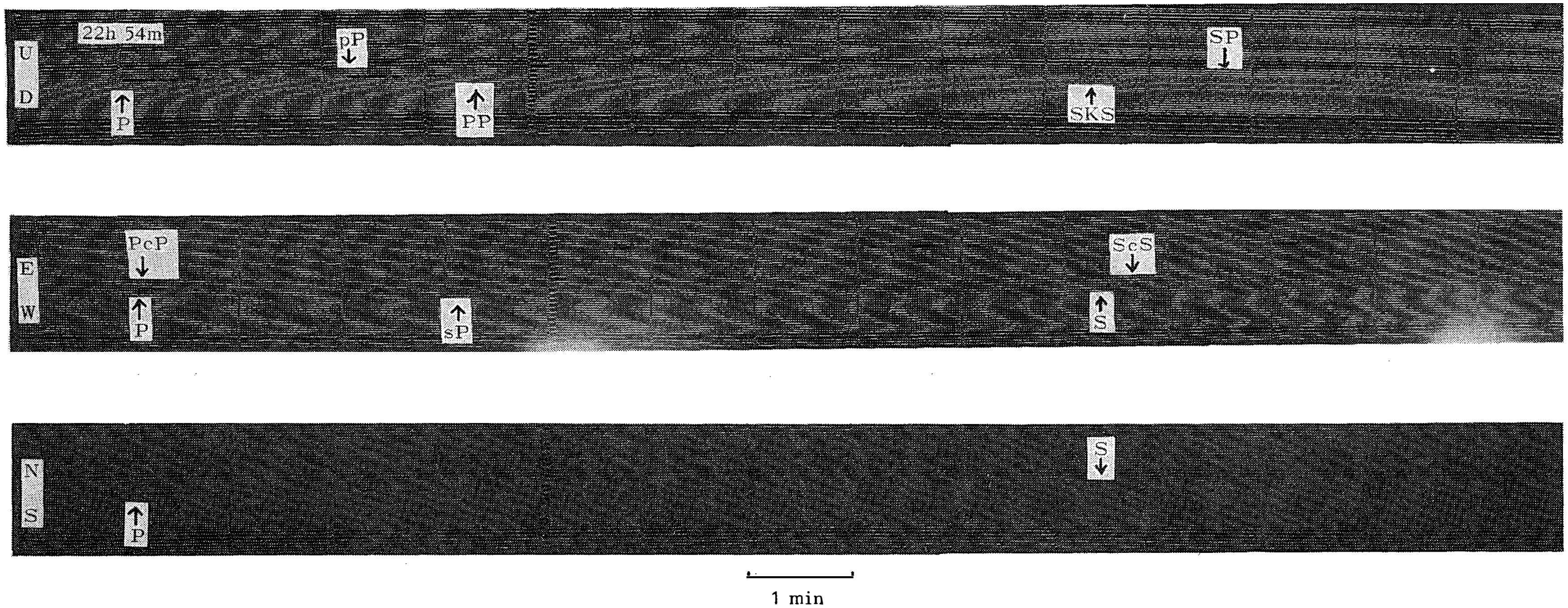


Plate 23

August 12, 1967	
Origin time	$09^h\ 39^m\ 44.3^s$
Lat.	24.71°S
Long.	177.47°W
Depth	134 km
M	5.8

△=82.7°

South of Fiji Is.

Note: *SKS* phase first seen at this distant.

Plate 24

October 13, 1969	
Origin time	$06^h\ 56^m\ 01.6^s$
Lat.	18.85°S
Long.	169.31°E
Depth	246 km
M	5.9

△=85.3°

New Hebrides Is.

Felt at Port Vila

Note: Small initial *P* and large *PcP* phase.

Plate 25

September 12, 1968	
Origin time	$22^h\ 44^m\ 06.5^s$
Lat.	21.55°S
Long.	179.36°W
Depth	635 km
M	5.9

△=85.4°

Fiji Is. region

Note: The deepest earthquake in this series, *P* and *PcP* phases arrived almost at the same time at this depth and distance.

Plate 26

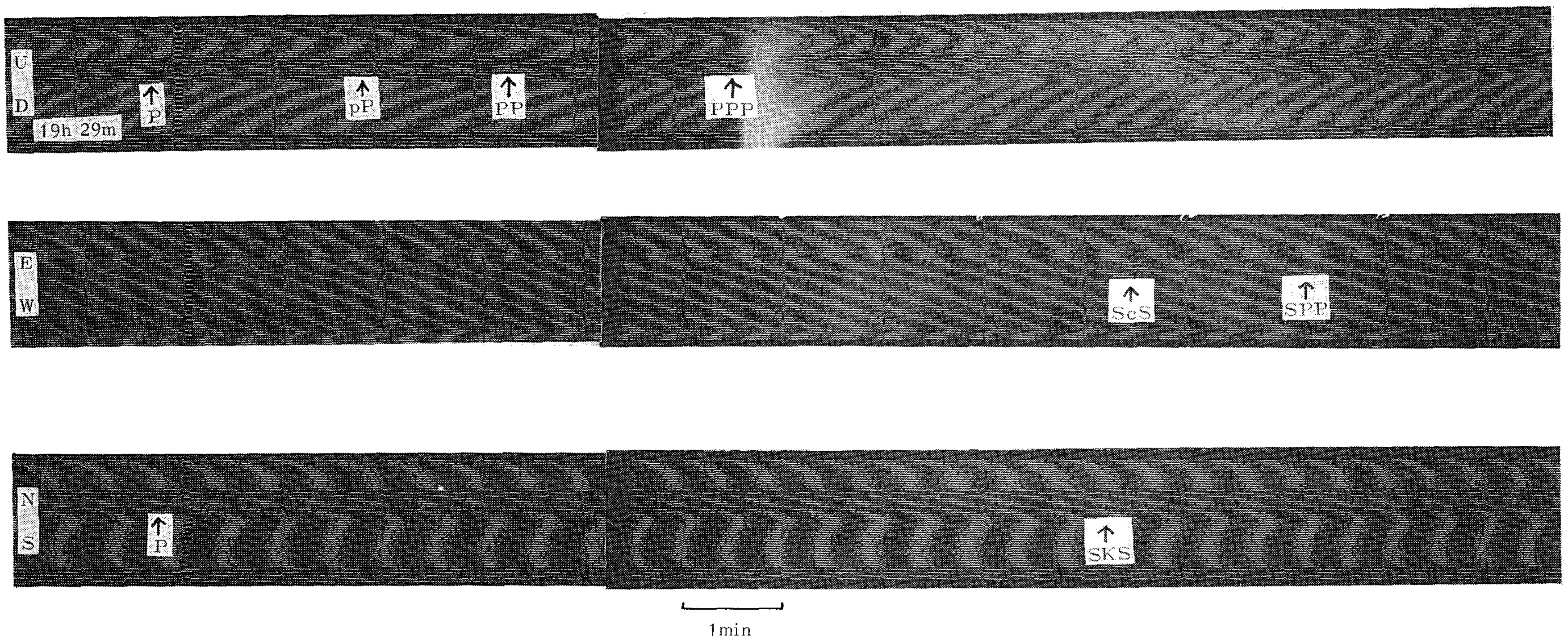
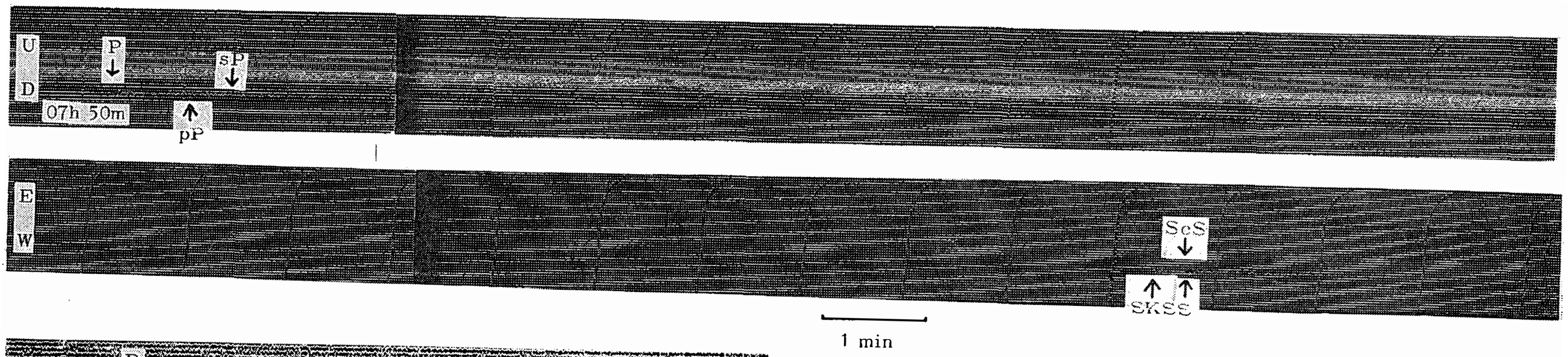


Plate 27



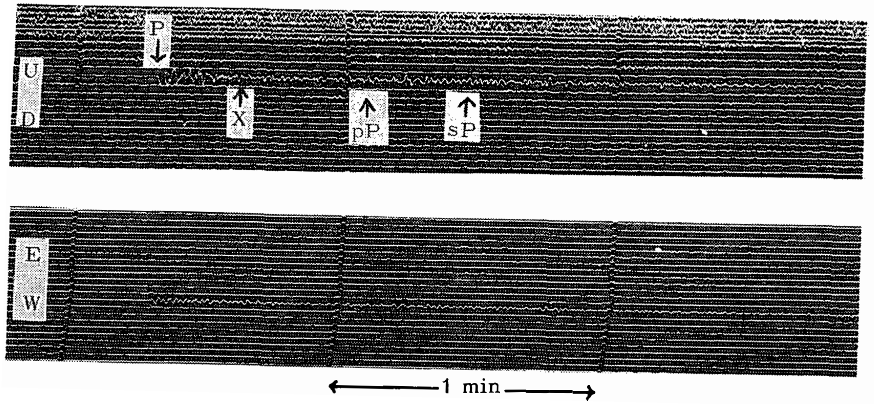
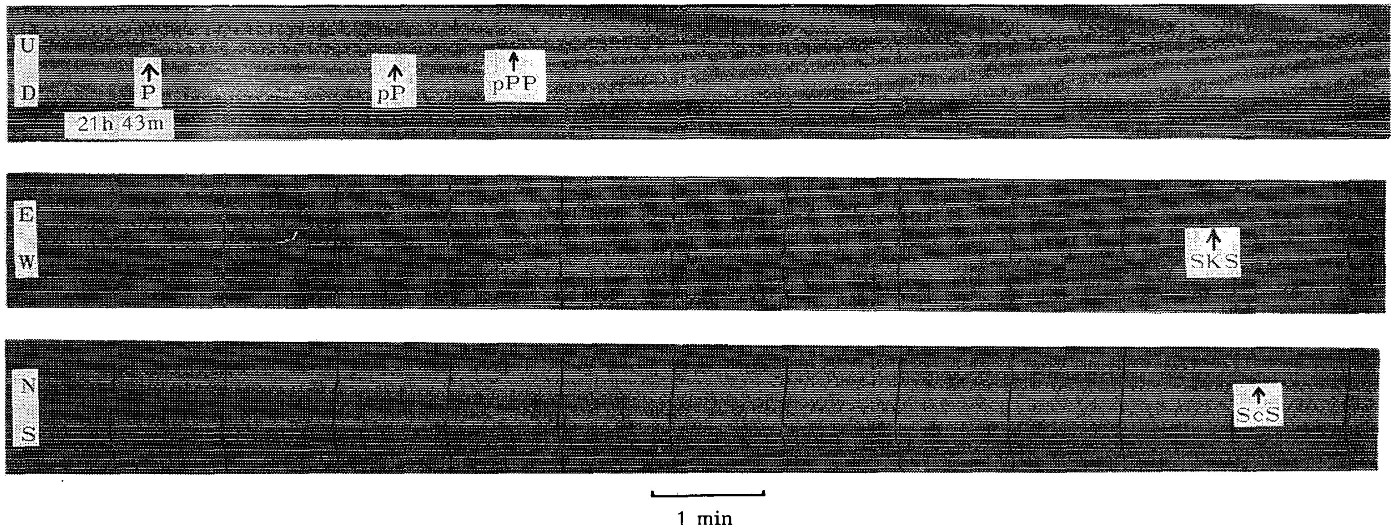


Plate 28



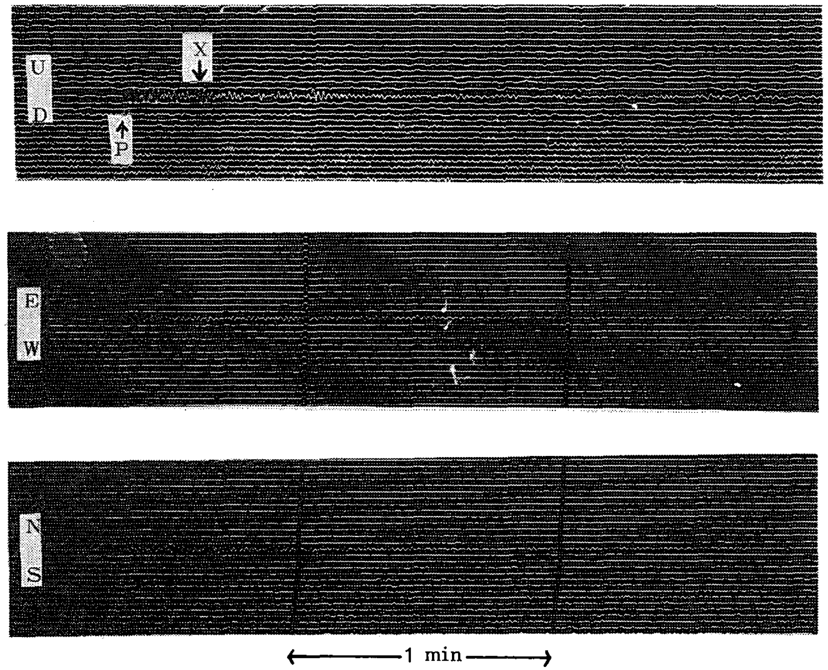


Plate 26

October 12, 1968

Origin time	$19^h\ 17^m\ 39.9^s$
Lat.	20. 88°S
Long.	178. 78°W
Depth	607 km
M	5. 7

△=86. 2°

Fiji Is. region

Note: *SKS* phase is the first arrived of *S* group.

