THE SURFACE REFLECTED SHEAR WAVES OF THE EARTHQUAKE OF MAY 25, 1944

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TABLE 1

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

Station No.	Station	Δ	Azimuth	Instrument	Component
1	College	80.5	60.4	Mc Comb-Romberg	N, E
2	Sitke a	82.7	62.4	(not used)	
3	Ukiah	87.1	83.7	Mc Comb-Romberg	NE, NW
4	Berkley	87.7	84.4	(not used)	
5	Victoria	88.0	83.2	Milne-Shaw	N, E
6	Pasadena	90.7	86.8	L.P. Benioff	N, E, Z
7	Logan	95.9	89.0	L.P. Wood-Anderson	N, E
8	Tucson	96.8	89.1	L.P. Wood-Anderson	N, E
9	Salt Lake City	95.9	89.1	Mc Comb-Romberg	N, E
10	Saskatoon	98.7	83.5	Milne-Shaw	N
11	Rapid City	101.8	82.2	L.P. Wood-Anderson	E
12	Lincoln	107.3	62.4	Mc Comb-Romberg	E
13	Chicago	111.5	69.2	Mc Comb-Romberg	N, E
14	St. Louis	112.7	75.1	(not used)	
15	Ottawa	120.0	60.1	Milne-Shaw	N, E
16	Columbia	121.0	70.5	Mc Comb-Romberg	N, E
17	Seven Falls	121.9	54.5	Milne-Shaw	E
18	Burlington	122.0	58.2	Milne-Shaw	NE, NW
19	Bermuda	134.0	58.4	Milne-Shaw	NE, NW
20	San Juan	138.7	72.8	Wenner	N, E
21	Fordham	123.6	70.6	(not used)	

TABLE 2

Travel Times, O - C (J - B), Periods, and Amplitudes for S, SS, SSS, and SSSS

Station No.	Component	Travel Times & O -C (J-B) S (m s)	SS (m s)	SSS (m s)	SSSS (m s)	Periods in Sec. S	SS	SSS	SSSS	Amplitudes in mm. S	SS	SSS	SSSS
1.	N	20- 14	25-14	28- 38									
		-11	-29	-27		24	16	20		4.5	3.5	3.5	
3.	N 40W	21- 28	27-22										
		-7	2			30	30			5.5	4.5		
5.	N	21- 29	27-25	31- 08									
		-14	- 8	3		22.5	10	15		6	5	5	
5.	E		27-24	31- 05									
			- 9	0			15	15			4.5	4.5	
6.	E		28-07	31- 52									
			- 6	3			26	22			22	22	
6.	Z		28-17	31- 37									
			4	- 12			27	28			19	19	
7.	E		29-29	32- 31	35-59								
			1	20	-15		20	20			18.5	9	6
8.	E		29-37	33- 14	36-29								
			- 2	0	1		19	20	20		12.5	13.5	6
9.	N										3	2.5	
9.	E		29-30	33- 14									
			2	7							3.5	3.5	
10.	N		29-49	33- 52	36-56								
			-17	- 4	- 6						5	4.5	3.5
11.	E		30-50	34- 46									
			1	4							5.5	4	
12	E		32-18	35- 38	39-36								
			15	-31	13		20	20	22		1.5	2	1.5
13.	N		32-59	37- 02									
			- 1	- 5			20	16			4	4	
13.	E		33-00	37- 02									
			0	- 5			28	24	16		8.5	10	4.5
15.	N						16	16			5	3	
15.	E		34-52	39- 27	42-51								
			0	7	2		24	15	18		7.5	3	3.5
16.	E		35-05										
			0										
17.	E						41	32	24		7	3	3
18.	NW		35-09	39- 58	43-13								
			- 9	8	- 8		32	24	20		12	6	6
19.	NW		38-03	43- 03									
			16	17			30	24			8.5	4	
20.	E		38-36	43- 36	47-37								
			- 7	-18	- 6						20	18	12

