OBSERVATIONS ON THE RECORDED GROUND MOTION DUE TO P, PcP, S, AND ScS*

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ABSTRACT

The recorded motion of a point at the surface of the earth, in the vertical plane of propagation, upon the arrival of PcP and ScS, as well as of the direct P and S waves, is reproduced from the seismograms of the vertical, N–S and E–W component, long-period Benioff seismographs. It is found that P and PcP produce a back-and-forth vibration in the general direction of the incoming ray, and that S and ScS produce a motion the largest displacement of which is approximately perpendicular to the ray. PcP motion starts close to the vertical, but its horizontal component later increases. A minor S phase arriving close to and after PcP and a minor P phase arriving close to and before ScS are observed. The effect of these minor phases on the smaller component of the ground vibration caused by the waves reflected from the mantle-core boundary is discussed.

Introduction

The amplitudes of the waves that are reflected at the mantle-core boundary has been studied by Martner[1] for shallow earthquakes and by Ergin[2] for intermediate and deep-focus earthquakes. Both authors have found that the values of ground displacement divided by period[3] of the main component of these waves (i.e., w/T of PcP and ScP and u/T of ScS and PcS) are in fairly good agreement with the calculated values based on the assumption that PcP and ScP are pure compressional waves and ScS and PcS pure shear waves. But u/T of PcP and of ScP were found to be five to ten times larger, and w/T of ScS and of PcS to be about three times larger, than the expected value. It is interesting to note that the discrepancies are larger for the waves with shorter period than for those with longer period. In this connection, upon the suggestion of Professor Gutenberg, the recorded motion of a point at the surface of the earth due to PcP and ScS as well as to the direct P and S waves, in the vertical plane of propagation, has been drawn, the motions recorded by the N–S and E–W component seismographs along the azimuth being first combined, and then the resultant motion—which is either away from or toward the source—with the up-and-down motion recorded by the vertical seismograph. Only the seismograms recorded at the Seismological Laboratory, Pasadena, by the long-period Benioff electromagnetic instruments (T_o = 1 sec., T_g = 90 sec.) were used. This work is mainly concerned with the direction of vibration of the ground motion. Therefore, the difference between the true and the recorded ground motion should have no serious effect on the present problem as long as the vertical and the horizontal component instruments have nearly the same characteristics. This condition is reasonably well fulfilled by those instruments the seismograms of which were

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1 S. T. Martner, "Observations on Seismic Waves Reflected at the Core Boundary of the Earth," *Bull. Seism. Soc. Am.*, 40: 95–109 (1950).

2 K. Ergin, "Amplitudes of PcP, PcS, ScS, and ScP in Deep-Focus Earthquakes," (diss. Calif. Inst. Technology, 1950).

3 The quantity "amplitude of the ground displacement divided by period" is proportional to the amplitude of the velocity of the ground motion in a simple harmonic motion.