Plate 27

November 14, 1969

Origin time	$07^h\ 37^m\ 45.7^s$
Lat.	19. 67°S
Long.	175. 85°W
Depth	209 km
M	5. 5

△=88. 0°

Tonga Is.

Note: *S* and *ScS* phase arrived nearly the same time.

Plate 28

November 24, 1969

Origin time	$21^h\ 31^m\ 17.6^s$
Lat.	17. 99°S
Long.	178. 40°W
Depth	593 km
M	5. 4

△=89. 1°

Fiji Is. region

Note: The amplitude of *S* group is small.

Plate 29

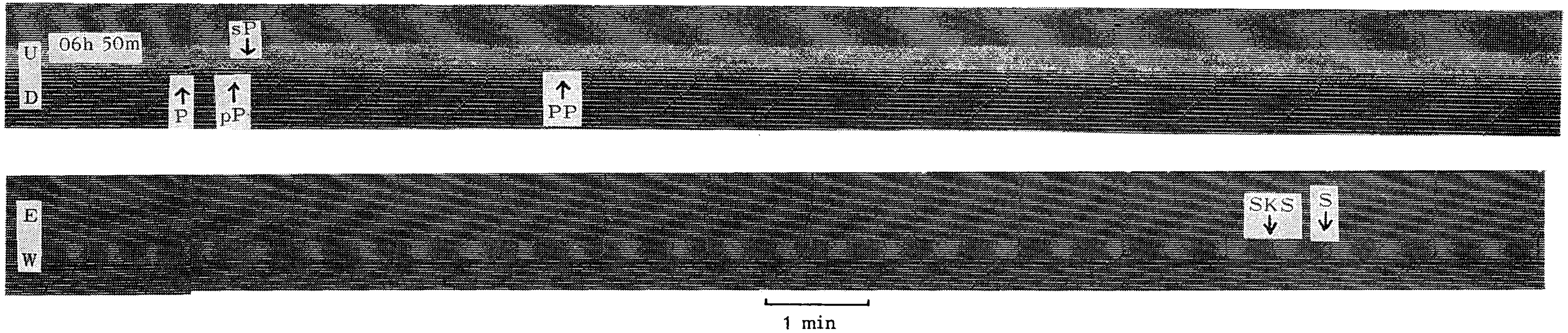


Plate 30

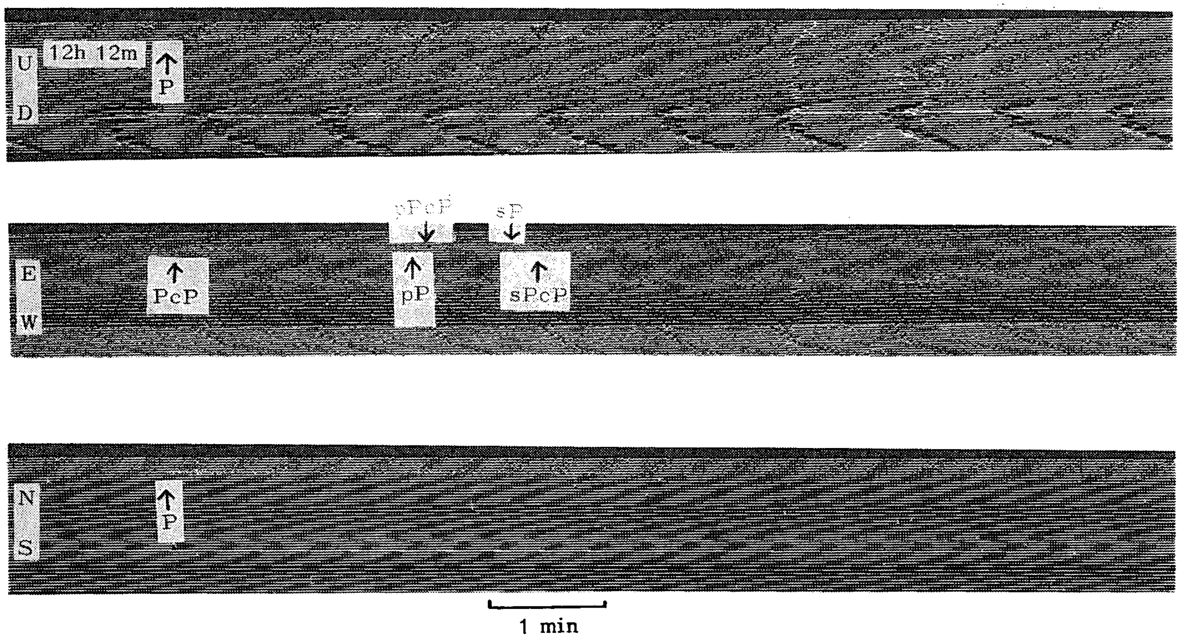


Plate 31

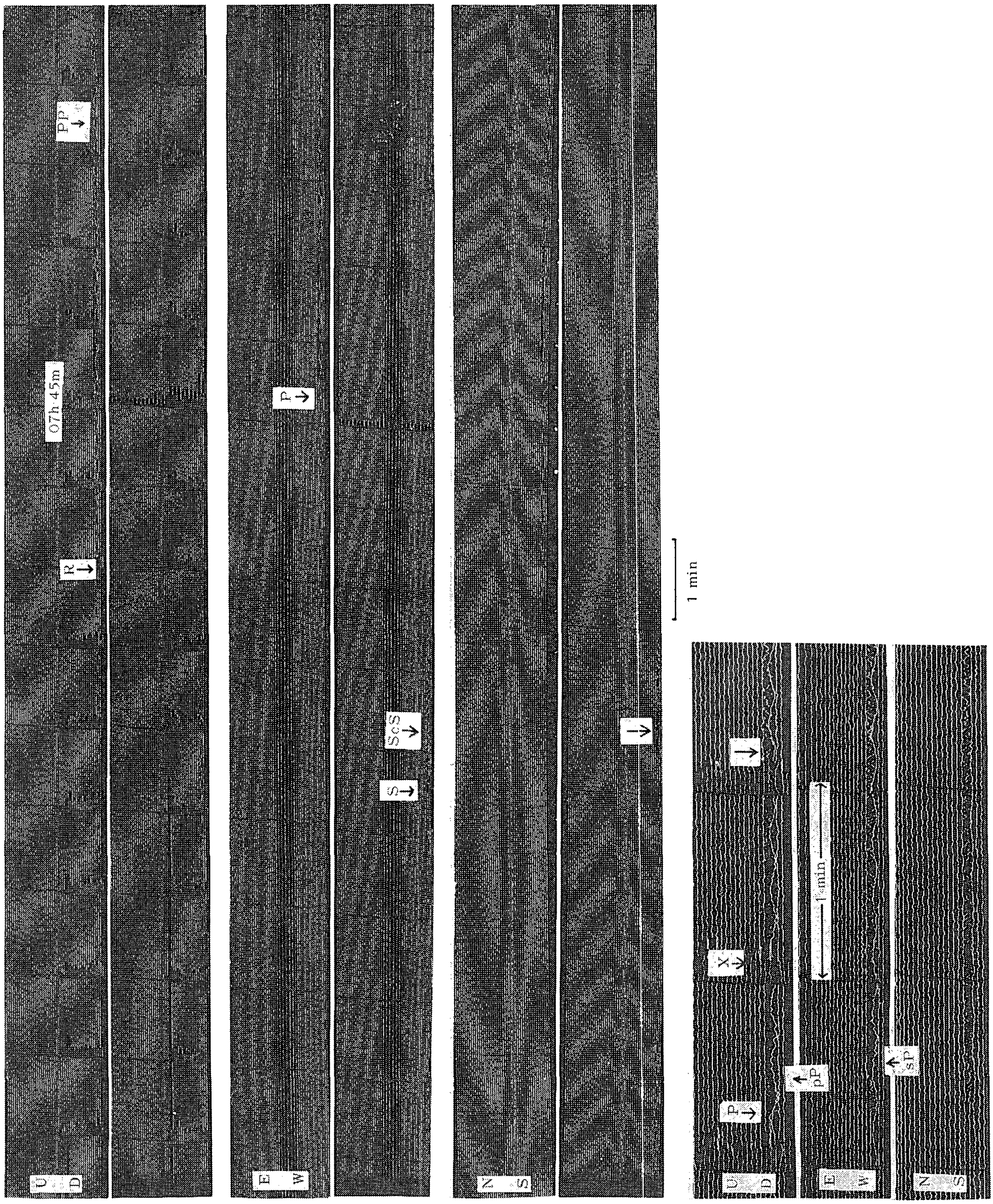


Plate 32

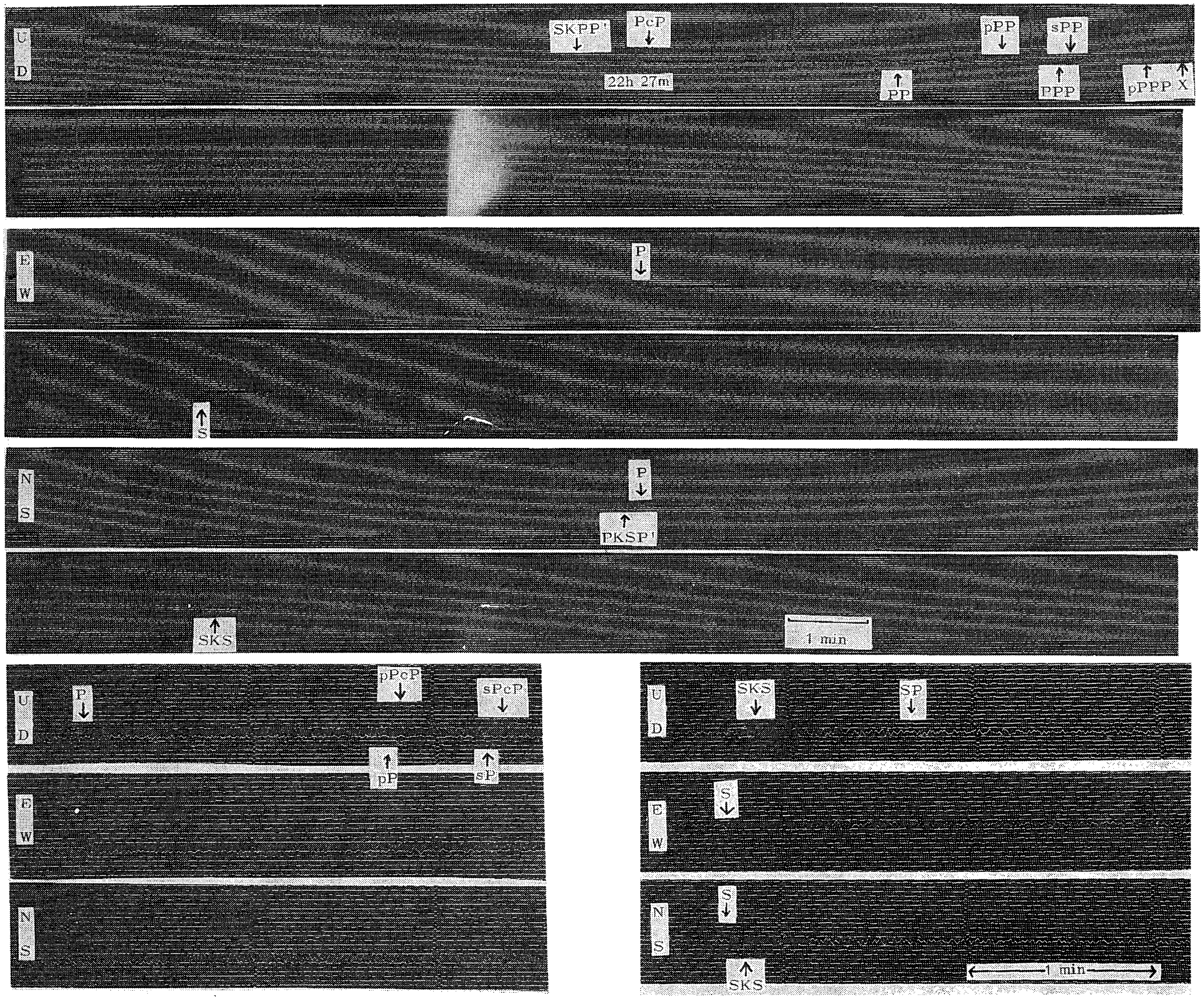

U
D
SKPP'
PcP
22h 27m
PP
pPP
sPP
PPP
pPPP
X
E
W
P
S
N
S
P
PKSP'
SKS
1 min
U
D
P
pPcP
sPcP
pP
sP
E
W
N
S
U
D
SKS
SP
E
W
S
N
S
S
SKS
1 min

Plate 29

October 26, 1969

Origin time	06^h 38^m 03.4^s
Lat.	16.17°S
Long.	173.95°W
Depth	127 km
M	5.8

$\triangle = 91.8°$

Tonga Is.

Felt at Apia

Plate 30

July 10, 1967

Origin time	12^h 01^m 31.5^s
Lat.	5.92°S
Long.	113.14°E
Depth	591 km
M	5.4

$\triangle = 78.6°$

Java Sea

Note: Pairs of *P* and *PcP*, *pP* and *pPcP*, and *sP* and *sPcP*.

