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# THE sP, SP, AND PS WAVES OF THE DEEP FOCUS EARTHQUAKE OF MAY 25, 1944

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. Seismic waves

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TABLE 1

Stations from which records were obtained, epicentral distance (Δ), instrument type, and component.

| Station No. | Station | Δ | Instrument | Component |
|---|---|---|---|---|
| 1 | Hawaii | 47.0 | Milne-Shaw | N, E |
| 2 | Berkeley | 79.3 | Galitzin | N, E, Z |
| 3 | Ukiah | 79.5 | Mc Comb-Romberg | NE, NW |
| 4 | Pasadena | 79.7 | L. P. Benioff | N, E, Z |
| 5 | Tucson | 83.8 | Wood-Anderson | N, E, Z |
| 6 | Victoria | 85.4 | Milne-Shaw | N, E |
| 7 | Sitka | 86.6 | Wenner | N, E |
| 8 | Logan | 88.1 | Wood-Anderson | N, E |
| 9 | Salt Lake City | 89.5 | Mc Comb-Romberg | N, E |
| 10 | College | 89.9 | Mc Comb-Romberg | N |
| 11 | Rapid City | 94.7 | Wood-Anderson | E |
| 12 | Saskatoon | 96.3 | Milne-Shaw | N |
| 13 | Lincoln | 97.8 | Mc Comb-Romberg | E |
| 14 | St. Louis | 101.7 | Macelwane-Sprengnether | N, E, Z |
| 15 | Chicago | 104.6 | Mc Comb-Romberg | N, E |
| 16 | Columbia | 107.5 | Mc Comb-Romberg | N, E |
| 17 | Ottawa | 113.8 | Milne-Shaw | N, E |
| 18 | Burlington | 115.5 | Milne-Shaw | NE, NW |
| 19 | Seven Falls | 117.3 | Milne-Shaw | E |

# TABLE 2

Travel Times, O - C (J - B), Periods, and Amplitudes for sP, SP, and PS

| Station No. | Component | Travel Times & O - C (J - B) sP (m s) | SP (m s) | PS (m s) | Periods in Sec. sP | SP | PS | Amplitudes in mm. sP | SP | PS |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. | N | 10-54 | 13-53 | | | | | | | |
| | | 3 | - 4 | | 3.2 | 5.3 | | 3.0 | 9.0 | |
| 2. | Z | 14-16 | 21-02 | | | | | | | |
| | | 0 | - 7 | | 4.6 | 6.0 | | 3.0 | 4.5 | |
| 2. | E | 14-18 | 21-15 | | | | | | | |
| | | 2 | 6 | | 5.4 | 5.6 | | 6.5 | 24.1 | |
| 3. | N40W | | 21-03 | | | | | | | |
| | | | - 8 | | | 6.7 | | | 2.9 | |
| 4. | Z | 14-21 | 21-12 | | | | | | | |
| | | - 9 | - 1 | | 5.0 | 6.0 | | 5.0 | 3.5 | |
| 4. | E | 14-30 | 21-22 | | | | | | | |
| | | 9 | 9 | | 5.6 | 8.0 | 6.2 | 5.0 | 6.0 | 6.5 |
| 5. | E | 14-38 | 22-12 | 23-22 | | | | | | |
| | | - 1 | 8 | - 6 | 3.2 | 10.0 | 6.8 | 1.6 | 5.2 | 5.5 |
| 6. | N | 14-49 | 22-22 | | | | | | | |
| | | 2 | - 1 | | ? | 8.0 | | 1.0 | 4.5 | |
| 6. | E | 14-49 | 22-23 | | | | | | | |
| | | 2 | 0 | | ? | 6.4 | | 1.2 | 4.5 | |
| 7. | N | 14-57 | 22-28 | | | | | | | |
| | | 3 | -10 | | 5.3 | 10.0 | | 2.2 | 7.5 | |
| 8. | E | 15-16 | 22-57 | | | | | | | |
| | | 5 | 2 | | ? | 4.5 | | 1.5 | 3.0 | |
| 9. | E | 15-08 | 22-59 | 24-36 | | | | | | |
| | | 0 | -11 | 3 | 4.0 | 7.2 | 8.0 | 1.0 | 1.7 | 1.5 |
| 10. | N | 15-13 | 23-06 | | | | | | | |
| | | 4 | - 9 | | 12.0 | ? | | | 1.0 | 1.5 |
| 11. | E | | 24-11 | | | | | | | |
| | | | 4 | | | 5.6 | | | 2.5 | |
| 12. | N | 15-39 | 24-23 | 25-38 | | | | | | |
| | | 0 | 0 | - 1 | | 9.4 | 9.4 | .8 | 2.0 | 1.6 |
| 13. | E | | 24-49 | 26-03 | | | | | | |
| | | | 10 | 9 | | 6.1 | 6.1 | | .7 | 1.2 |
| 14. | Z | | 25-34 | 26-44 | | | | | | |
| | | | 8 | 4 | | 3.0 | 2.4 | | 1.4 | 1.5 |
| 14. | E | 16-07 | 25-27 | 26-48 | | | | | | |
| | | 4 | 1 | 8 | 6.0 | 19.4 | 12.2 | 5.0 | 6.5 | 5.0 |
| 15. | E | | 25-58 | 27-05 | | | | | | |
| | | | 10 | 6 | | 10.0 | 8.0 | | 1.7 | 2.0 |
| 16. | E | | 26-14 | 27-31 | | | | | | |
| | | | - 3 | 4 | | 10.0 | 10.0 | | 1.0 | .6 |

| Station | Component | Travel Times & O - C (J - B) | | | Periods in Sec. | | | Amplitudes in mm. | | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | | sP | SP | PS | sP | SP | PS | sP | SP | PS |
| | | m s | m s | m s | | | | | | |
| 17. | E | | 22-22 | 28-23 | | | | | | |
| | | | 6 | 0 | | 10.8 | 7.5 | | 2.0 | 1.7 |
| 18. | NE | | 27-38 | 28-39 | | | | | | |
| | | | 6 | 0 | | 11.5 | 6.2 | | 2.3 | 1.9 |
| 19. | E | | 27-45 | 28-54 | | | | | | |
| | | | - 3 | - 2 | | 10.2 | 10.2 | | 1.3 | 1.3 |