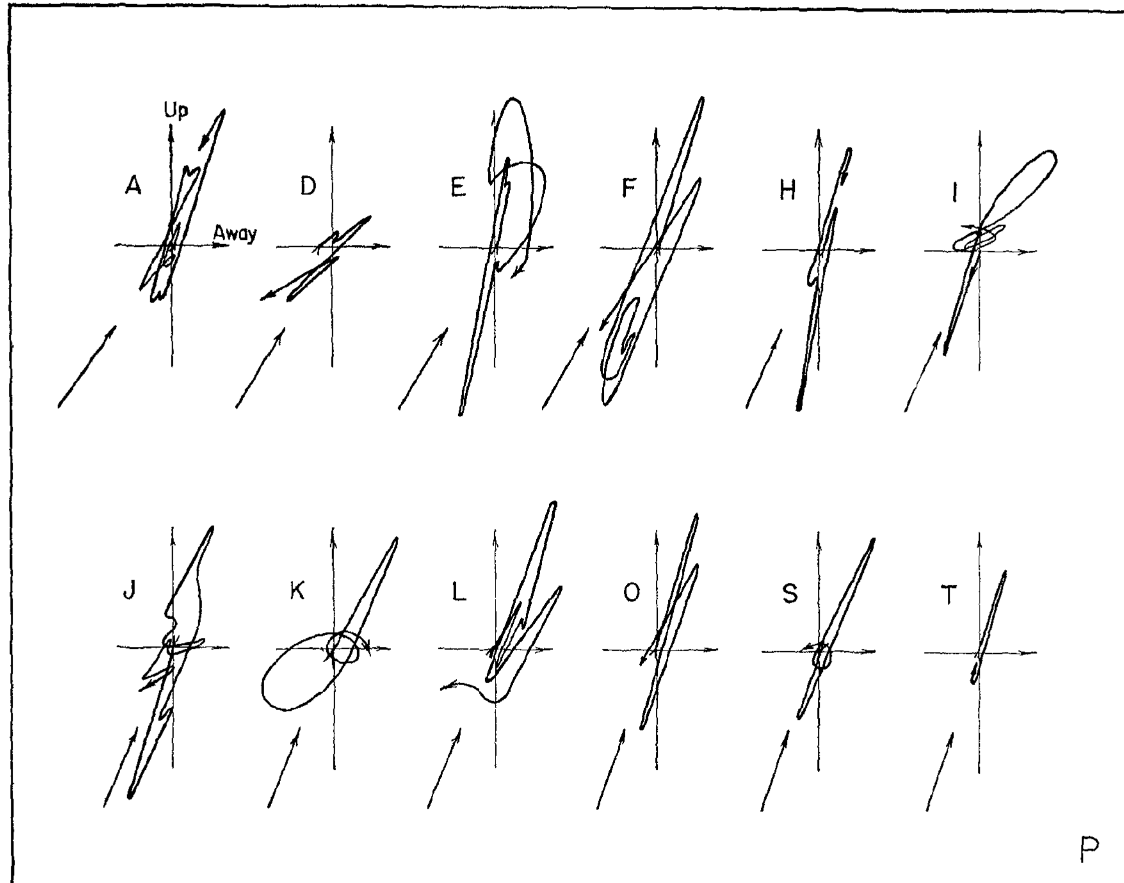

Fig. 1. Recorded ground motion due to the direct P wave. Capital letters refer to the shocks listed in table 1. For each shock, the direction of motion is the same as given in plot A. The straight arrow under each figure indicates the theoretical direction of vibration of the ground, corresponding to the epicentral distance involved.

used. Theoretically, the motion obtained as described above should represent the whole motion due to a pure compressional wave and only the SV part of the motion due to a pure shear wave.

The earthquake data used for this investigation are listed in table 1.

TABLE 1

EARTHQUAKE DATA USED

Symbol	Region	Date	Time	h	Location		M	Δ°
			h. m. s.		lat.	long.		
A	5	1942, Aug. 6	23:36:59	50±	14 N	91 W	7.9	31
B	1	1948, May 14	22:31:43	N	54½ N	161 W	7.5	36
C	1	1946, Apr. 1	12:28:54	N	52¾ N	163½ W	7.4	37
D	7	1948, Apr. 21	20:22:02	40	19¼ N	69¼ W	7.3	45½
E	7	1946, Aug. 4	17:51:05	N	19¼ N	69 W	8.1	45½
F	7	1943, July 29	03:02:16	N	19¼ N	67½ W	7¾	47
G	1	1940, July 14	05:52:53	80	51¾ N	177½ W	7¾	48½
H	8	1942, Aug. 24	22:50:27	60±	15 S	76 W	8.1	63
I	8	1950, July 9	04:39:57	600	8½ S	71 W	7+	64
J	8	1944, Feb. 29	03:41:53	200	14½ S	70½ W	7.0	66
K	8	1948, May 11	08:55:41	70	17½ S	70¼ W	7.1	68½
L	19	1950, Feb. 28	10:20:58	350	46 N	143½ E	7¾	70
M	12	1949, Aug. 6	00:35:37	70	18½ S	174½ W	7.6	75
N	31	1941, Nov. 25	18:03:55	N	37½ N	18½ W	8.3	76½
O	8	1943, Apr. 6	16:07:15	60±	30¾ S	72 W	7.9	77½
P	8	1944, Jan. 15	23:49:30	50±	31¼ S	68¾ W	7.4	78½
Q	8	1950, Aug. 15	22:51:28	600	27 S	62½ W	7¼–7½	80
R	12	1944, May 25	01:16:37	640	21½ S	179½ W	7.2	80½
S	8	1949, Apr. 20	03:29:08	70	37 S	74 W	7.4	81
T	12	1949, Feb. 13	18:24:24	60	33½ S	178 W	7.4	87
U	14	1949, July 23	10:26:45	150±	18½ S	170 E	7.2	87