Plate 31

August 21, 1967

Origin time	07^h 33^m 00.6^s
Lat.	3.64°N
Long.	95.76°E
Depth	N
M	5.9

$\triangle = 81.9°$

Off W. coast of Northern Sumatra.

Note: The shock on the upper part of seismogram is treated in Plate 12.

Plate 32

February 11, 1969

Origin time	22^h 16^m 13.5^s
Lat.	06.70°S
Long.	126.85°E
Depth	450 km
M	6.0

$\triangle = 82.8°$

Banda Sea

Note: Large *SKPP′* phase. Clear *S* and *SKS* phases.

Plate 33

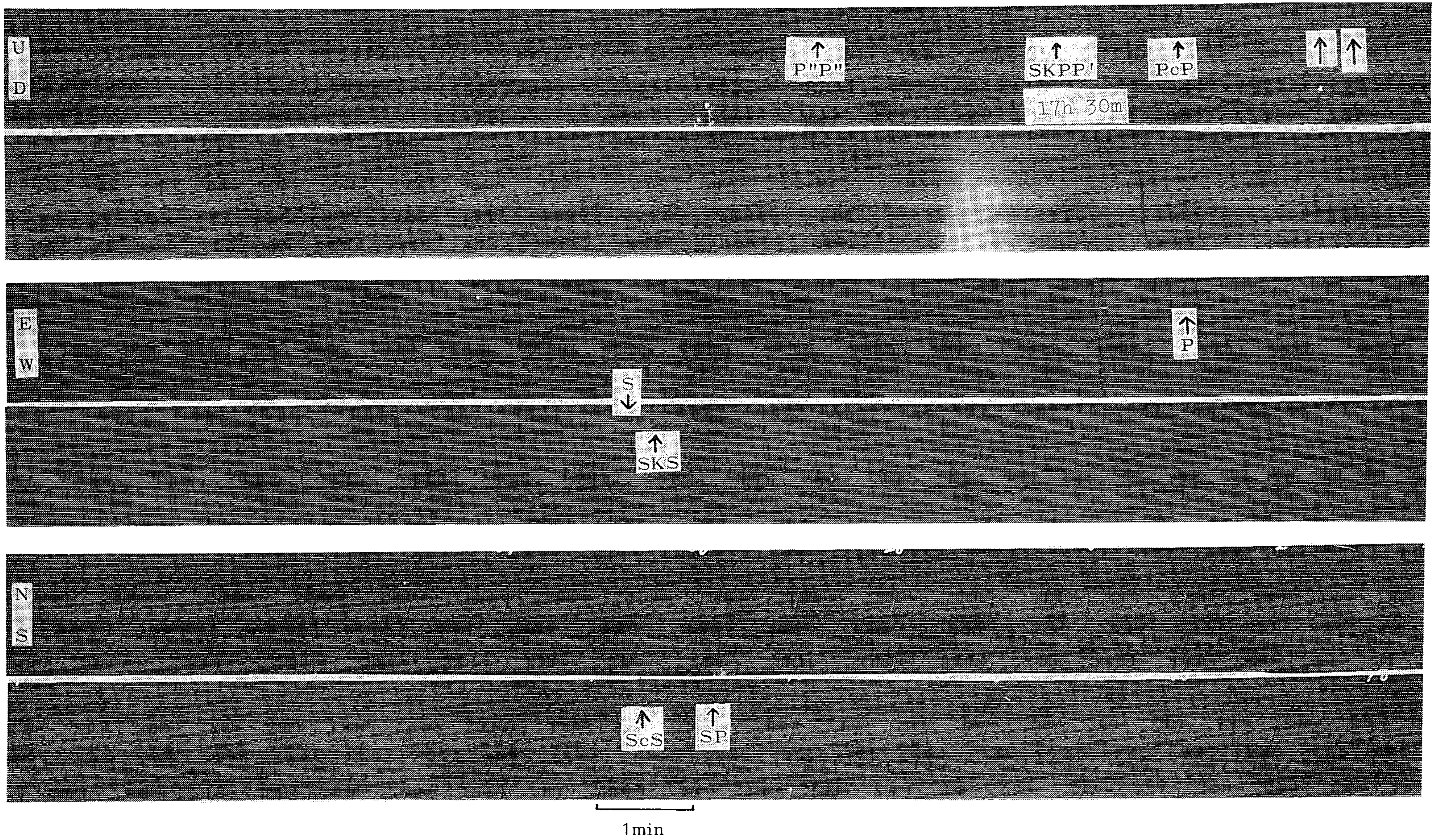


Plate 34

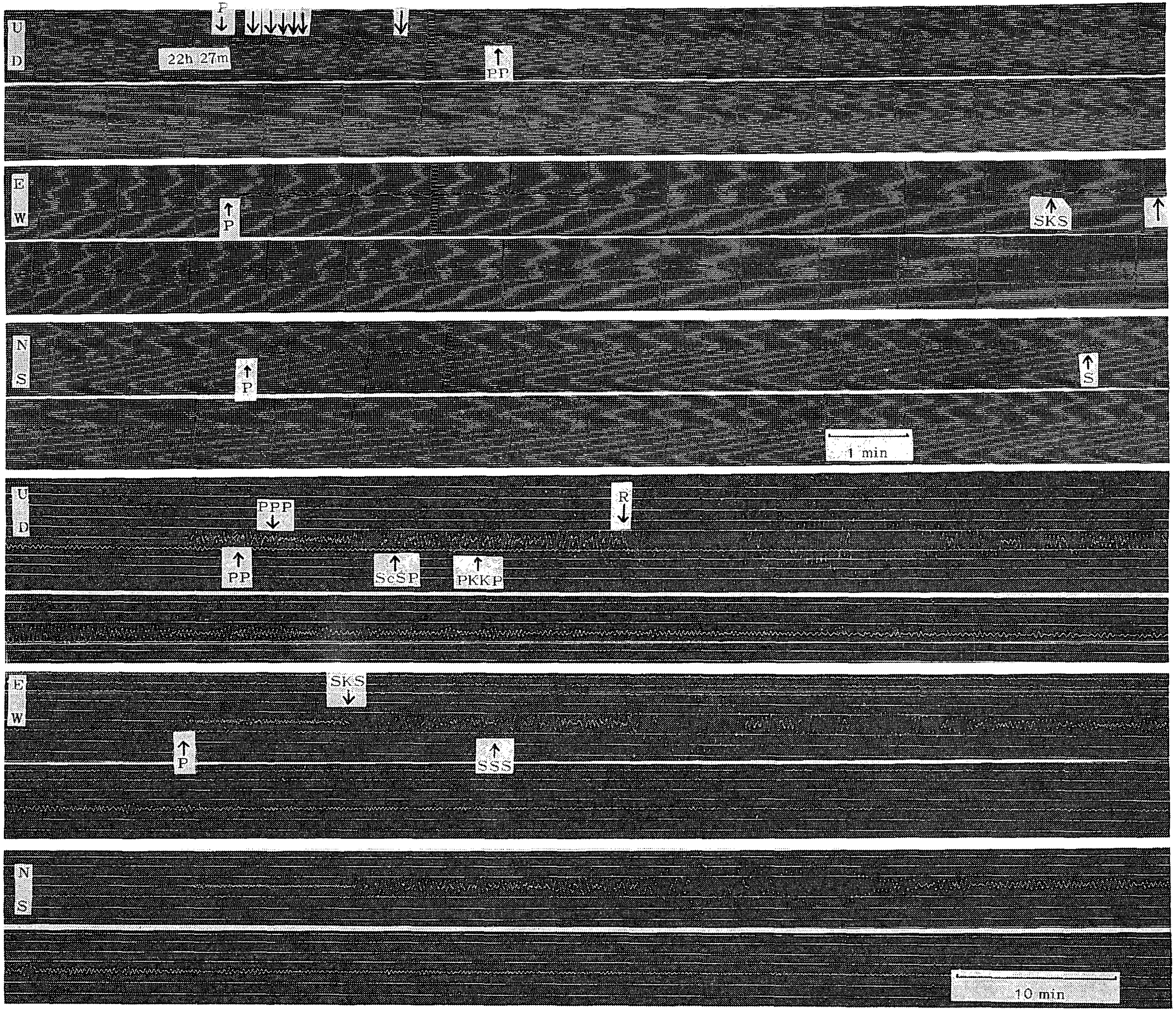

U
D
P
22h 27m
PP
E
W
P
SKS
N
S
P
S
1 min
U
D
PPP
R
PP
ScSP
PKKP
E
W
SKS
P
SSS
N
S
10 min

Plate 35

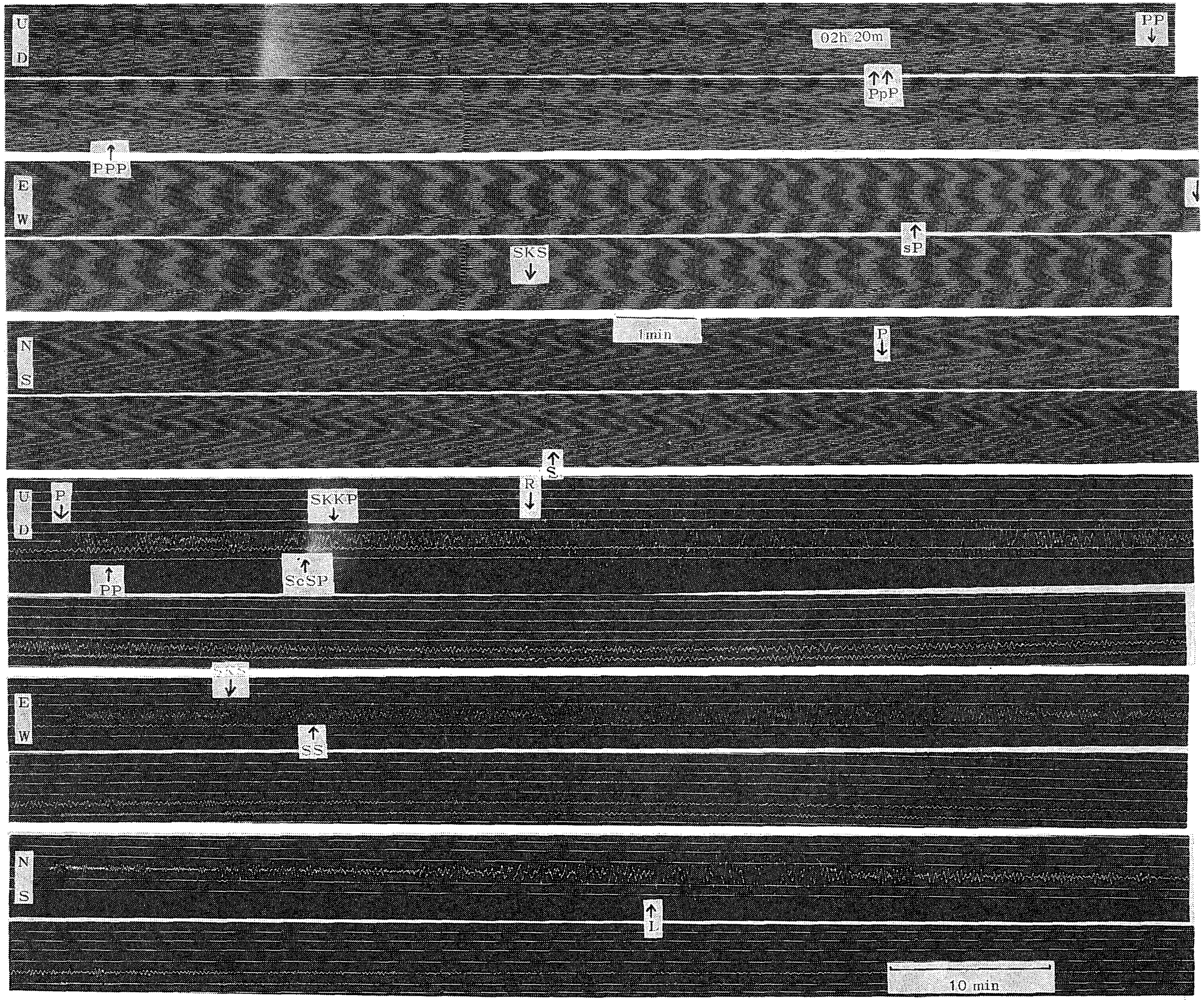

U
D
02h 20m
PP
PpP
PPP
E
W
sP
SKS
1min
N
S
P
S
R
SKKP
ScSP
PP
SKS
SS
L
10 min

Plate 33

August 4, 1968

Origin time	17^h 19^m 19.6^s
Lat.	5.65°S
Long.	125.35°E
Depth	521 km
M	6.2

$\triangle = 83.3°$

Banda Sea

Note: *S*, *SKS* and *ScS* phases arrived during 10 seconds. Core phase of $P''P''$.

Plate 34

August 14, 1968

Origin time	22^h 14^m 19.4^s
Lat.	0.16°N
Long.	119.79°E
Depth	23 km
M	6.0

$\triangle = 86.7°$

Northern Celebes

Note: Small initial *P* phase. Unexplained of *P* group are identified.