TABLE 3

| Station No. | Period SP / Period PS |
|---|---|
| 5. | 1.47 |
| 9. | .90 |
| 12. | 1.00 |
| 13. | 1.00 |
| 14. | 1.59 |
| 15. | 1.25 |
| 16. | 1.20 |
| 17. | 1.44 |
| 18. | 1.25 |
| 19. | 1.00 |

TABLE 4

| Station No. | Period sP / Period SP |
|---|---|
| 1. | .375 |
| 2. | .946 |
| 4. | .7 |
| 5. | .612 |
| 7. | .736 |
| 9. | .555 |
| 10. | .606 |
| 14. | .474 |

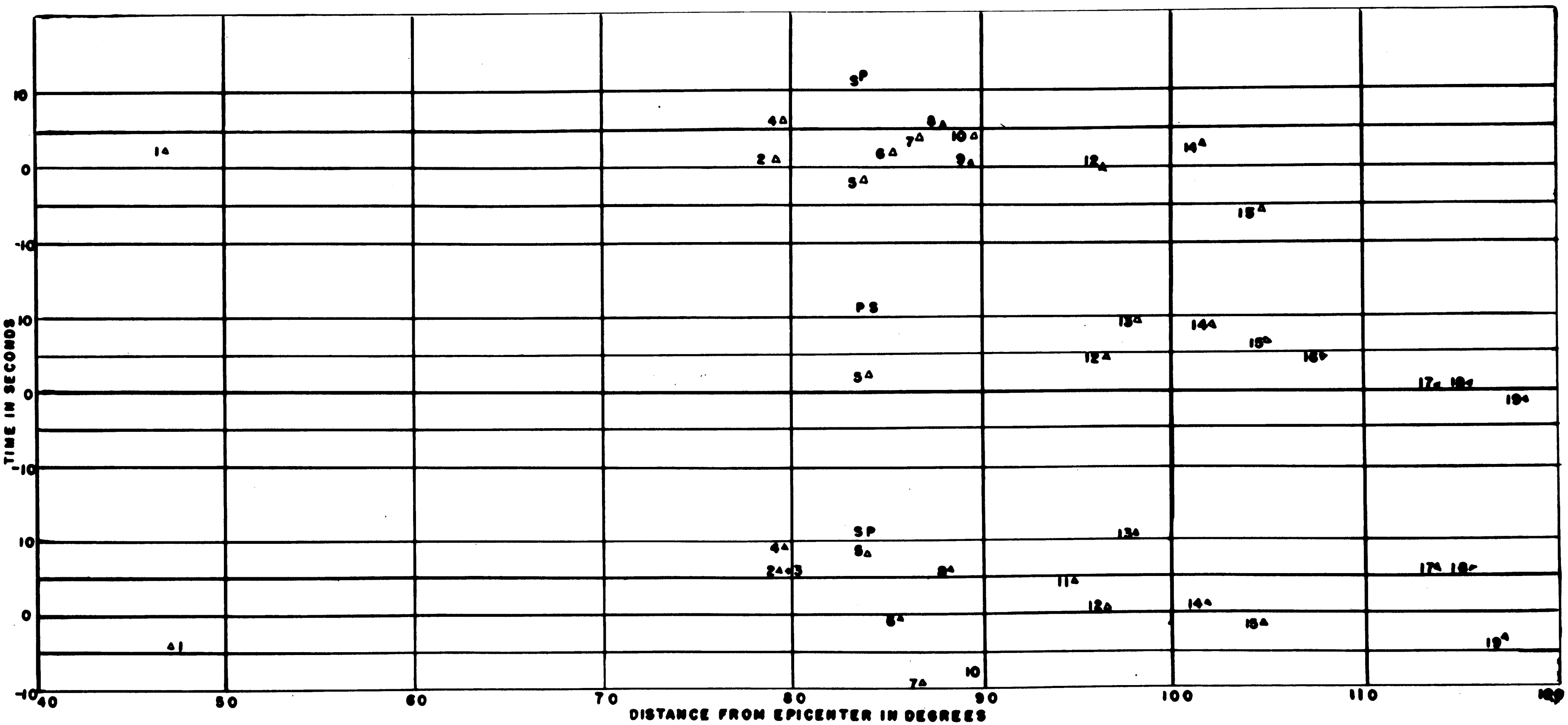



FIGURE 1

RESIDUALS WITH RESPECT TO J-B TABLES

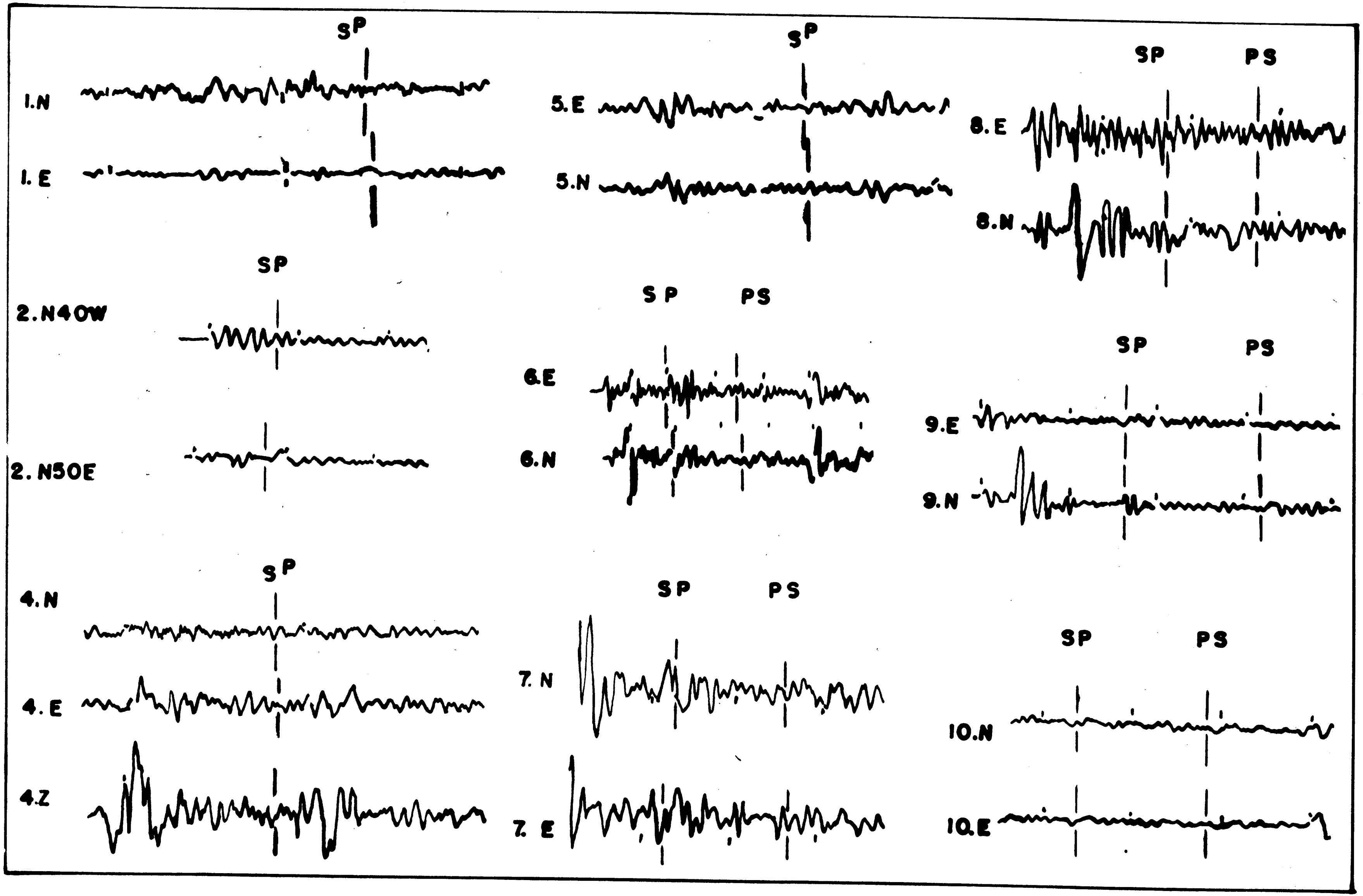



FIGURE 2 TRACINGS OF SEISMOGRAMS

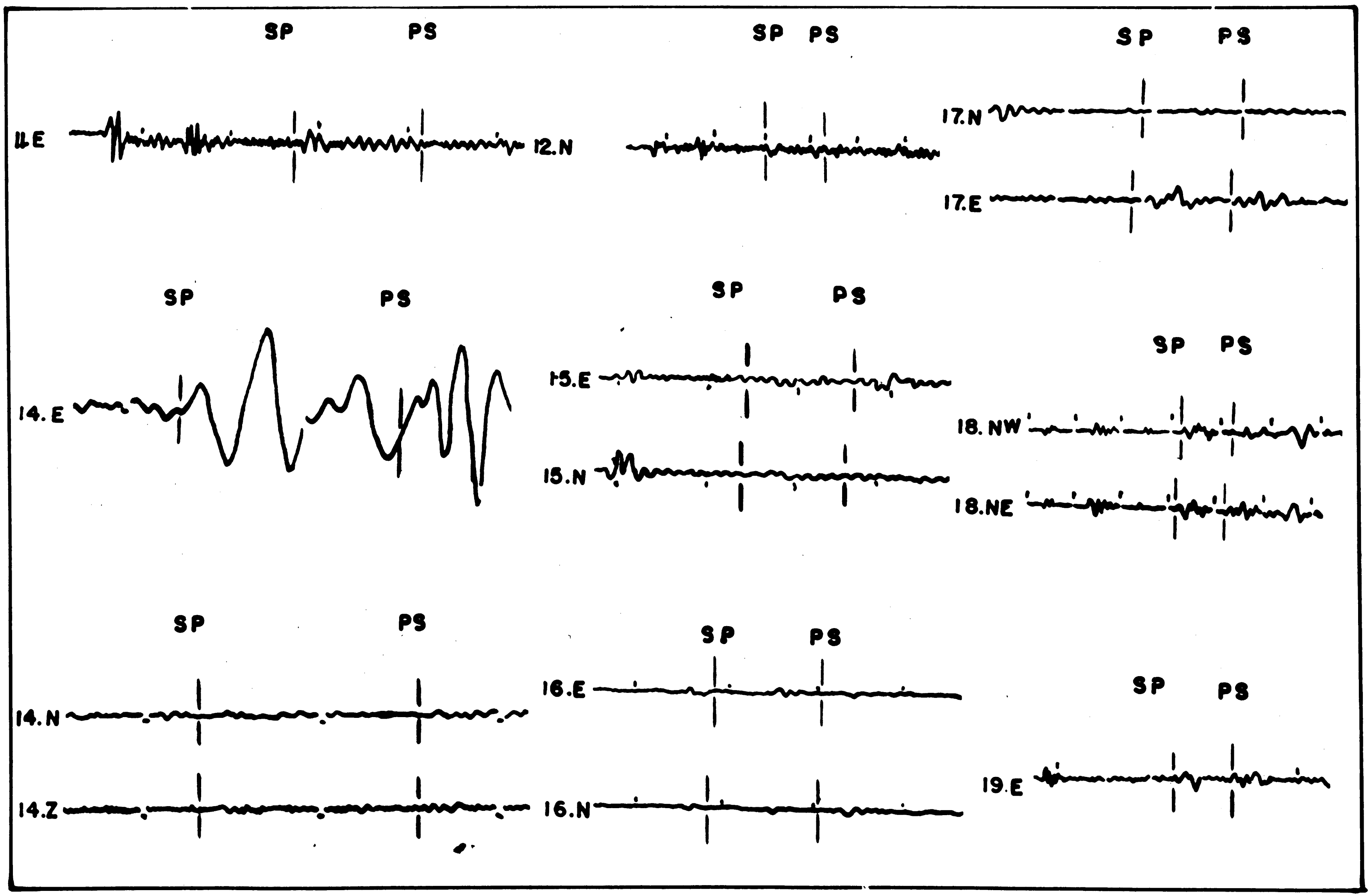