RECORDED MOTION

The recorded ground motions due to P, PcP, S, and ScS are given in figures 1 to 4, respectively. The earthquakes were so selected as to cover the epicentral distance range 30°–90°.

The motion due to the direct P wave (fig. 1) is a back-and-forth movement in the general direction of the incoming wave. The direction of vibration varies from one case to the other; nevertheless, the angle of vibration (the angle between the normal to the surface of the earth and the direction of vibration) tends to decrease as the epicentral distance increases. The difference in the angle of vibration as related to the motion due to one and the other of two shocks that have originated from the same vicinity at different times is noteworthy (fig. 1, D and 1, E). The first pulse of the direct P motion is usually steeper than the following ones. In two cases shown in figure 1, I and K, the P motion starts in the direction that would correspond to the direction indicated by the theory for a pure compressional wave at the distance given, but after the first half of the first cycle the horizontal component of the mo-

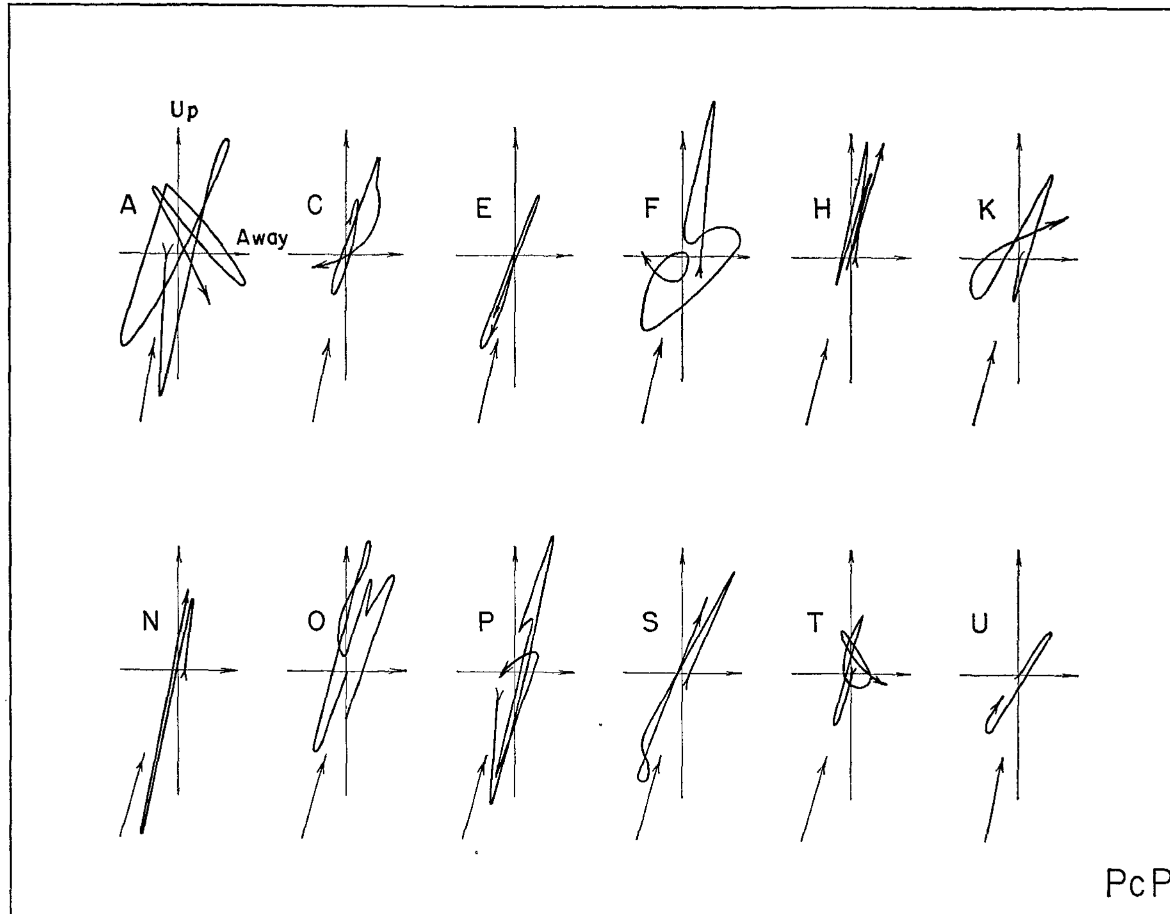

Fig. 2. Recorded ground motion due to PcP. Notations are as in figure 1.

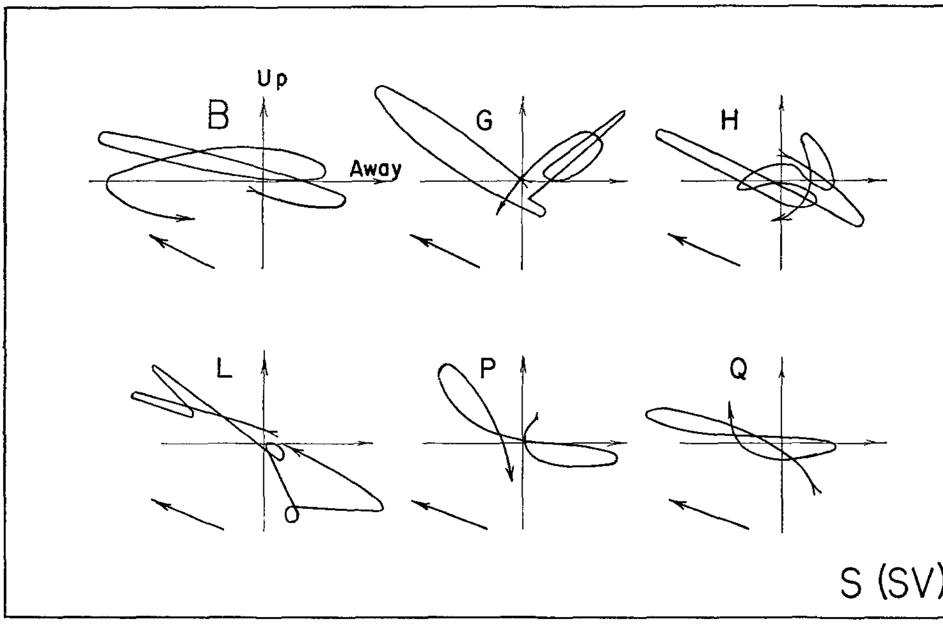

Fig. 3. Recorded ground motion due to the SV part of the direct S wave. Notations are as in figure 1.