Plate 35

August 10, 1968

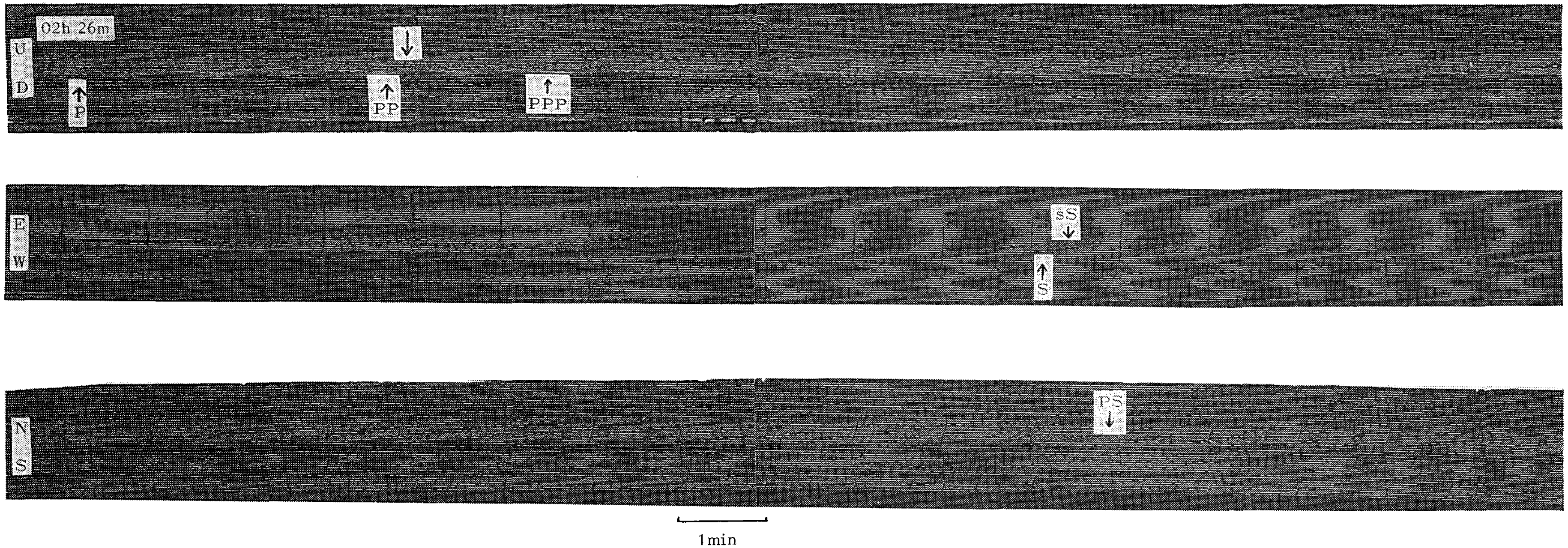
Origin time	02^h 07^m 04.4^s
Lat.	1.42°N
Long.	126.22°E
Depth	N
M	6.3

$\triangle = 87.5°$

Molucca passage

Note: Small initial *P* phase. *S* phase is not clear detected on the short period records.

Plate 36



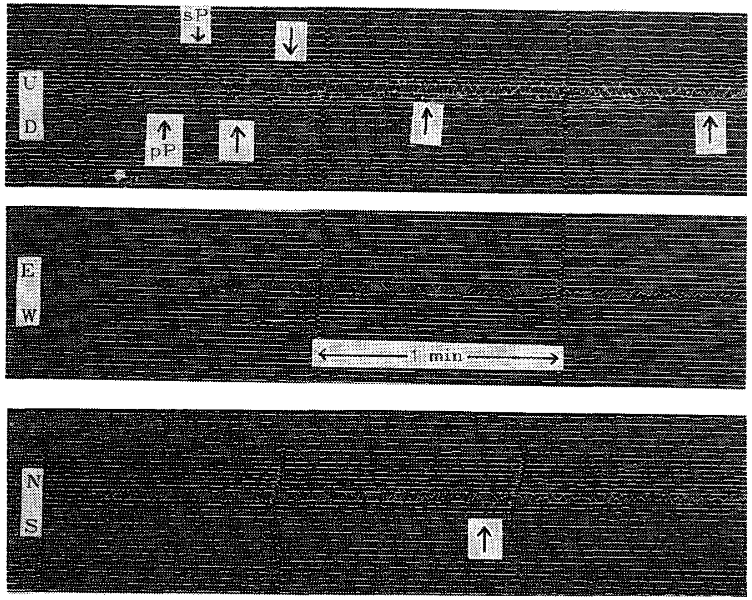


Plate 37

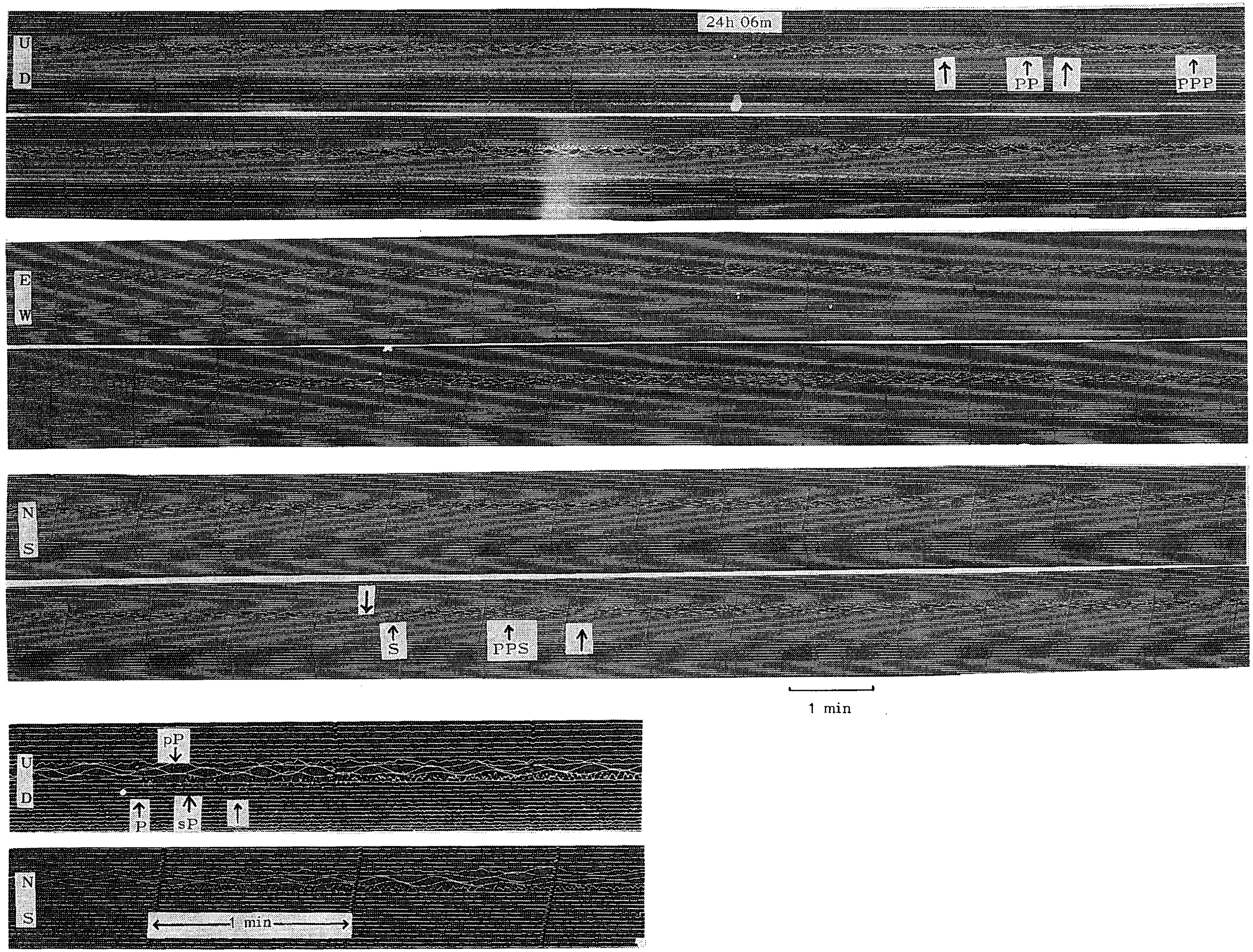
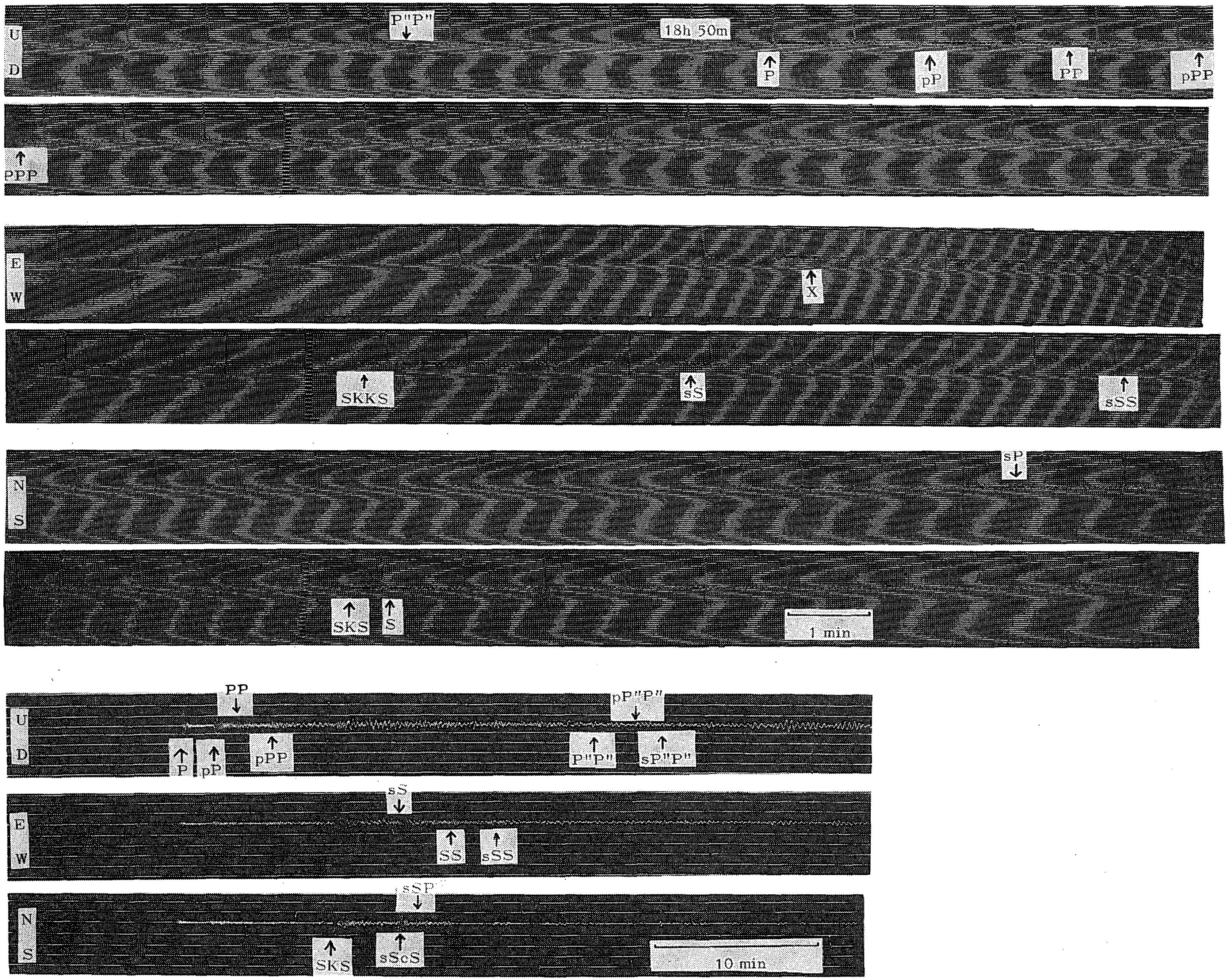


Plate 38



U
D
P"P"
18h 50m
P
pP
PP
pPP
PPP
E
W
X
SKKS
sS
sSS
N
S
sP
SKS
S
1 min
U
D
PP
pP"P"
P
pP
pPP
P"P"
sP"P"
E
W
sS
SS
sSS
N
S
sSP
SKS
sScS
10 min

Plate 36

August 5, 1969	
Origin time	$02^h\ 13^m\ 09.6^s$
Lat.	1.30°N
Long.	126.20°E
Depth	34 km
M	6.1

△=90.0°

Molucca passage

Felt at Manado, Celebes

Note: Small initial *P* phase and large following phases.

Plate 37

August 11, 1969	
Origin time	$23^h\ 52^m\ 56.9^s$
Lat.	1.73°N
Long.	126.47°E
Depth	34 km
M	6.1

△=90.5°

Molucca passage

Felt at Mindanao, Celebes

Note: The shock of the upper part is arranged in Plate 50.

Plate 38

August 18, 1968	
Origin time	$18^h\ 38^m\ 30.6^s$
Lat.	10.11°S
Long.	159.87°E
Depth	538 km
M	6.2

△=90.9°

Solomon Is.

Note: The same arrival of *sS* and *sScS*. *SKKS* phase is identified clearly.