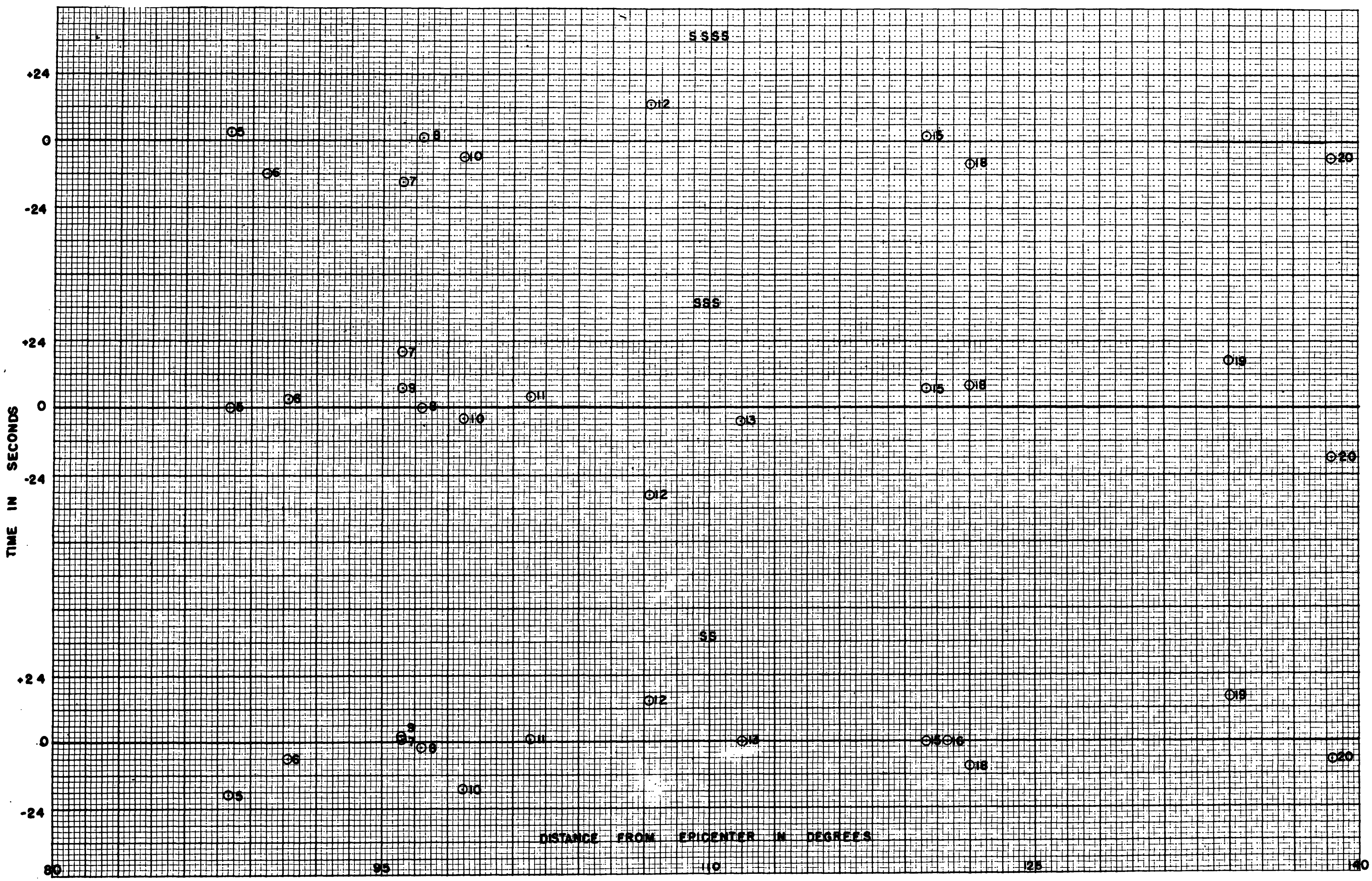

FIG.1

RESIDUALS WITH RESPECT TO J-B TABLES

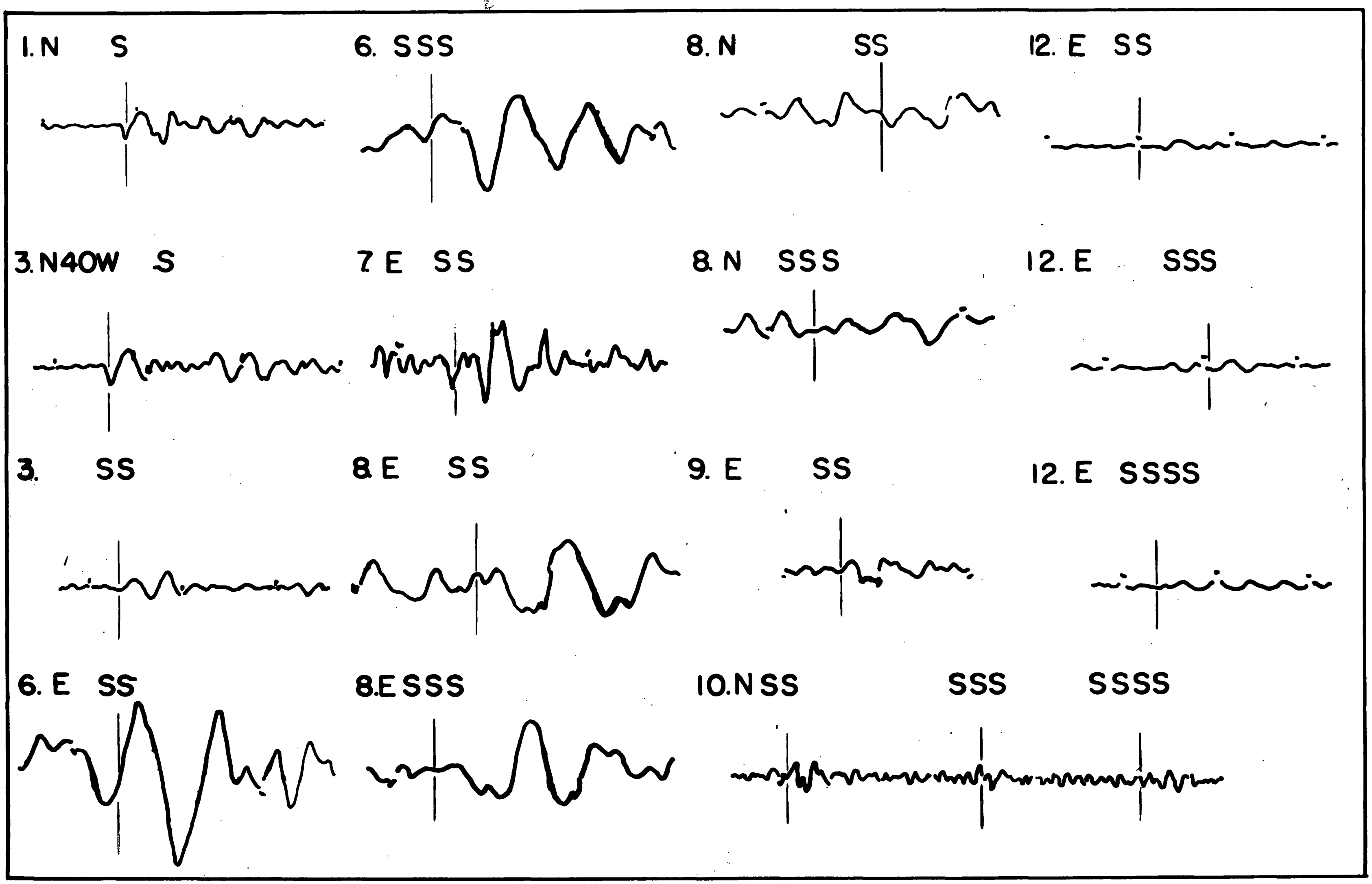

FIG. 2 TRACINGS OF SEISMOGRAMS

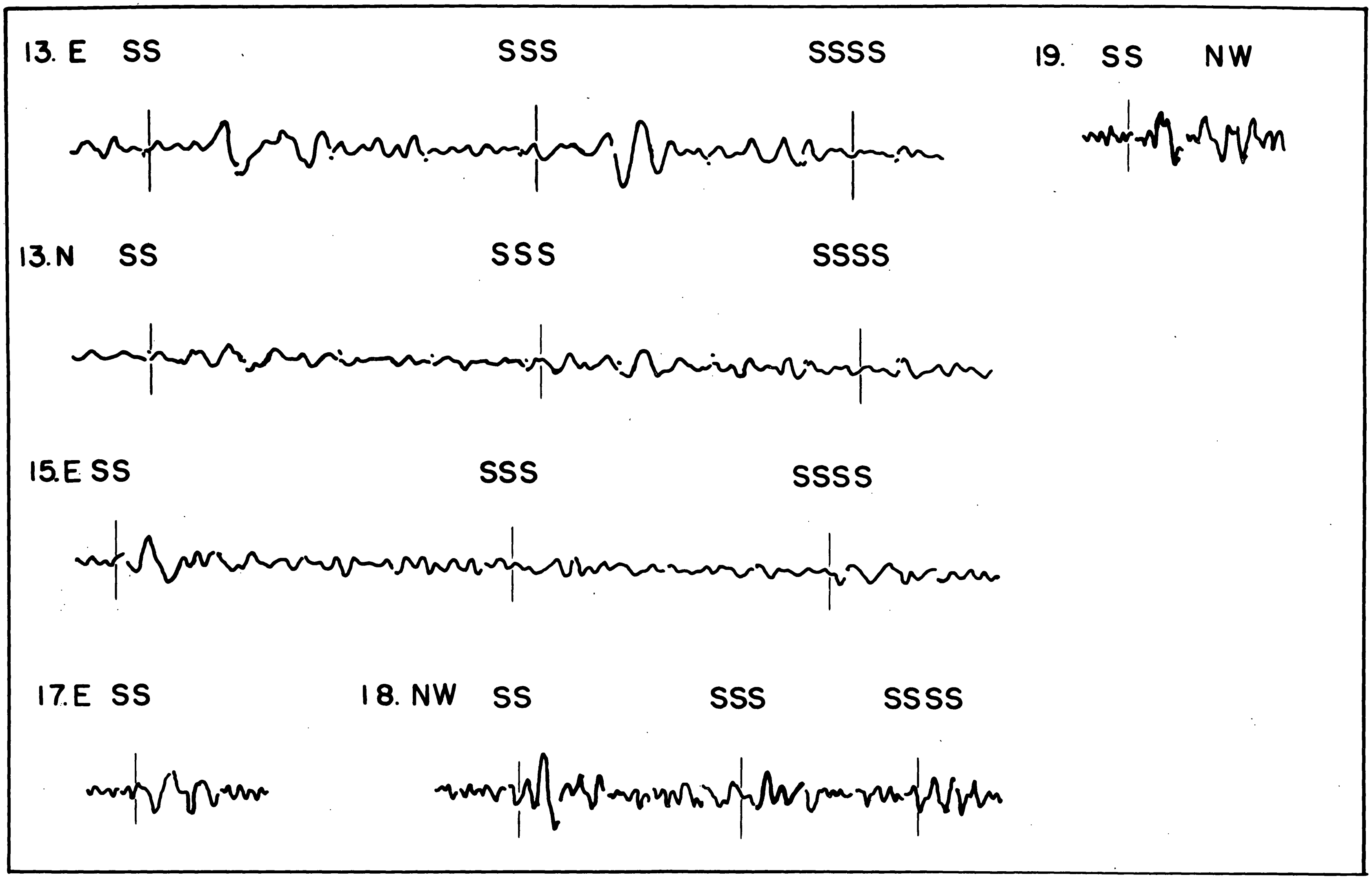

FIG. 3 TRACINGS OF SEISMOGRAMS

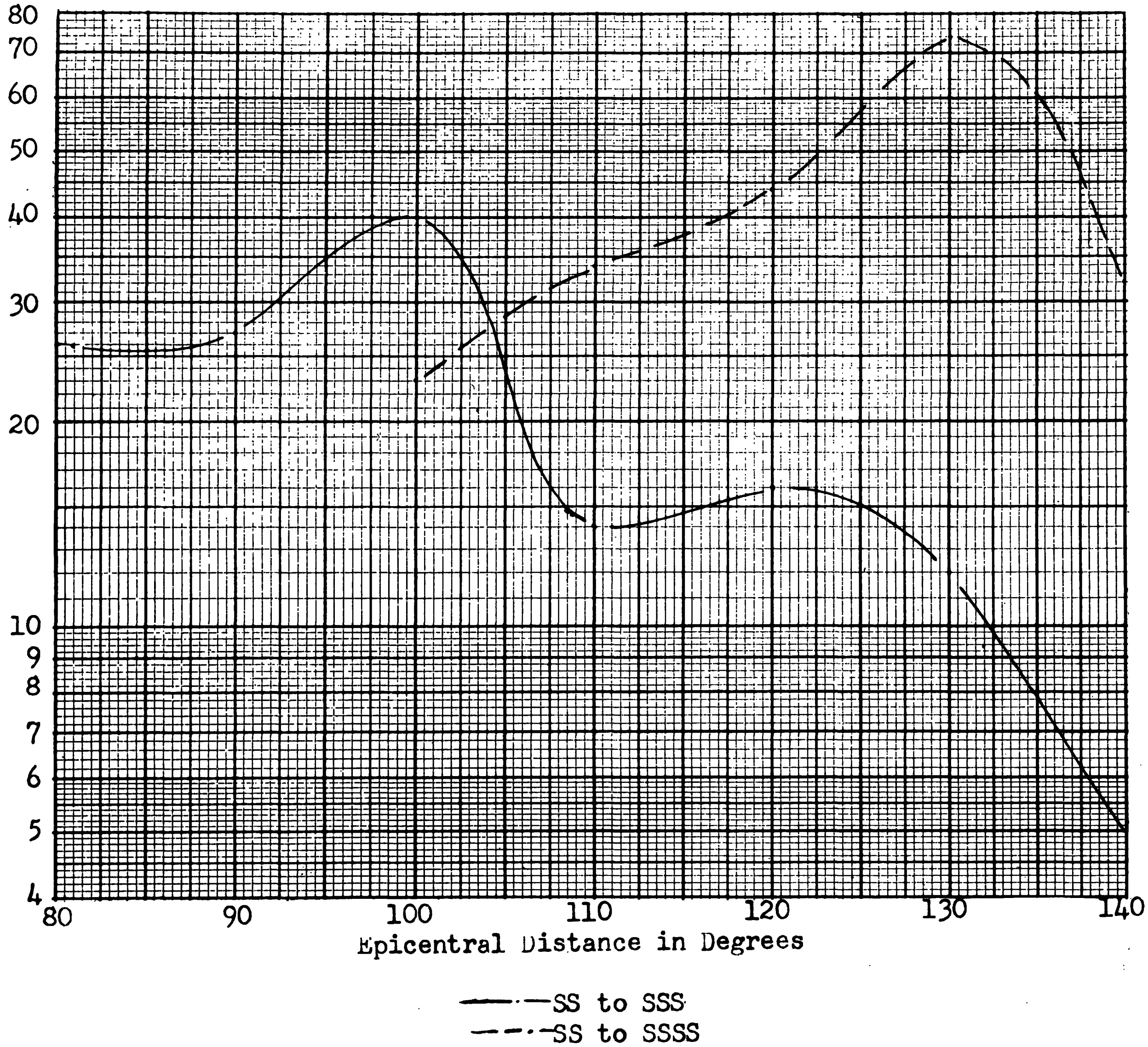

Figure 4 COMPUTED AMPLITUDE RATIOS

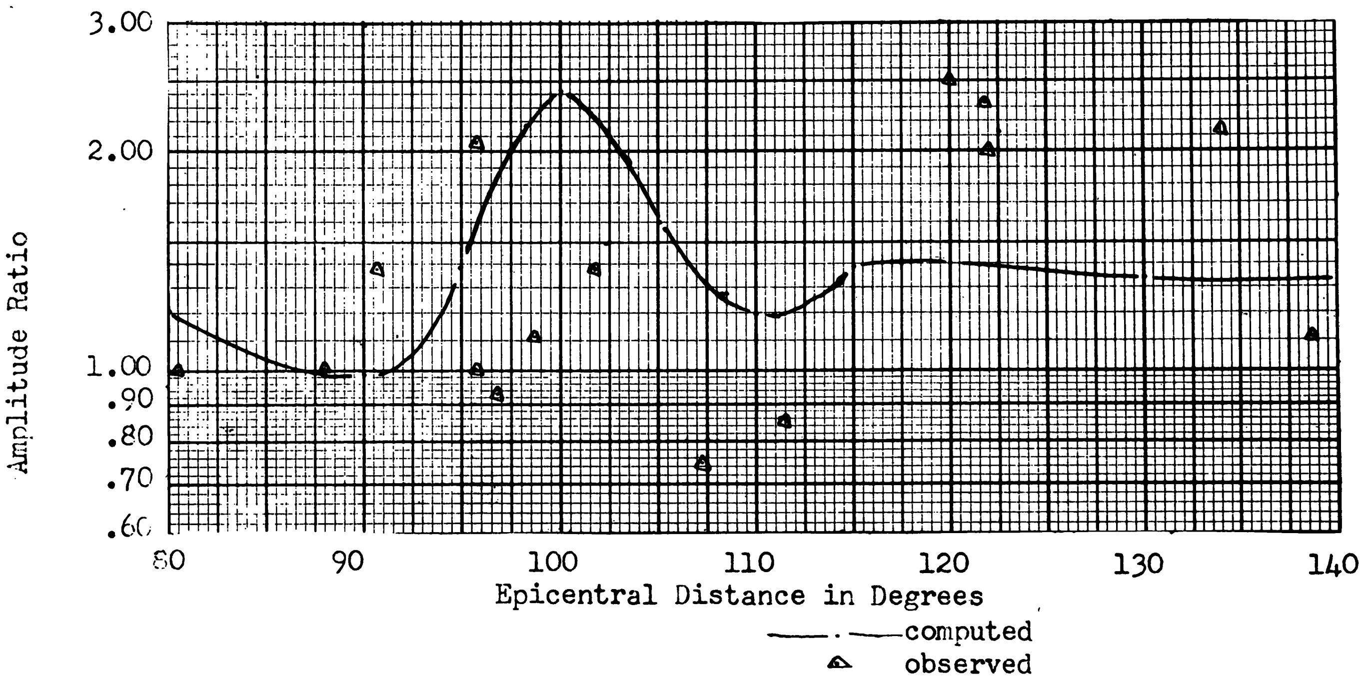

Figure 5 AMPLITUDE RATIOS OF SS TO SSS
Computed (Total Reflection) and Observed

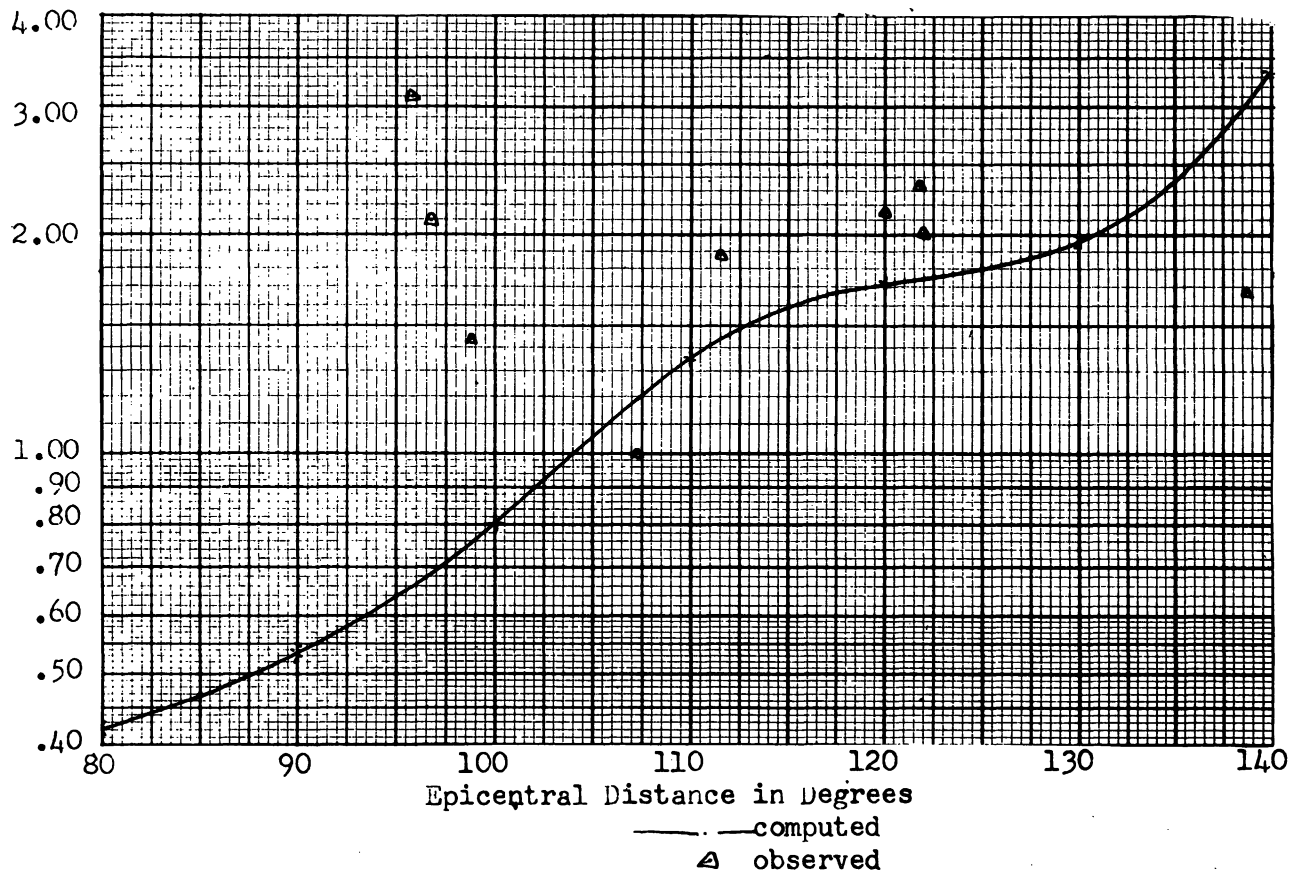

Figure 6 AMPLITUDE RATIOS OF SS TO SSSS
Computed (Total Reflection) and Observed

INTRODUCTION

The various surface reflected shear waves, SS, SSS, etc., are frequently observed, but their travel times have been studied in only a few instances. (Gutenberg, 1934). While considerable study has been made of the amplitude ratios of the surface reflected P waves (Gutenbert, 1935 and Mei, 1943) no such studies have been reported for the S waves. Such results are reported here.