FIGURE 3 TRACINGS OF SEISMOGRAMS

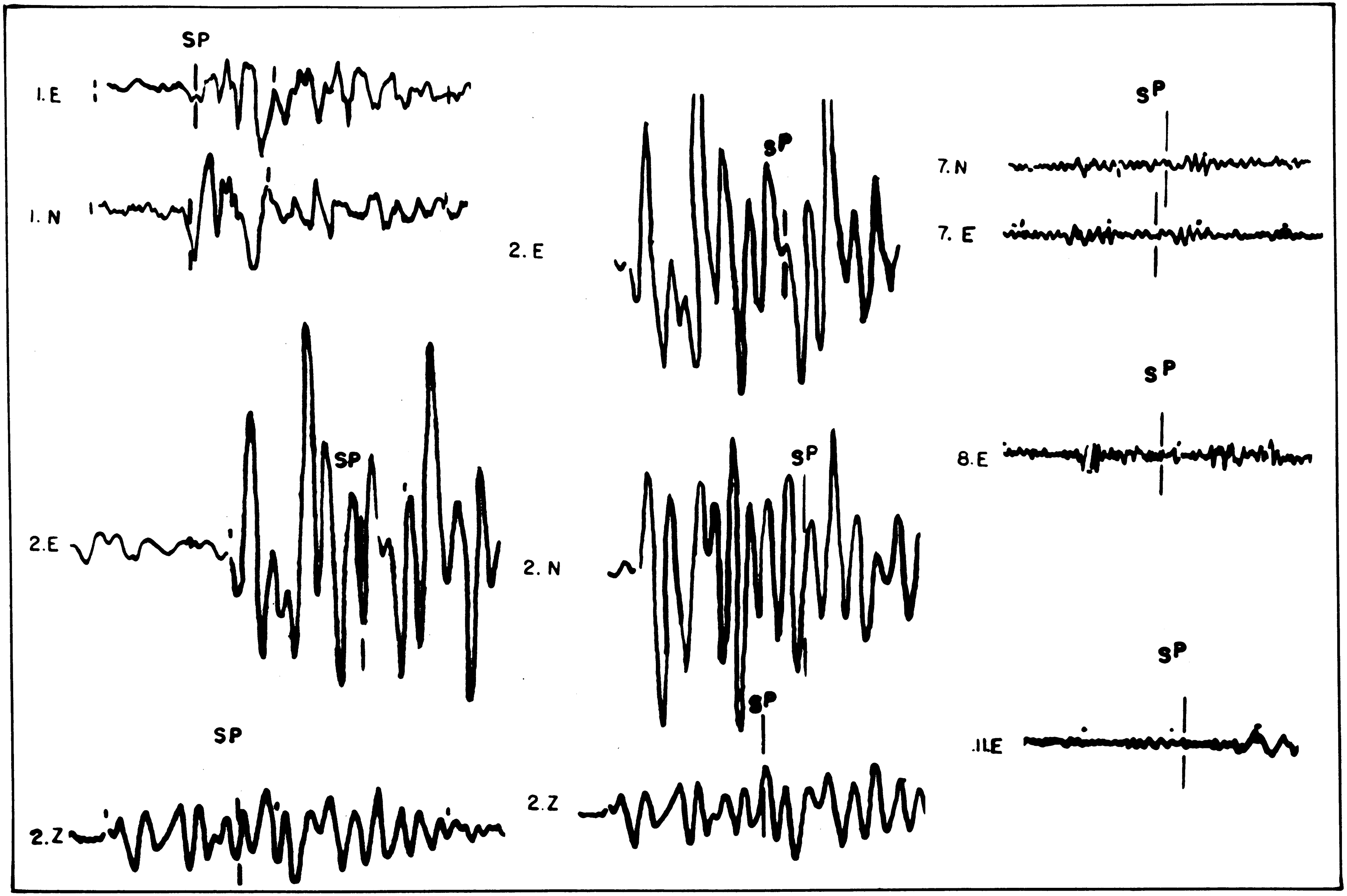



**FIGURE 4** **TRACINGS OF SEISMOGRAMS**

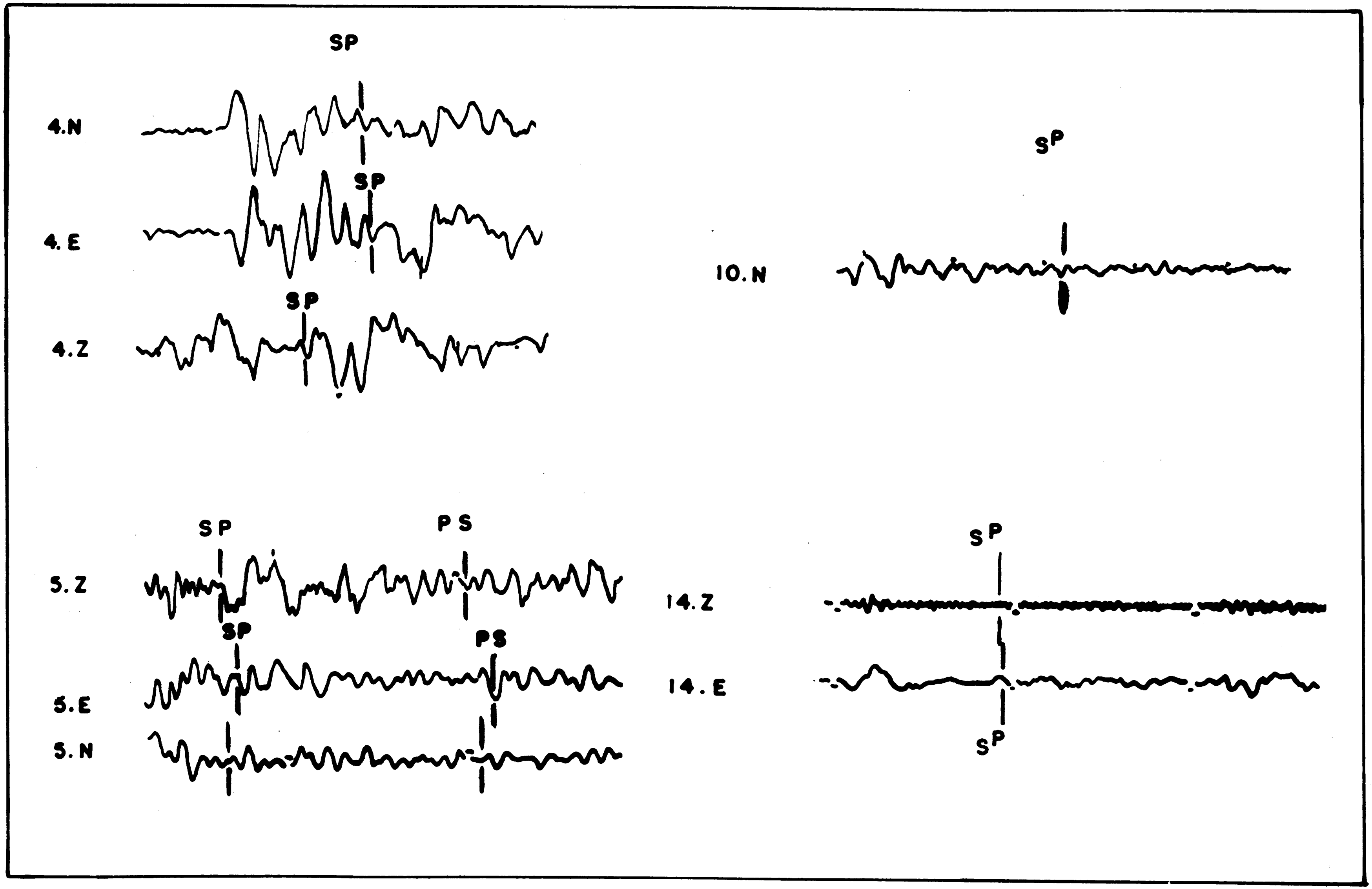
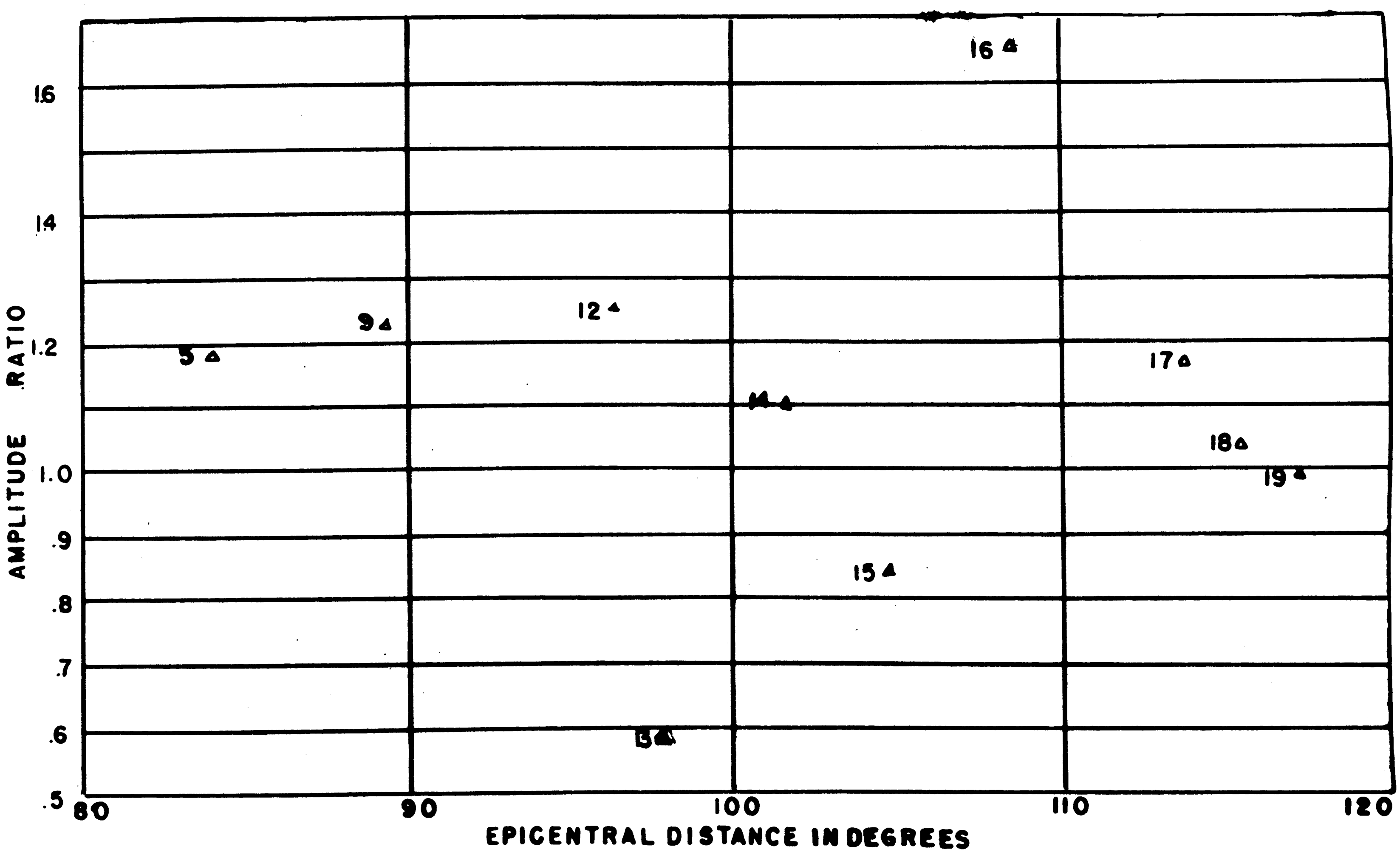