Plate 39

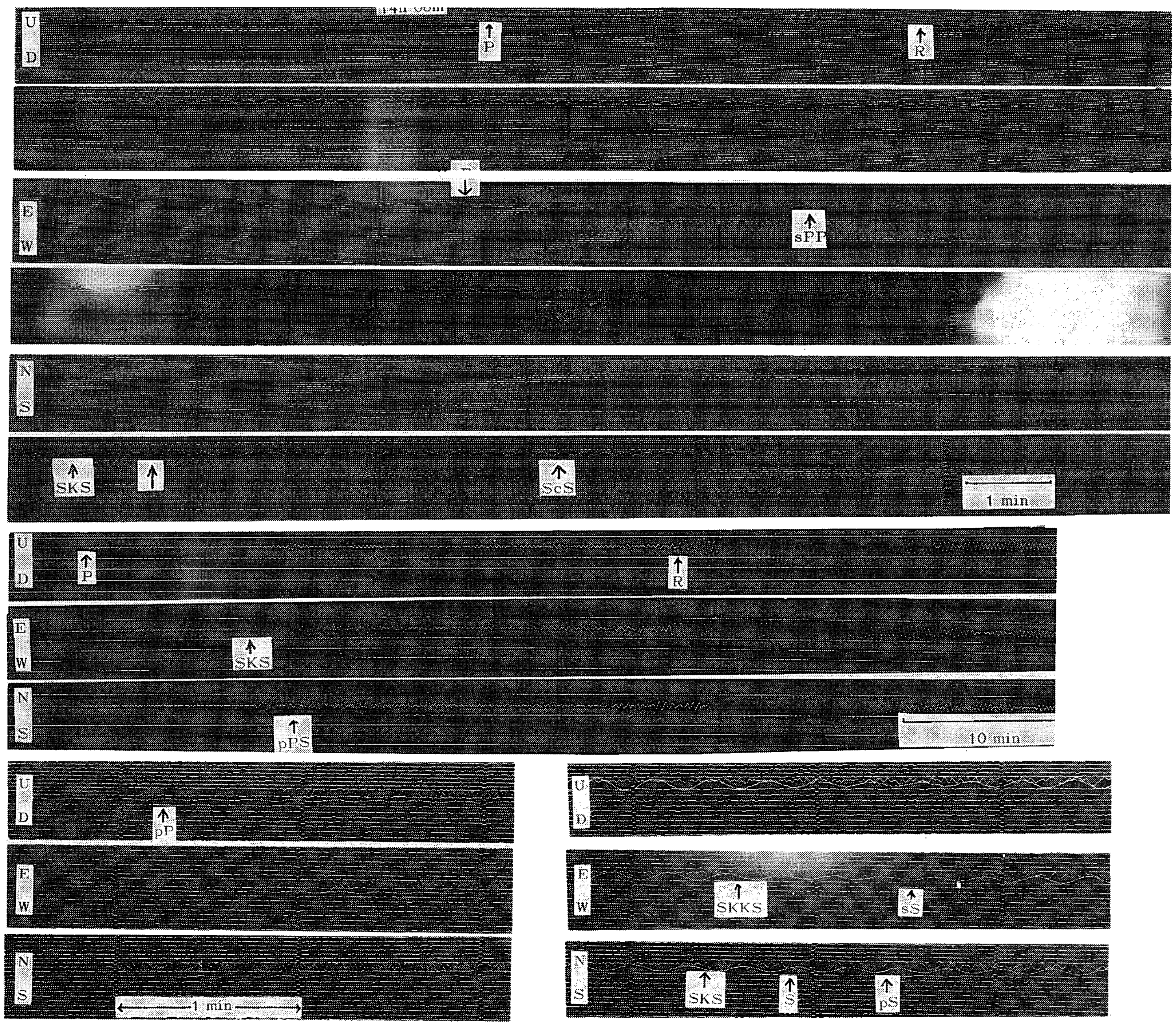

U
D
P
R
E
W
sPP
N
S
SKS
ScS
1 min
U
D
P
R
E
W
SKS
N
S
pPS
10 min
U
D
pP
E
W
N
S
1 min
U
D
E
W
SKKS
sS
N
S
SKS
S
pS

Plate 40

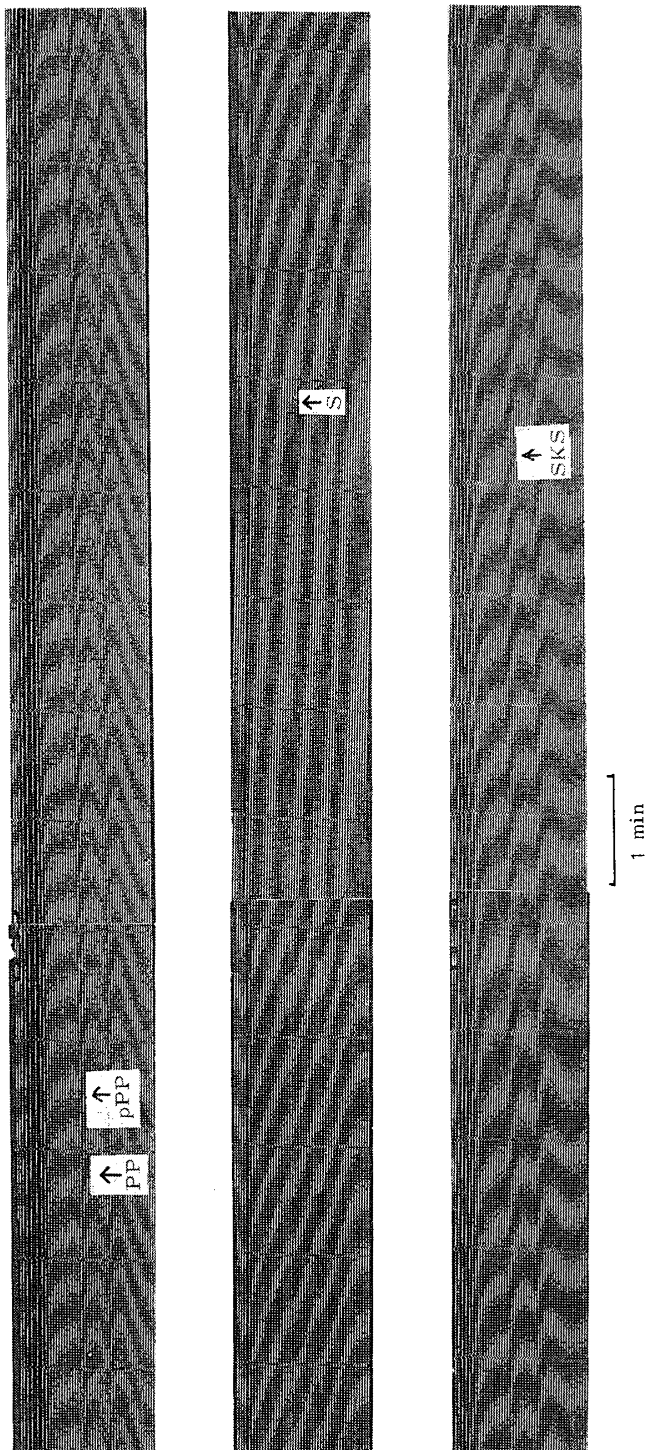


Plate 41

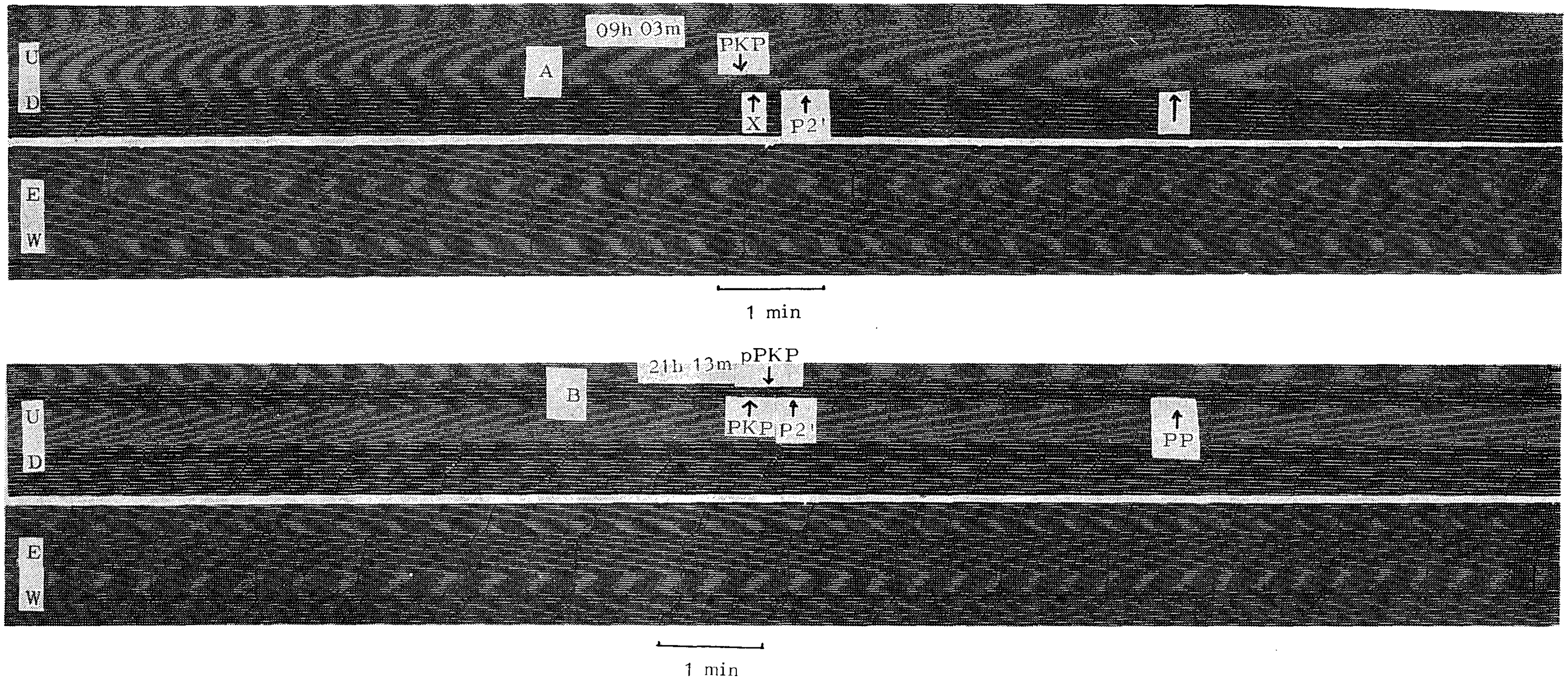


Plate 39

September 16, 1968

Origin time	$13^h\ 55^m\ 36.1^s$
Lat.	6.07°S
Long.	148.68°E
Depth	59 km
M	5.8

△=91.1°

New Britain region

Plate 40

November 28, 1968

Origin time	$16^h\ 30^m\ 32.1^s$
Lat.	6.79°S
Long.	156.23°E
Depth	169 km
M	5.7

△=92.9°

Solomon Is.

Note: Clear *P* wave group. Small *S* phases.

Plate 41

A October 18, 1969

Origin time	$08^h\ 44^m\ 00.0^s$
Lat.	52.49°N
Long.	173.48°E
Depth	24 km
M	5.6

△=153.0°

Near Is., Aleutian Is.

Note: Small initial *P* and after 7 seconds very clear unexplained phase.

B October 21, 1969

Origin time	$20^h\ 53^m\ 47.5^s$
Lat.	51.31°N
Long.	179.24°W
Depth	48 km
M	5.9

△=154.5°

Andreanof Is., Aleutian Is.

Note: Large P_2' phase of Gutenberg-Richter.