The earthquake of May 25, 1944, was selected for study because its location (epicenter at 153°E, 3°S as given in the Seismological Laboratory Bulletin of the California Institute of Technology, April-June, 1944) placed many North American stations within the range of epicentral distances (80° to 140°) over which it was desired to study the behavior of surface reflected seismic waves. Also, its magnitude (7 1/2) made it probable that satisfactory records would be obtained from most of these stations. The location of the epicenter is such that most of the records are polarized with the longitudinal motion showing on the E-W components.

O = 12:58.07 Surface Forms

A discussion of a study made of the reflected S phases of the above earthquake will be presented in this paper.

DATA

Stations from which records were obtained, the distance and azimuth from station to epicenter, the type of instrument at the station and the components of motion recorded are listed in Table 1. Each station was assigned a number, which identifies it in the various figures.

Where possible, the travel times, periods, and amplitudes of S, SS, SSS, and SSSS were measured. The data so obtained are given in Table 2. The differences between observed travel times and the travel times computed from the Jeffreys-Bullen, 1940, (J - B) tables for surface focus were calculated and are given in Table 2 immediately below the associated travel time. Figures 2 and 3 are tracings from some of the records measured. The vertical lines indicate the points where the phases designated above them should arrive, as computed from the J - B tables.

The location of the epicenter from the C. I. T. Bulletin (1944) was used in calculating the epicentral distances and azimuths. Using this epicenter, the time of occurrence was determined by subtracting the travel time of P (from the J - B tables) from its known arrival time at three of the nearer stations (Berkeley, Victoria, and Pasadena).

The differences between the observed and the computed travel times for the SS, SSS, and SSSS phases are plotted against epicentral distances in Figure 1. The times in the J - B tables are for reflection at the surface of the earth for those phases which have experienced one or more reflections. Reflection from a deeper discontinuity would give travel times consistently less than those computed from the tables. Moreover, these