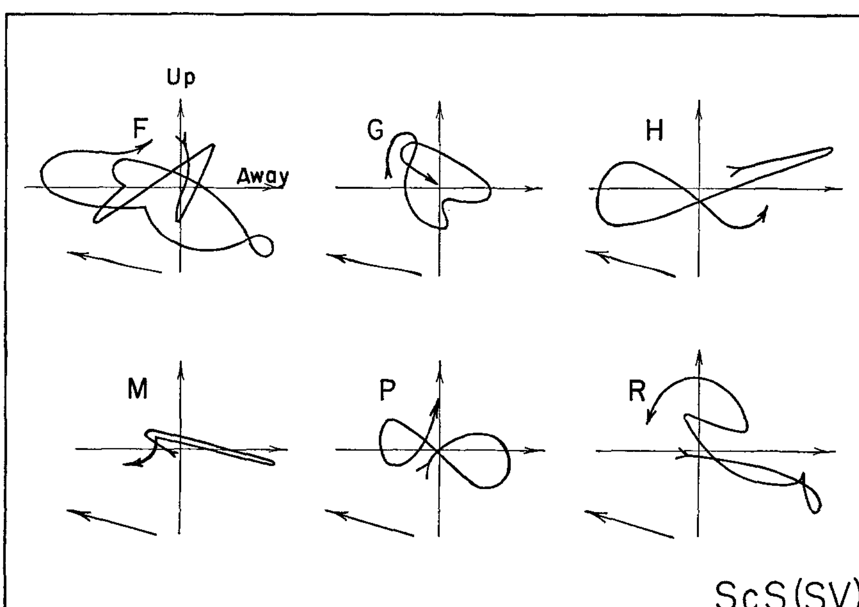

Fig. 4. Recorded ground motion due to the SV part of ScS. Notations are as in figure 1.

tion becomes larger. The case shown in figure 1, L exhibits a similar phenomenon.

In all instances given in figure 2, the PcP motion starts close to the vertical, but thereafter the horizontal component becomes larger. In two cases (fig. 2, A and T) there is clearly established the existence of an S phase that follows PcP; in the first case it arrives 20 seconds, and in the second case 10 seconds, later than PcP. The PcP motion in the horizontal plane for the case of figure 2, A is reproduced in figure 5, which indicates the presence of an SH Component. Figure 2, F shows a case in which a wave with a relatively large horizontal component arriving only after a half cycle of the steep P motion is recorded.

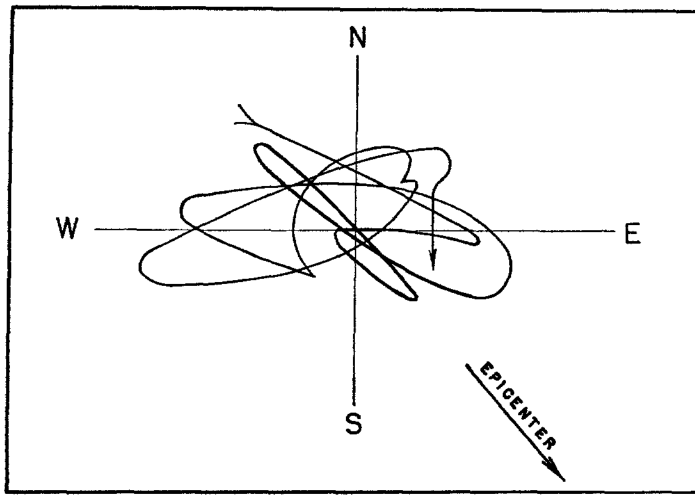

Fig. 5. Horizontal component of the recorded ground motion due to PcP of shock A, showing the presence of the SH component.

The ground motions due to S and ScS waves are given in figures 3 and 4. They indicate the presence of a vibration in which the largest displacement of the ground is in the general vicinity of, but not exactly in, a direction that is perpendicular to the direction of propagation (SV-type motion). In some cases the vertical component of the motion is smaller (fig. 3, B), and in others larger (fig. 3, G), than would be expected from the theory. There are cases in which S is followed by a P-type motion that precedes sS (fig. 3, G), and others in which a P-type motion precedes ScS (fig. 4, F and H). In all cases, S and ScS have a large SH component which is perpendicular to the plane of the paper (not reproduced). The SV motion of figure 4, F starts with a large angle of vibration, but toward the end of the SV motion it becomes smaller and may be considered as being perpendicular to the direction of the ray. Apparently, the first part of the ScS is affected by the later part of the preceding P motion, and toward the end of the ScS motion this effect disappears. Figure 4, M presents an ideal example for the SV part of a pure shear wave for the given epicentral distance ($\Delta = 75°$).