Plate 42

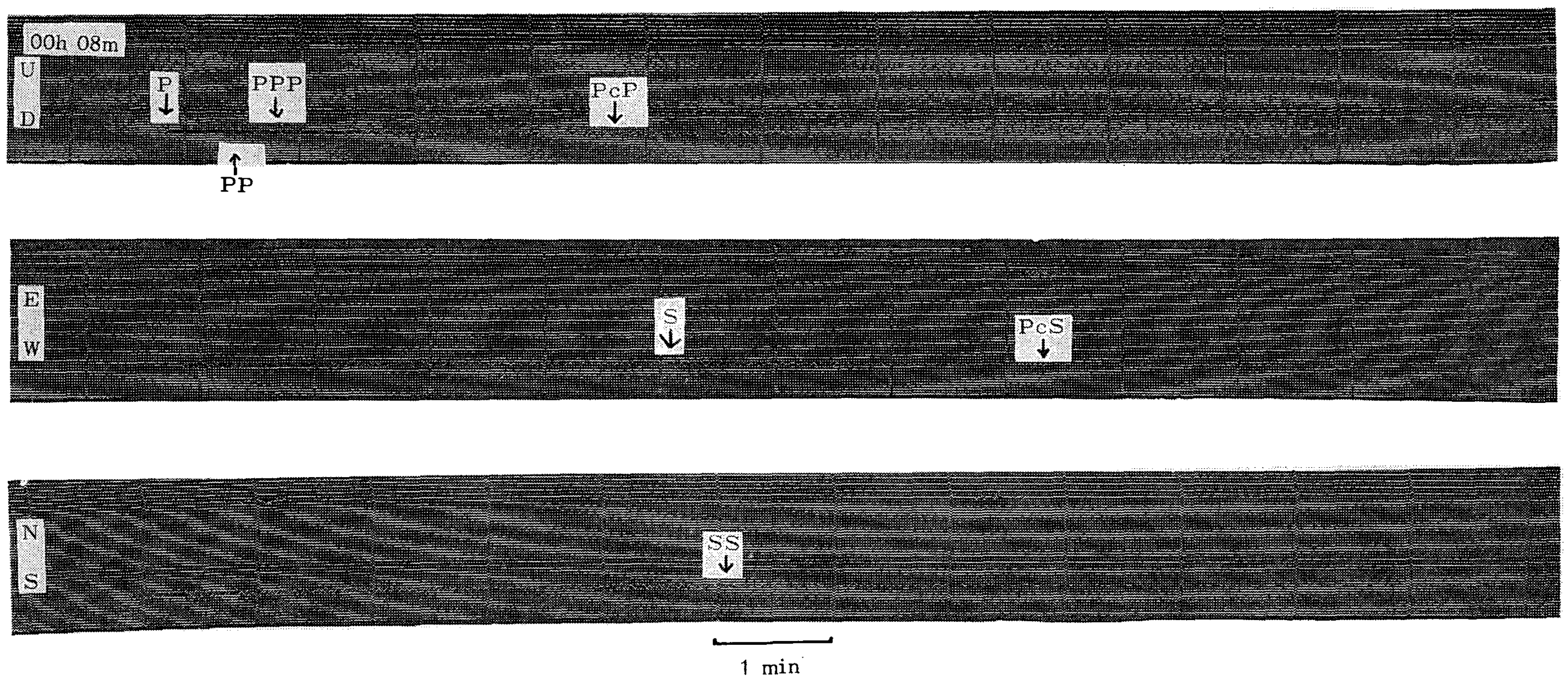


Plate 43

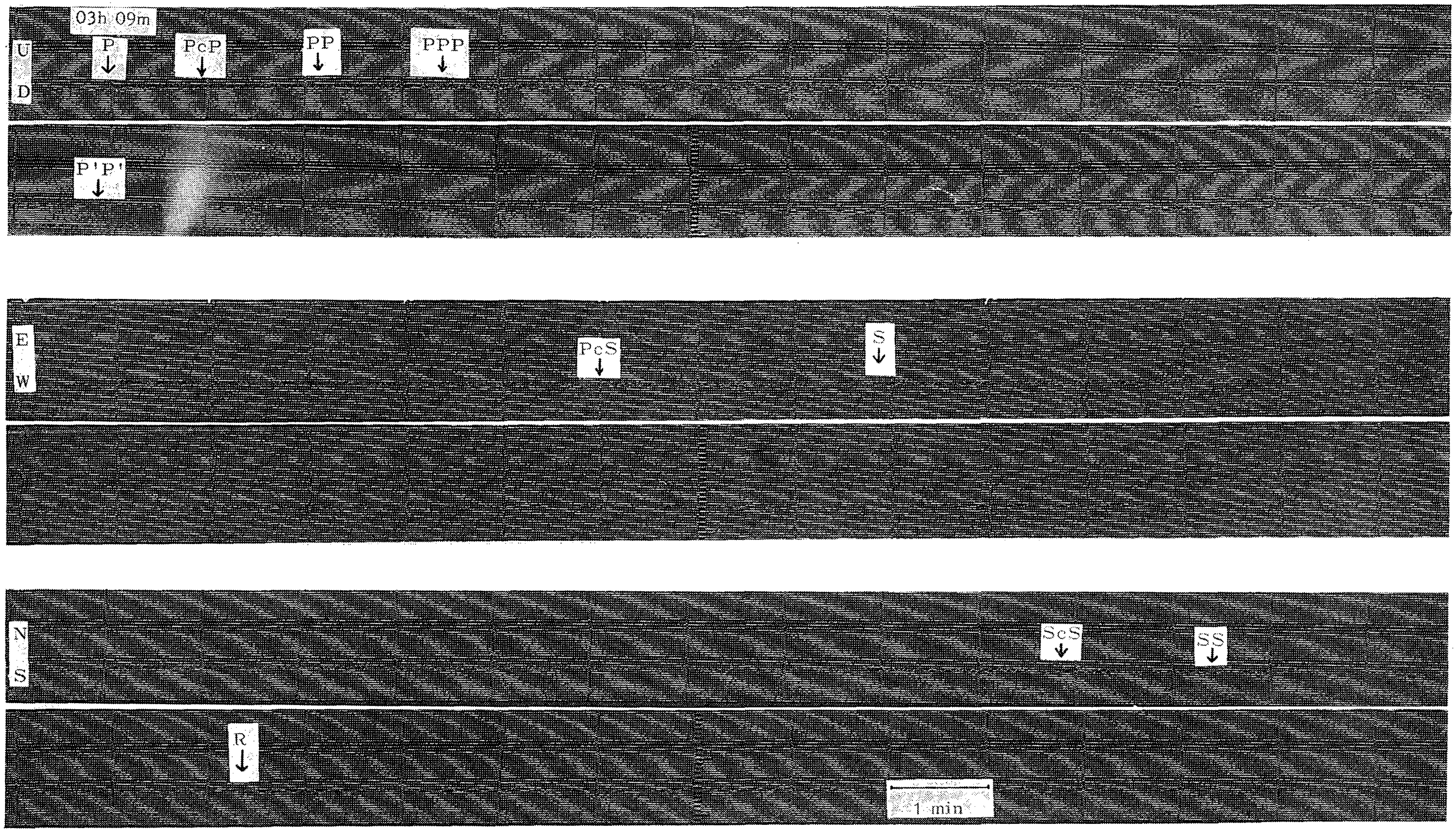


Plate 44

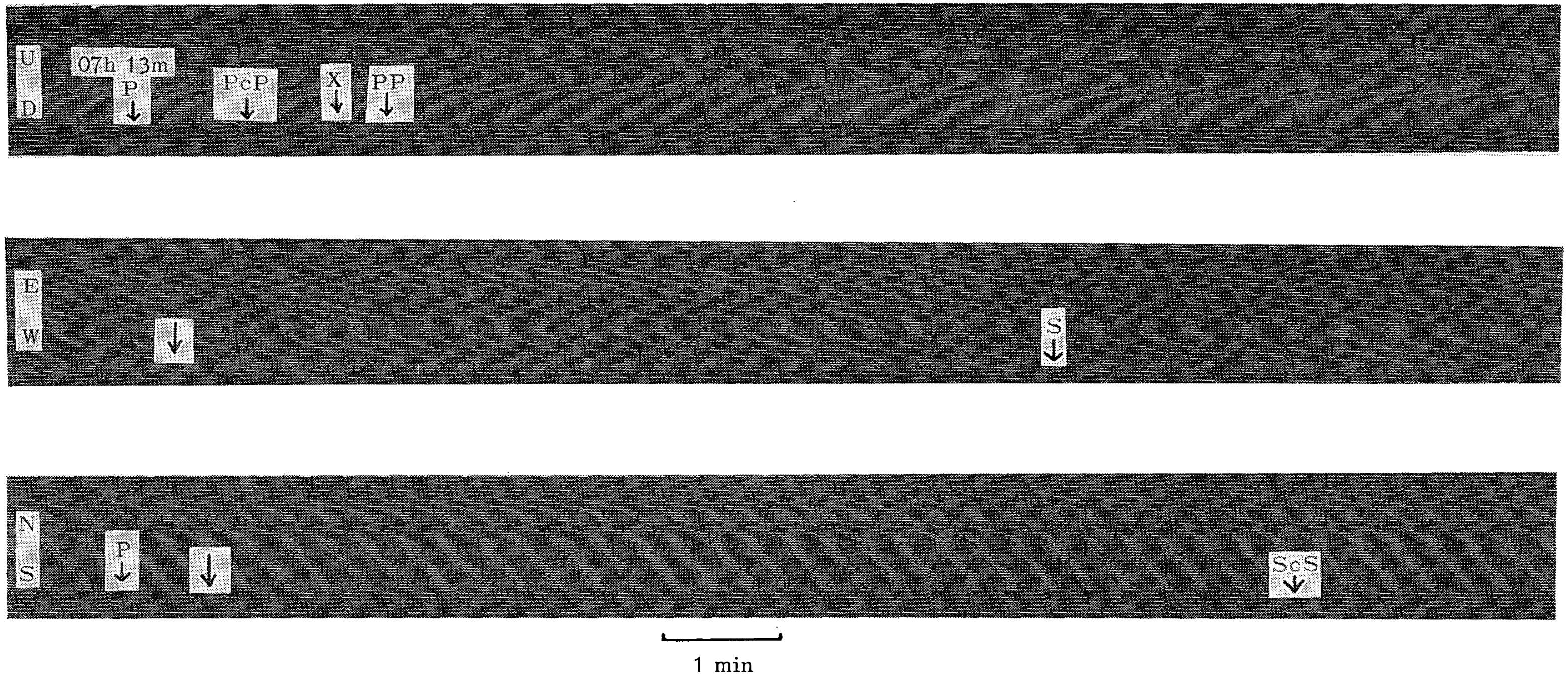


Plate 42

November 26, 1968

Origin time	00^h 03^m 14.3^s
Lat.	57.53°S
Long.	6.79°W
Depth	N
M	5.6

$\triangle=23.1°$

South Atlantic ridge

Note: Not so short period P wave group as in Plates 1–6 at nearly the same distance.

Plate 43

October 14, 1968

Origin time	02^h 58^m 47.8^s
Lat.	31.52°S
Long.	116.97°E
Depth	0 km
M	6.0

$\triangle=56.5°$

Western Australia

28 injured and all buildings damaged or destroyed at Meckering. Slight damage at Kalgoorlie, Perth, and York. Felt over a wide area of southwestern Australia.

Note: An example of the minor seismic activity. Clear S and ScS phases. Core phase of $P'P'$ can be recognized.

Plate 44

September 25, 1968

Origin time	07^h 02^m 51.8^s
Lat.	46.39°S
Long.	166.78°E
Depth	N
M	5.5

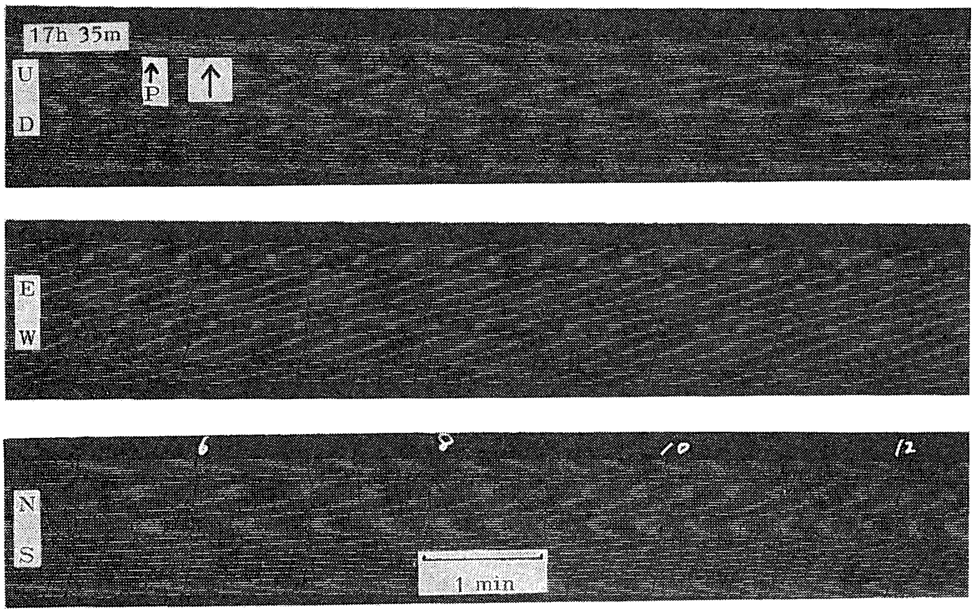
$\triangle=58.5°$

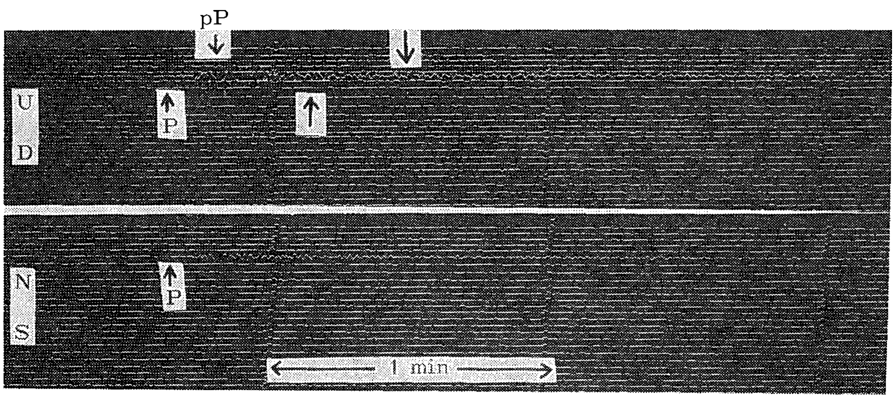
Off west coast of south Is., N. Z.

Felt extensively in south New Zealand

Note: Small S phases. Short periods of P wave group.

Plate 45





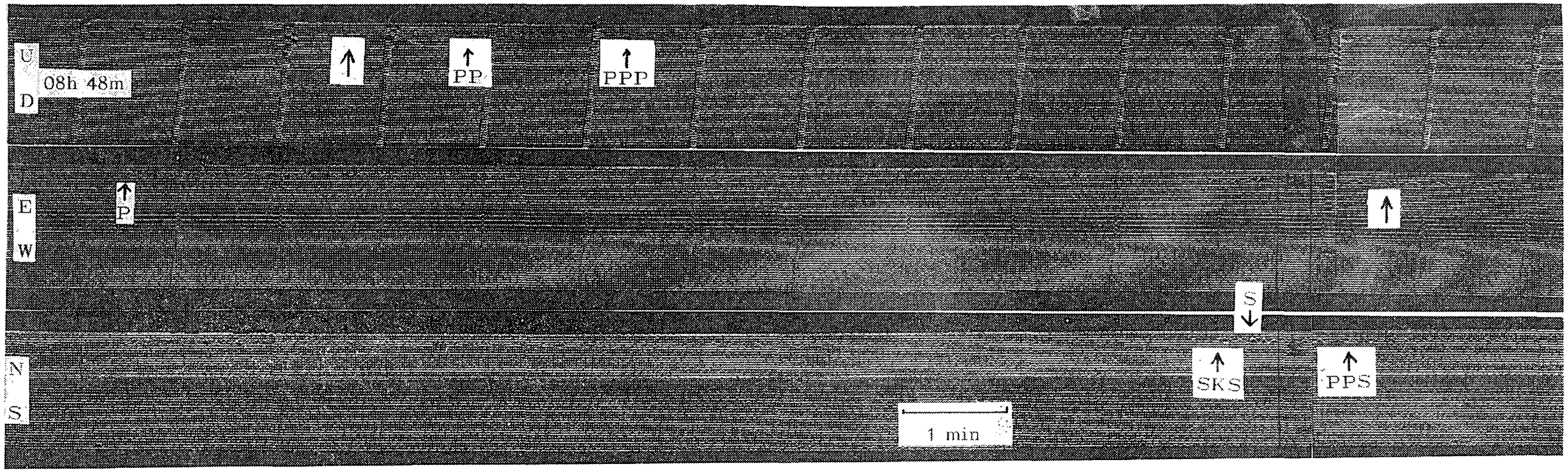
August 19, 1969	
Origin time	$17^h\ 26^m\ 07.4^s$
Lat.	56.67°S
Long.	142.05°W
Depth	N
M	4.4

△=70.7°

South Pacific cordillera

Note: M=4.4 was determined by 1 station. Ms=5.5 from 2 stations. Small initial *P* phases.