differences should be progressively greater the greater the number of reflections. (17 seconds for SS over these distances, 33 seconds at 80° to 35 seconds at 140° for SSS, 38 seconds at 80° to 47 seconds at 140° for SSSS.) However, as is evident from Figure 1, neither of these effects are observed. The differences show only a random distribution on either side of zero. Also, the magnitude of most of these differences is in the order of half a period or less. It would seem, then, that the phases which have undergone reflection have been reflected at the surface, and that these differences are due to inherent lack of preciseness in the records. Quoting in this connection from Gutenberg and Richter (1934), "..SS usually appears with a longer period than the waves thus far discussed, so that its arrival cannot ordinarily be timed with the same exactness". This effect is still more true of SSS and SSSS, for, quoting from the same source, "The beginning of SSS, and still more so of SSSS, is generally not very sharp; both are usually long waves". The average of the SS residuals is -1 sec. if the College reading is excluded and only -2 3/4 seconds if it is included. This indicates a very shallow focus assuming the epicenter correct.

THEORETICAL CONSIDERATIONS

The ratios of the horizontal displacements from an SV, SS, SSS, and SSSS (U_{ss}/U_{sss} and U_{ss}/U_{ssss}) that would theoretically be expected were computed. The method of so doing was patterned after Dana's calculation of the relative amplitudes of certain waves in terms of the horizontal and vertical components of the relative displacement which they produce at the surface of the earth (Dana, 1945).