FIGURE 5 TRACINGS OF SEISMOGRAMS




OBSERVED AMPLITUDE RATIO OF SP TO PS

FIGURE 6

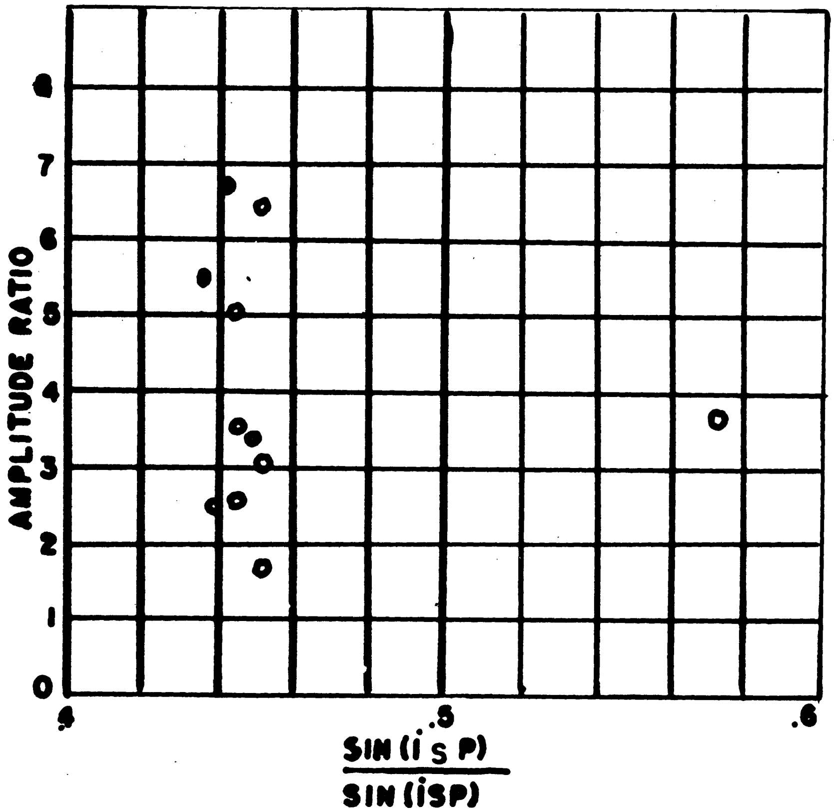
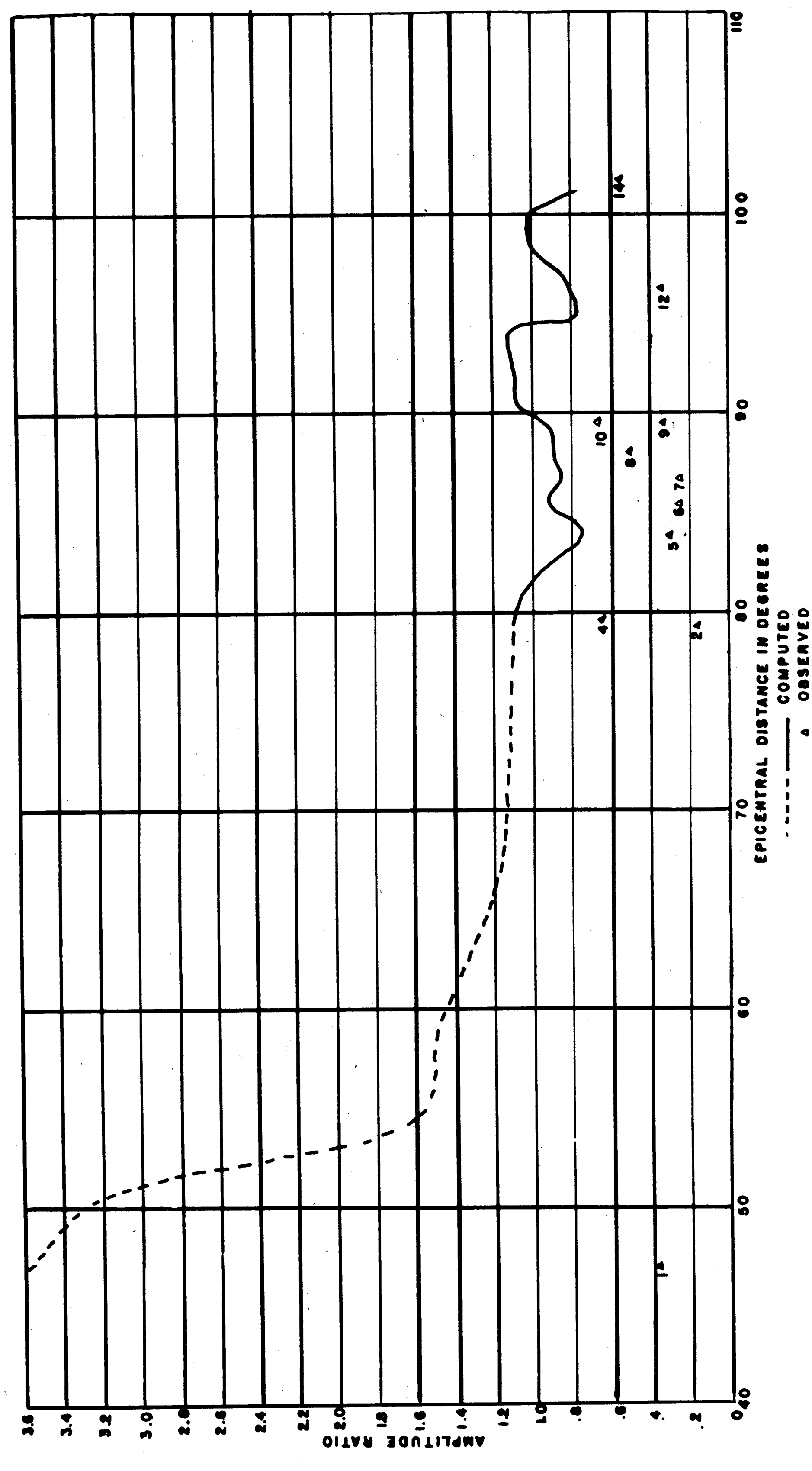