Plate 46



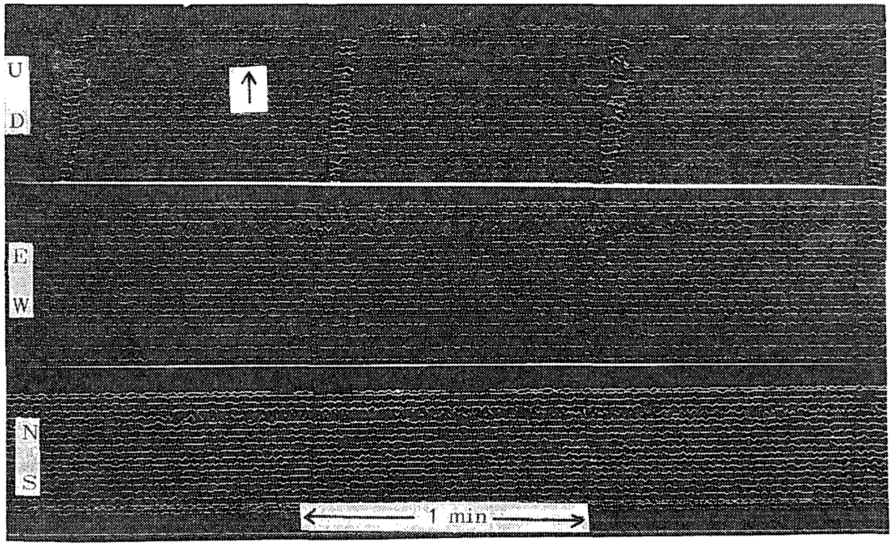


Plate 47

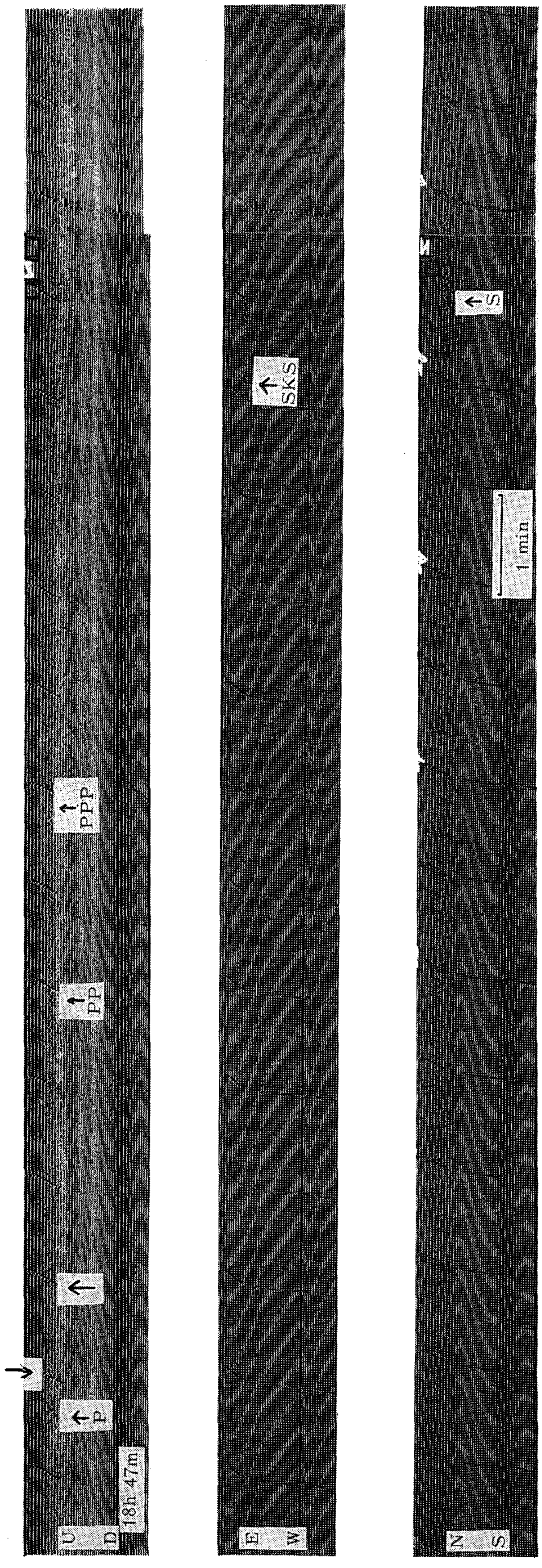


Plate 48

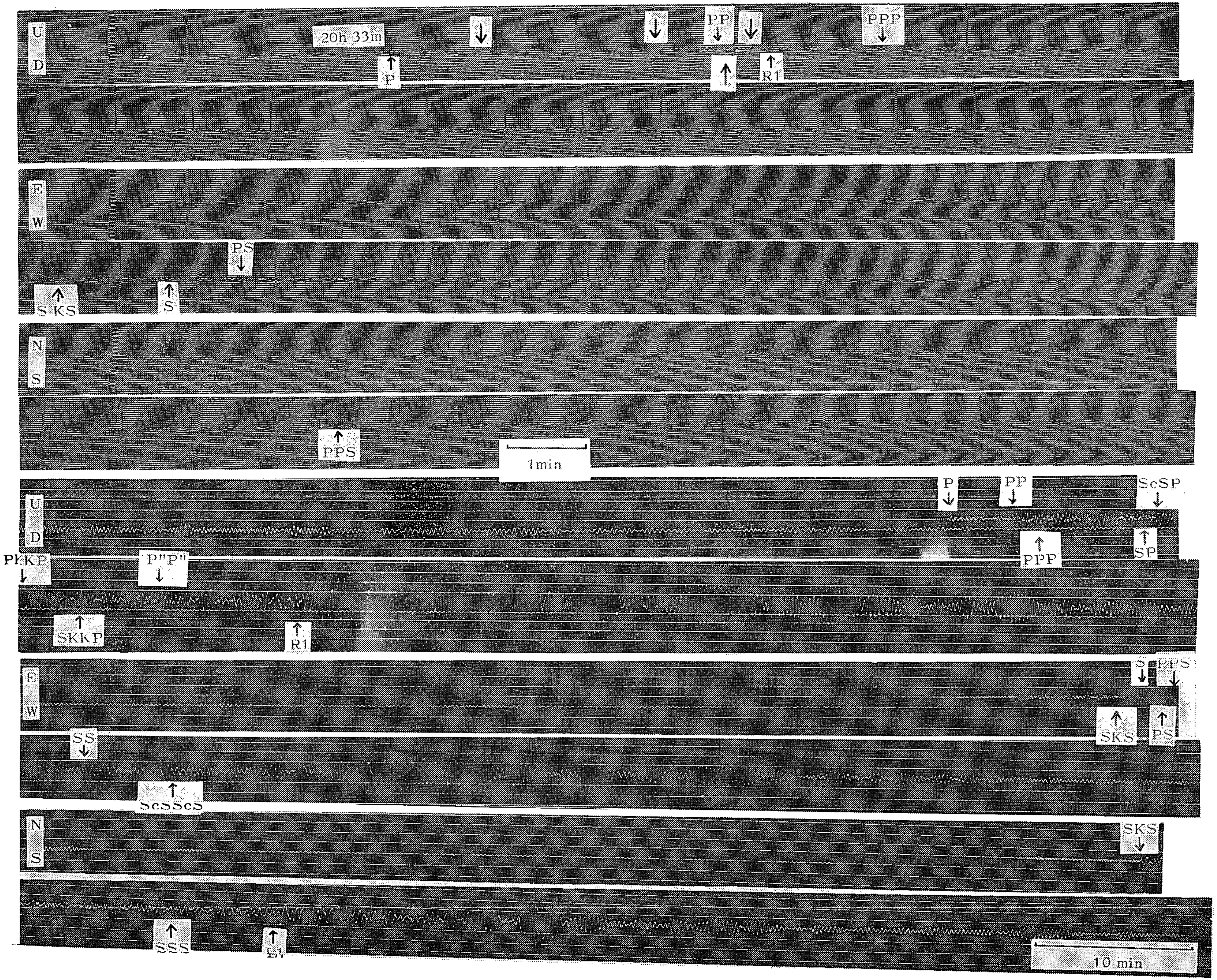

U
D
20h 33m
P
PP
PPP
R1
E
W
PS
SKS
S
N
S
PPS
1min
U
D
P
PP
ScSP
PPP
SP
PKP
P"P"
SKKP
R1
E
W
S
PPS
SKS
PS
SS
ScSScS
N
S
SKS
SSS
L1
10 min

Plate 46

November 23, 1967

Origin time	$08^h\ 35^m\ 49.5^s$
Lat.	14.53°N
Long.	52.07°E
Depth	3 km
M	5.8

$\triangle = 83.8°$

Eastern gulf of Aden

Note: Unexplained phase of *S* wave group.

Plate 47

November 7, 1969

Origin time	$18^h\ 33^m\ 59.9^s$
Lat.	27.85°N
Long.	60.06°E
Depth	35 km
M	6.1

$\triangle = 97.7°$

Southern Iran

Felt in southern Iran

Note: Small *P* and *S* phases.

Plate 48

August 1, 1968

Origin time	$20^h\ 19^m\ 21.9^s$
Lat.	16.01°N
Long.	122.20°E
Depth	37 km
M	5.9

$\triangle = 107.7°$

Luzon, Philippine Is.

Note: Core phases of *PKKP*, *SKKP*, $P''P''$, etc. and reflected waves at core boundary of *ScSP* and *ScSScS* are detected.