The expression used for the amplitude A of a seismic wave is given by Dana (1945) as:

$$A = CTf\sqrt{e^{-\int k\,dD}\ \frac{\tan i_0}{\sin \Delta}\ \frac{di_0}{d\Delta}}$$

The constant C depends only on the energy of the shock and the type of wave (P, SH, or SV). These ratios were computed for SV waves from a single earthquake and therefore C will cancel in the expression for the ratios. The periods of SS, SSS, and SSSS as observed were roughly the same and were taken as equal. The exponential term, the absorption factor, was taken to be unity since the absorption is probably approximately the same for SS, SSS, and SSSS in any given case. The expression for the ratio of amplitudes then becomes

$$\frac{A_{ss}}{A_{sss}} = \frac{f_{ss}}{f_{sss}}\sqrt{\frac{(\tan i_0\ \ di_0/d\Delta)_{ss}}{(\tan i_0\ \ di_0/d\Delta)_{sss}}}$$

and similarly for the ratio of A_{ss}/A_{sss}, where f is the product of the square roots of the fractions of the incident energy which is reflected at each reflection and i_0 is the angle of incidence at the surface of the earth. The values of f were taken from Gutenberg (1944). The values of i_0 were calculated, as in Dana (1945), from the expression

$$\sin i_0 = V_0/\bar{V}$$

where V_0 is the true velocity in the surface material (taken to be 3.5 km./sec.) of the wave, and $\bar{V}$ is the apparent velocity ($d\Delta/dt$) of that same wave. ($d\Delta/dt$) was computed from the J - B tables.

The ratios of the horizontal ground displacements, U_{ss}/U_{sss} and U_{ss}/U_{ssss}, were determined from the amplitude ratios by use of the chart of U/A in the paper by Gutenberg (1944). These ratios were computed only for SV waves, since the energy of the S phases appears to be nearly all SV. (See Fig. 2, tracings No. 8). Also, only the horizontal components were considered because of the lack of stations with comparable vertical instruments.

The amplitudes measured (listed in Table 2) were the maximum, rather than the initial, trace amplitudes. Also, they were measured from crest to crest. The periods measured were those of these maximum amplitudes.

RESULTS AND CONCLUSIONS

As may be seen in the curves of figures 4, 5, and 6, the computed and the observed ratios are in poor agreement. In computing i_0, the use of a value of V_0 which corresponds to that of shear waves in the crustal structure implies that the waves are refracted from the higher velocity material below the crust into the lower velocity material of the crust, and that it is this lower velocity which determines the angle of incidence at the surface. However, the crustal structure of the earth is only of the order of magnitude of a half a wave length in thickness (for these waves). It would seem probable, then, that the crustal layer might have but relatively little effect on the angle of incidence at the surface, and that this angle would be determined largely by the velocity of the underlying material. This opinion appears to be substantiated by the computed curves in figures 5 and 6. These curves were computed assuming critical reflection, i.e. f unity. This would be true for values of V_0=4 1/2 km./sec. or greater. The expression for A_{ss}/ A_{sss} then becomes

$$\frac{A_{ss}}{A_{sss}} = \sqrt{\frac{\bar{V}_{sss} \left| \frac{d\bar{V}}{d\Delta} \right|_{ss}}{\bar{V}_{ss} \left| \frac{d\bar{V}}{d\Delta} \right|_{sss}} \quad \frac{\tan i_{o\,ss}}{\tan i_{o\,sss}}} \approx \sqrt{\frac{\bar{V}_{sss} \left| \frac{d\bar{V}}{d\Delta} \right|_{ss}}{\bar{V}_{ss} \left| \frac{d\bar{V}}{d\Delta} \right|_{sss}}}$$

There is very good agreement for the ratios so computed and the observed ratios. For the ratio of A_{ss}/ A_{sss} the two curves agree not only in order of magnitude but in their general shape.

It seems apparent, then that the surface reflected shear waves of this earthquake have been reflected from the surface of the earth rather than from the bottom of the crust, but that the angle of incidence at the surface is controlled by the velocity below the crust. This is in agreement with work by Mei (1943) who found that the observed opponent angles of emergence for P and PP agreed much better with the calculated values when V_0 was assumed to be 8 km./ second instead of 6 km./second. Reflection from the free surface is indicated also by the large size of the SS/SSS and SS/SSSS amplitude ratios.

The reflection points for these waves were all under the Pacific Ocean except for the third reflection point of SSSS for Ottawa, Columbia Seven Falls, Burlington, Bermuda, and San Juan, and for the second reflection point of SSS for San Juan. These exceptions lie within the borders of the North American continent. While the crustal structure of the Pacific basin is known to differ from that of the continents in that it has higher velocity material close to the surface, the shear wave velocity at the surface must be much less than 4 1/2 km./second (Gutenberg, 1936). Perhaps as has been suggested by Mei (1943), the crustal layers act as a load rather than as an elastic medium for the incident waves.

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