FIGURE 7 AMPLITUDE RATIO OF sP TO SP




AMPLITUDE RATIO OF $_sP$ TO SP

FIGURE 8

## INTRODUCTION

The surface reflected waves sP, SP, and PS are frequently observed at certain distances. However, there has been only a limited study made of these waves. The PS wave travel-times have been studied by Gutenberg and Richter (1934), and in a later paper (1935), they discussed the energy going into the transformed SP and PS waves. Jeffreys (1942) published the travel times of the sP wave. As far as the writer knows no energy study has been made of the sP wave. This paper presents data concerning travel-times, amplitudes, and periods of the sP, SP, and PS waves.

The earthquake of May 25, 1944 with its epicenter near the Tonga Islands was selected for study as it placed many North American stations at a distance well suited for a study of sP, SP, and PS waves. A deep-focus earthquake was desired as sP, SP, and PS waves are usually well defined waves and are not usually confused with other waves with nearly the same travel times.

## EPICENTER AND TIME OF ORGIN

The method used to find the epicenter was a simple one, yet accurate enough for the results desired. Epicenters for this earthquake have been published by the United States Coast and Geodetic Survey[3] and the Seismological Service of Canada[4]. Using each one as an assumed epicenter, the distance between epicenter and station was computed. Then taking an assumed time of orgin, the travel time of the P wave was computed from the J-B tables and checked with the observed P readings for the following stations, Riverview, Hawaii, Sitka, Pasadena, Taoubaya, Perth, Wellington, and Brisbane. These stations were used as they gave good control both east-west and north-south of the epicenter. They also have quite sensitive instruments. Then the assumed epicenter and time of orgin were shifted until the residuals of the computed and observed travel times for the eight stations were all within six seconds with an average of zero. The final epicenter was placed at 22°S and 178°W with a time of orgin at 01h 06m 38s U. T., May 25, 1944.

DEPTH OF FOCUS

The lack of large surface waves and the clearly developed pP wave, with the large time interval pP-P, indicated an unusual depth of focus. This interval at 101.7 degrees (St. Louis) is 133 seconds. By use of a graph, pP-P time interval plotted against depth (the Gutenberg-Richter, 1936, table for the travel time of the pP wave at different depths) the calculated depth was interpolated for each station. The average depth for all the stations was 605 kilometers, with a variation of from 590 kilometers to 618 kilometers. The adopted depth was 605 kilometers below the surface corr e-sponding to 0.09 of the earth's radius below the base of the crust.

This earthquake is evidently one of the most deep-seated disturbances that has occured in recent years. It is in the same area and at about the same depth as one reported by Brunner (1938-1939).

## DATA

Stations from which data were obtained, the distance from station to epicenter, the type and components of instruments at each station are given in Table 1. The epicenter-station distance was computed using the geocentric coordinates as given by Macelwane and Sohon[6]. Each station was assigned a number, which identifies it in the various figures.

Where possible, the travel-times, periods, and amplitudes of sP, SP, and PS were measured. This data is given in Table 2. The travel-times for SP and PS were calculated from the standard Jeffreys-Bullen (1937-1940) tables, and the travel-times for sP were calculated from tables by Jeffreys (1942). Table 3 gives the observed period ratio of SP to PS, and Table 4 gives the observed period ratio of sP to SP.

Figures 2, 3, 4, and 5 are tracings of the seismograms that were measured. The vertical lines indicate the points where the phases designated above them should arrive according to the J-B tables.

The differences between the computed and the observed travel times for sP, SP, and PS phases are plotted against epicentral distances in Figure 1.

The observed amplitude ratio of SP to PS is plotted against the epicentral distance in Figure 6.

## THEORETICAL CONSIDERATIONS

The ratios of the horizontal displacements from sP and SP waves that would be expected were computed. The method was patterned after Dana's (1945) calculation of the relative amplitudes of certain waves in terms of the horizontal and vertical components of the displacements which they produce at the surface of the earth.

The amplitude, A, of a seismic wave arriving at the surface of the earth is given by Dana (1945) as

$$A = CTf \sqrt{e^{-\int K dD} \frac{\operatorname{Tan} i_0}{\operatorname{Sin} \Delta} \frac{di_0}{d\Delta}} \qquad (1)$$

The constant C depends on the energy at the focus of the shock and the type of wave (P, SH, and SV). The ratios used here were computed for a single wave and for a single shock, therefore C will cancel. The periods (T) for sP and SP were roughly the same and were taken as equal. The exponential term, the absorption factor, was taken as unity since the absorption is probably small and approximately the same for sP and SP in any given case. $\Delta$ is the epicentral distance. The above equation for the ratio of the amplitudes then becomes

$$\frac{A_{sP}}{A_{SP}} = \frac{f_{sP}}{f_{SP}} \frac{\sqrt{\operatorname{Tan} i_0 \frac{di_0}{d\Delta}}}{\sqrt{\operatorname{Tan} i_0 \frac{di_0}{d\Delta}}} \qquad (2)$$

The ratio $\frac{\sin(i_o)_{sP}}{\sin(i_o)_{SP}}$ was plotted against the amplitude ratio $A_{sP}/A_{SP}$ (Figure 7), where $i_o$ is the angle of incidence at the surface of the earth. It was found to be very nearly constant for distances from 79 degrees to 102 degrees. As the ratio of the angles of incidence is very nearly constant, it follows that the ratio of reflected energies is also very nearly constant. Then the ratio $f_{sP}/f_{SP}$, where f is the product of square roots of the fractions of the energy remaining after reflection at the surface of the earth, will be constant. Also as the readings for the sP to SP ratio were all, except Hawaii, within this distance range, and if the sine ratio is nearly constant then the tangent ratio will be nearly constant.