Plate 49

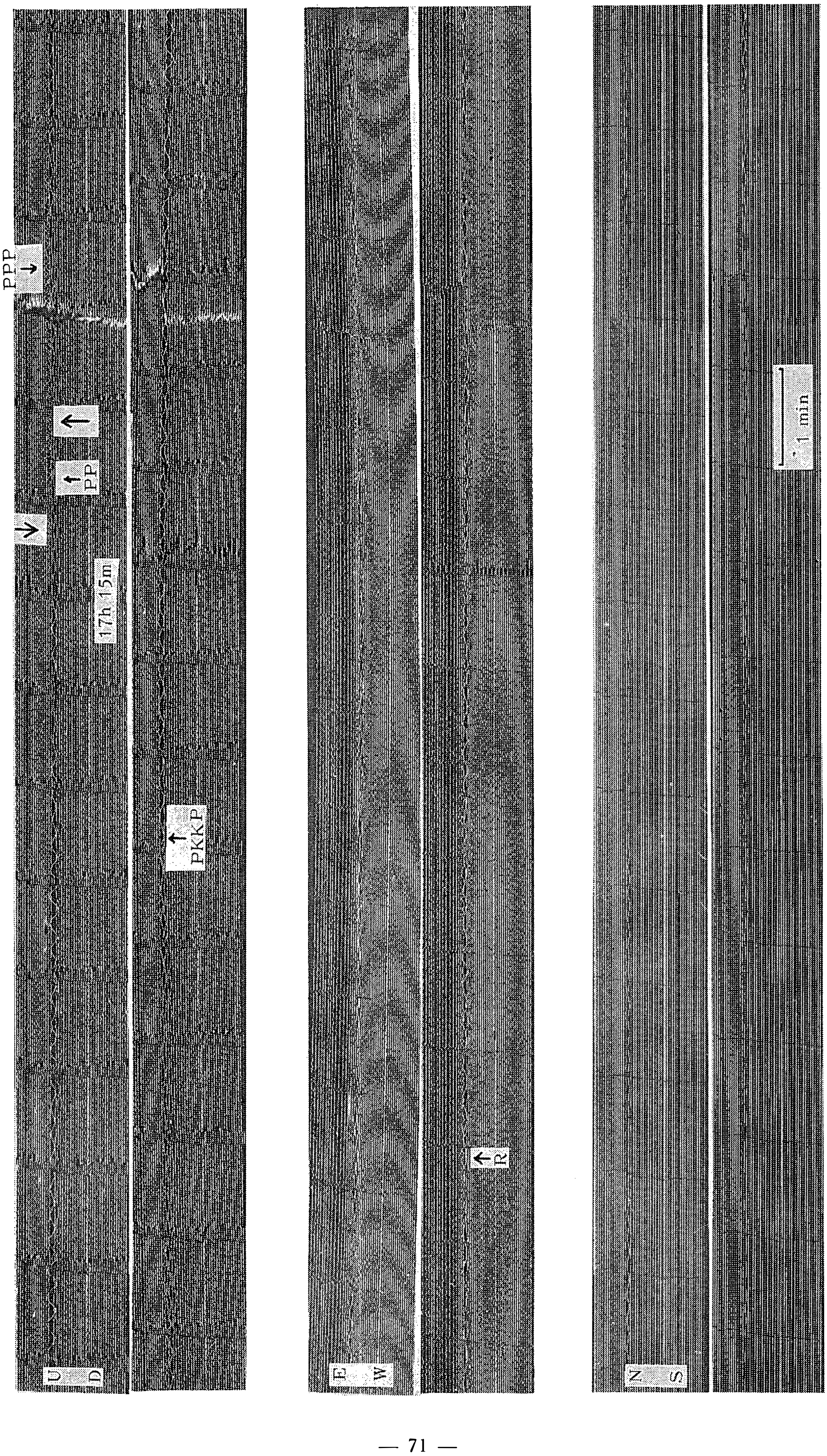


Plate 50

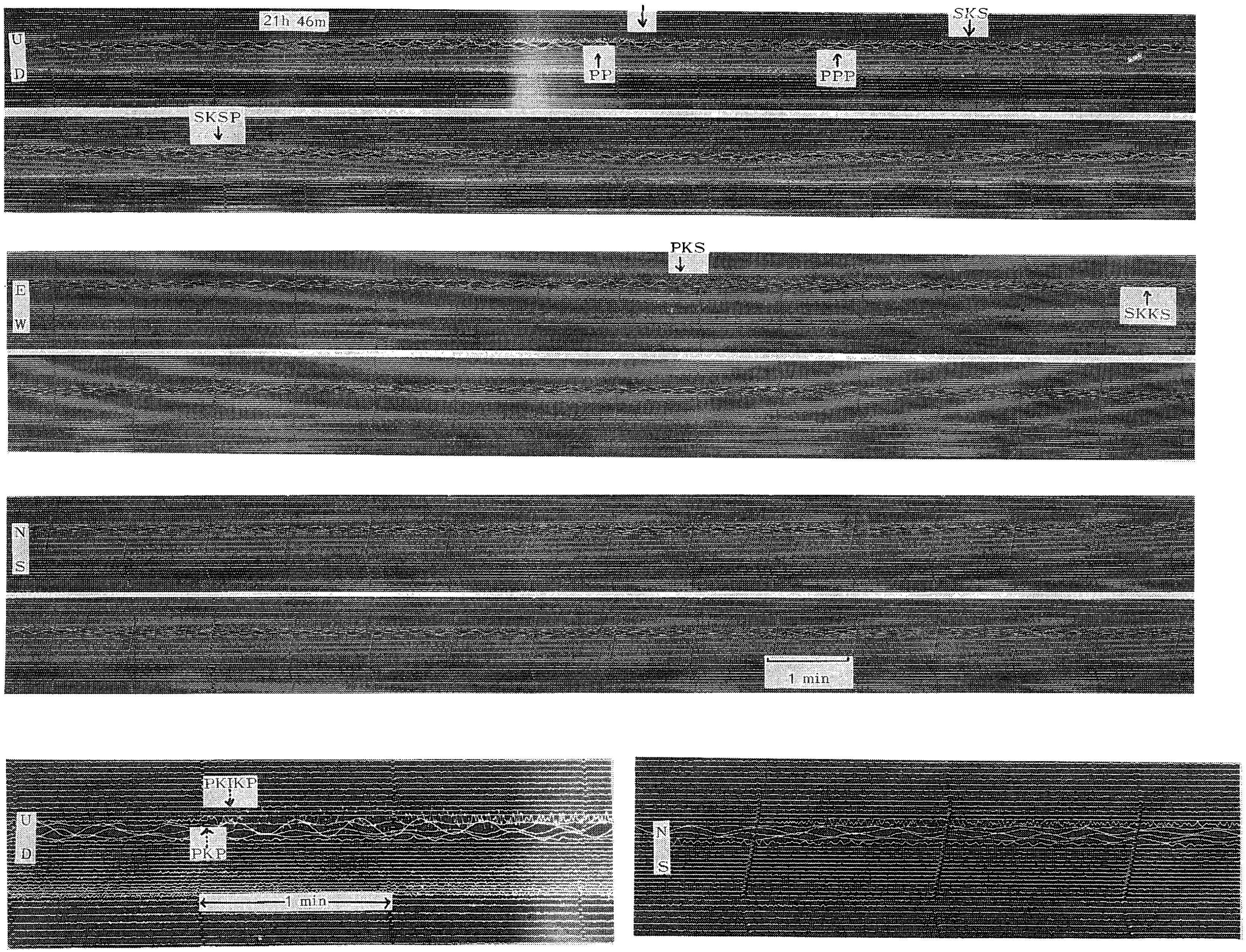

21h 46m
U
D
PP
PPP
SKS
SKSP
PKS
E
W
SKKS
N
S
1 min
PKIKP
PKP
U
D
1 min
N
S

Plate 51

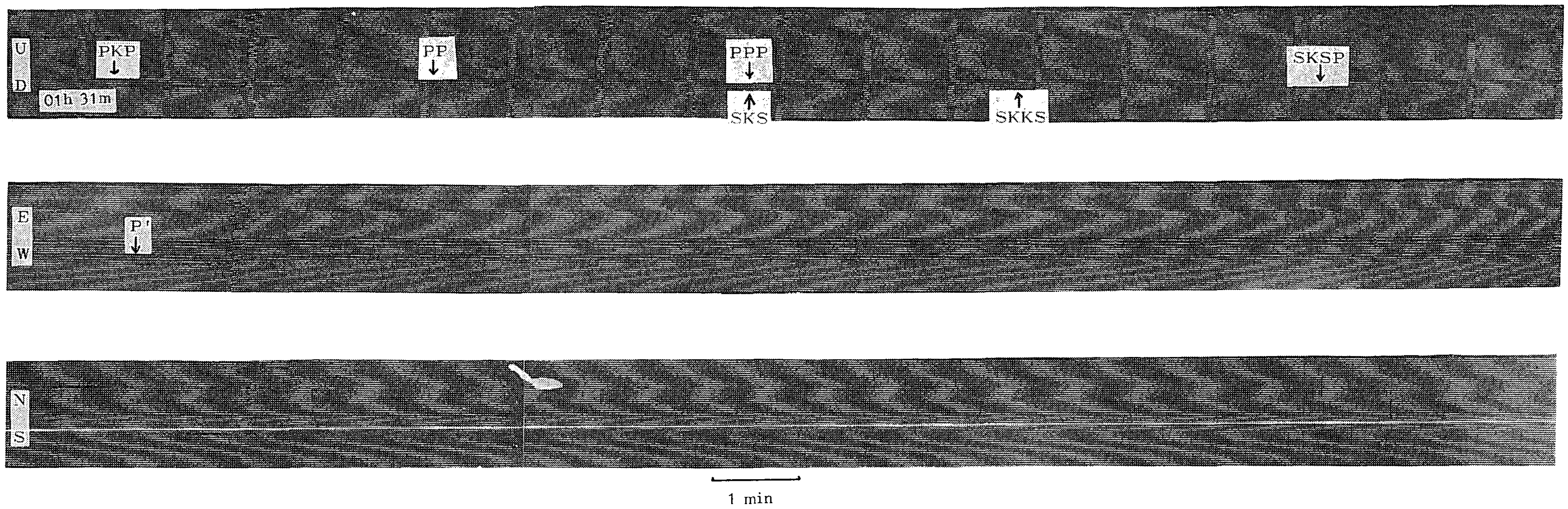


Plate 49

July 22, 1967	
Origin time	16^h 56^m 53.3^s
Lat.	40.66°N
Long.	30.77°E
Depth	4 km
M	6.0

△=109.5°

Turkey

Note: A sample on the shadow zone.
Undetected of the first *P* phase motion.

Plate 50

August 11, 1969	
Origin time	21^h 27^m 39.4^s
Lat.	43.55°N
Long.	147.35°E
Depth	22 km
M	7.1

△=136.1°

Kurile Is.

Damage in Shikotan, Southern Kurile Is. Felt widely in Hokkaido and in Honshu at least as far as Tokyo, 1100 km to the southwest.

Note: About 3 seconds before the above event, a smaller earthquake occurred near the same place. The data as follows.

Origin time	21^h 27^m 36.0^s
Lat.	43.50°N
Long.	147.82°E
Depth	45 km
M	6.2

For the succeeding shocks see Plate 37.

Plate 51

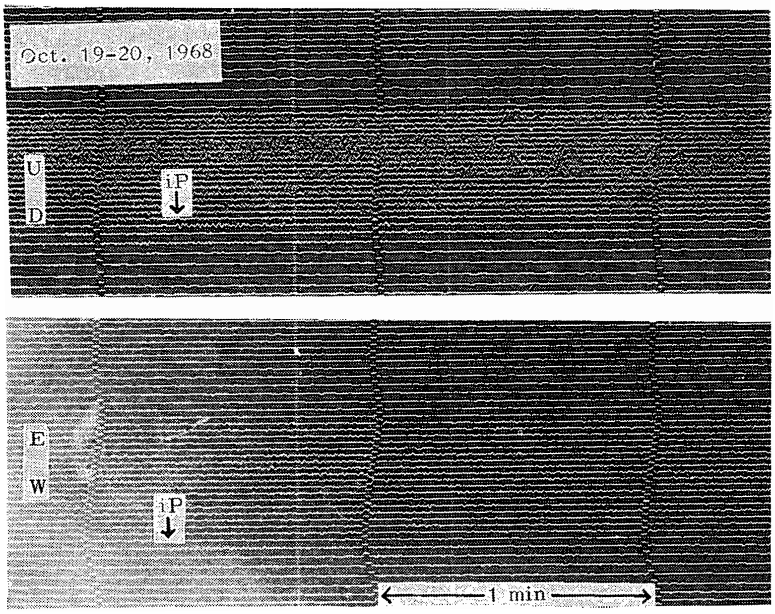
October 18, 1967	
Origin time	01^h 11^m 44.8^s
Lat.	79.80°N
Long.	2.37°E
Depth	N
M	5.7

△=150.1°

Greenland Sea

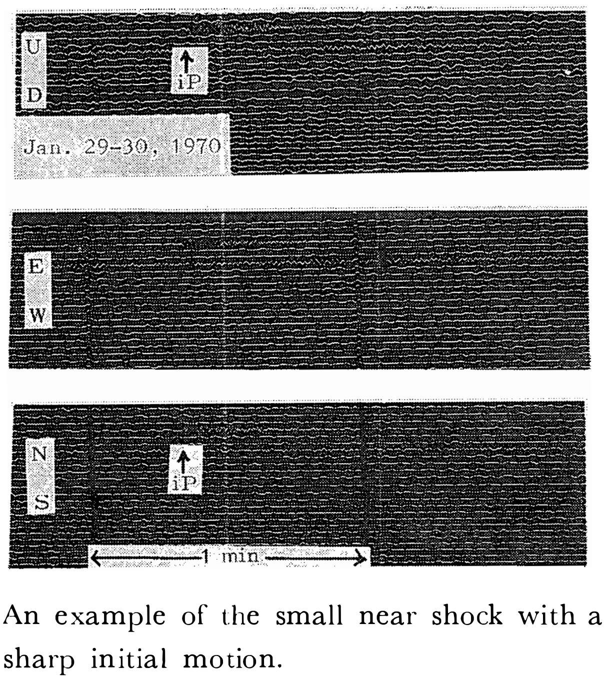
Note: Small initial *PKP* phase and large *P′* phases of Gutenberg-Richter.

Plate 52



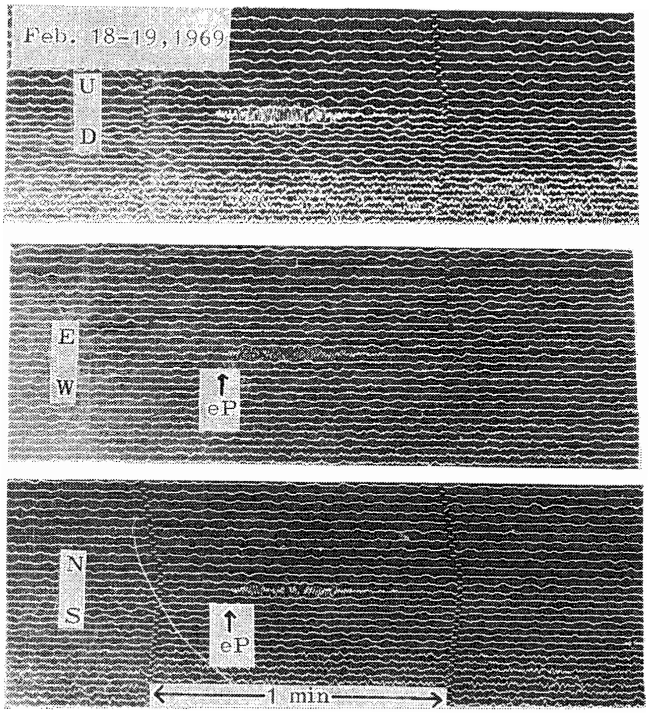
An example of the shock for which the phase readings of P from more than four stations are reported, but its epicenter is not determined.

Plate 53



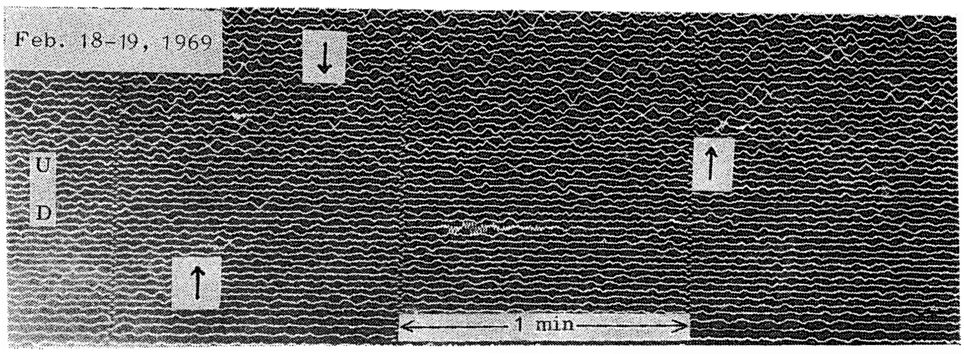
An example of the small near shock with a sharp initial motion.

Plate 54



An example of the small near shock with a weak first motion. The shock of this type is considered to be an iceshock.

Plate 55



An example of the iceshock swarm.