The foregoing analysis of the observed ground motion of P, PcP, S, and ScS provides information about the existence of smaller phases recorded close to these phases. The existence of S-type motion following PcP-type and P-type motion preceding sS and ScS was observed. These examples provide new evidence for the multiplicity of phases. For an excellent discussion of unexplained phases in seismograms the reader is referred to a paper by Gutenberg.[4] Besides the Mohorovičić discontinuity and the boundaries between the layers in the crust, he finds "additional discontinuities at about 80 km., and about 150 km., that are the loci of reflection and refraction, both including the changes from longitudinal to transverse waves and vice versa." These numerous minor phases with comparatively small amplitudes are recorded on the seismograms. Since PcP, ScS, PcS, and ScP arrive at the surface of the earth very steeply, making an angle of less than about 16 degrees with the normal, the horizontal component of PcP and of ScP and the vertical component of ScS and PcS are very small as compared with their other respective components. A minor phase arriving at the same time as, or shortly before or after, these waves may produce a ground motion large enough to make the minor component of the steep main phase much larger than it should be, especially if a minor S phase arrives too close to a steep P wave, or vice versa. Therefore, part of the abnormally large observed minor components of the core reflections can be accounted for by the ground motion due to the minor phases.

The effect of the discontinuities lying between the Mohorovičić discontinuity and 200 km. can be observed by the behavior of the energy contained in pP and P as a function of the focal depth as studied by Mooney.[5] Mooney found that "the ratio of the energy in pP to the energy in P averaged over a distance range 60°–90° is observed to decrease with depth, by 0.5 on a logarithmic scale of energy between 100 and 600 km. depth of focus." His results indicate that at least part of the decrease in the energy takes place rather suddenly between 100 and 200 km. $(A_t^1 - A_o)P$ increases between 100 and 200 km., whereas $(A_t^3 - A_o)pP$ decrease in the same range of focal depth.[6] If we assume one or more discontinuities between the Mohorovičić discontinuity and 200 km., for a shock originating above these discontinuities both P and pP cross them twice, but for a shock that originates below these discontinuities P crosses them only once, whereas pP crosses them three times, thus losing more energy than P does.

Conclusion

From the discussion presented above it is concluded that the major part of the large observed minor component of PcP and of ScS can be accounted for as a consequence of the structure of the earth's crust and of the upper few hundred kilometers of the mantle. Its direct effect on the ground motion, and consequently on the energy,

[4] B. Gutenberg, "Unexplained Phases in Seismograms," *Bull. Seism. Soc. Am.*, 39: 79–92 (1949).

[5] H. M. Mooney, "A Study of the Energy Content of the Seismic Waves P and pP," *Bull. Seism. Soc. Am.*, 41: 13–30 (1951).

[6] Where $A_t^1 = C - \log\left(\frac{u, w}{k\sqrt{E_1 T}}\right)$ calculated,

$$A_0 = M - \log\left(\frac{u, w}{T}\right)_{\text{obs.}} - 0.1\,(M - 7) + \text{station correction},$$

$(A_t^2)_P$ is A_t^1 corrected for observation,
$(A_t^3)_{pP}$ is $(A_t)_{pP}$ calculated from $(A_t^2)_P$.

(Mooney, *op. cit.*, fn. 5 above; details of calculations in Ergin, dissertation cited in fn. 2.)

is to reduce the energy contained in the waves with horizontal components that are comparable to their vertical components (P, pP, and others). It produces minor phases that arrive close to a main phase. Particularly if one of the components of the main phase is very small, the effect of the corresponding component of the minor phase makes it look much larger than it should be, and thus indirectly may be a source of misinterpretation. No attempt has been made to use the results as evidence for anisotropy of the crustal structure. It is suggested, however, that the study of PcP, ScS, and all other phases, except the direct longitudinal and transverse waves, cannot be used for the purpose of detecting anisotropy, as other factors may be involved which have greater effect on them than the anisotropy.

Records of the vector recorder[7] may provide more information on the horizontal ground motion than can be obtained by looking at the records of N–S and E–W component seismographs.

The author is indebted to Professor Beno Gutenberg for recommending the prob. lem and for his constructive criticism, and also to Professors C. F. Richter and H- Benioff, who reviewed the final draft and made valuable suggestions.

[7] H. Benioff, B. Gutenberg, and C. F. Richter, "Progress Report, Seismological Laboratory," *Trans. Am. Geophys. Union*, 31:463-467 (1950).

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