The amplitude ratio now becomes

$$\frac{A_{sP}}{A_{SP}} \approx \sqrt{\frac{(di_o/d\Delta)_{sP}}{(di_o/d\Delta)_{SP}}} \qquad (3)$$

This ratio was calculated by use of the J-B tables.

To allow for the velocity of the P branch of the sP and SP waves in the crust, the expression $\sin i_o = v/\bar{V}$ was used, where v is the true velocity in the surface material (taken to be 6 km./sec. and 8 km./sec.), and $\bar{V}$ is the apparent surface velocity of the same wave. $\bar{V}$ was computed from the J-B tables.

The graphs given by Gutenberg (1944) were used to compute the horizontal component of the ground displacements $H_{sP}/H_{SP}$ (Figure 3a in his paper).

These ratios were computed for P waves having velocities of 6 km./sec. and 8 km./sec. in the crustal layer, which are the extremes expected. Also, only the horizontal components were considered as there were too few stations with comparable vertical instruments.

## RESULTS AND CONCLUSIONS

In Figure 8 the computed curve calculated by equation 3 is shown as a solid line between 79 degrees and 102 degrees. Between these limits the ratio $\frac{\sin(i_0)_{SP}}{\sin(i_0)_{SP}}$ is known to be nearly constant (Figure 7), and this assumption was accepted in computing the curve. The dashed part of the curve was also computed on this assumption, but it was found that the ratio $\frac{\sin(i_0)_{SP}}{\sin(i_0)_{SP}}$ was not a constant at distances as short as 47 degrees; therefore the usefulness of equation 3 is doubtful. Also the whole curve was computed without the multiplying correction $\sin i_0 = v/\bar{V}$, where v is the actual velocity of a P wave in the crust, and $\bar{V}$ is the apparent velocity taken from the J-B tables. This correction is small ($\sin i_0 \approx 1$), and if this correction is applied the resulting curves would be nearly parallel to the uncorrected curve and slightly below. For example, at 86 degrees the uncorrected amplitude ratio is .90; for v=6 km./sec. the amplitude ratio is .72; and for v = 8 km./sec. the amplitude ratio is .82.

As can be seen from Table 8 the theoretical curve is in poor agreement with the observed amplitude ratios. However, at about 85 degrees and 95 degrees both the computed and the observed curves do have minima. Also, the average of the theoretical amplitude ratio curve points having v = 8 km./sec.

is .87, just twice as much as the observed amplitude ratio curve points, which is .43.

The minima observed amplitude ratio in the vicinity of 85 degrees and 95 degrees can be attributed to loss of part of the energy before it reaches the surface or it may be due to errors in the travel time curves used.

The ratio, $f_{sP}/f_{SP}$, would be expected to be about one half from Gutenberg's work (1935) and the $\sqrt{\frac{\tan(i_0)_{sP}}{\tan(i_0)_{SP}}}$ will be approximately .7 over the range of distance for which data have been taken. Therefore the values calculated from equation 3 should be about three times too large. This makes the agreement between the expected and the observed ratios fair. The dotted line on Figure 8 shows the values computed from equation 3 multiplied by one third.

Brunner (1938-1939) compared amplitudes of waves beginning with the corresponding direct waves and found both classes had nearly the same intensity. This would give an amplitude ratio for sP/SP of nearly one. This is in good agreement with the uncorrected theoretical amplitude ratio, as its average ratio (from 79 degrees to 102 degrees) is .95.

Table 3 is the observed ratio of the periods, SP to PS, and Table 4 is the observed ratio of the periods, sP to SP. If these ratios were plotted against distance in a graph, there would be just a scattering of points. Therefore within the limits of the observed distance, the data show no marked effect of distance. Gutenberg and Richter (1935) observed the same thing for P, PP, P', S, PKS, and SS.

The observed periods of the sP wave are quite consistent, with only one exception. They varied from 3.2 seconds to 6.0 seconds. The one exception is the College station with a period of 12 seconds. The College record is of unusual appearance and it is doubtful that 12 seconds is the true period.

There is a much greater variation in the periods of the SP waves. There are two equally common groups of the SP periods, with nearly every record falling into one or the other of the two groups. One group has a period variation of from 3 seconds to 6 seconds and the other from 9.4 seconds to 11.5, with only St. Louis (period of 19.4 seconds) falling much outside either of the two. There is some indication that the SP waves having their reflection points under the continent have larger periods than the SP waves having their reflection under the ocean (an average of 2.5 seconds per record). But the number of records is so small no conclusions should be drawn.

The periods of the PS waves fall into no groups, nor do they vary in any consistant way. Neglecting the vertical record at St. Louis, the periods vary from 6.1 seconds up to 12.2 seconds, being nearly evenly scattered.

Gutenberg and Richter (1934) found that although PS can be expected to appear at about 50 degrees, it is not found until about 78 degrees and then only uncertain identification can be made. At 84 degrees PS is clearly defined. This agrees very well with the results found for this earthquake. At Pasadena ($\Delta$ = 79.7 degrees) uncertain identification is made of PS on the east-west instrument, but at Tucson ($\Delta$ = 83.8 degrees) the PS wave shows up quite clearly.

The SP wave is identified throughout the range of stations used (47 degrees to 117 degrees distance). However, sP can be identified only out to 101.7 degrees, but this is to be expected as that is nearly the greatest distance that sP can travel without touching the earth's core.

quake

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