TRAVEL TIME CURVES AT SMALL DISTANCES AND WAVE VELOCITIES OF PRINCIPAL PHASES IN THE SOUTHERN CALIFORNIA RANGES

By

A.J. GROBECKER

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Division of the Geological Sciences

California Institute of Technology

Pasadena, California

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Four shocks with epicenters in the region of the northern end of the Peninsular Range of Southern California were studied. Travel times of numerous phases of these four shocks were measured from seismograph records of stations at Pasadena, Mount Wilson, Riverside, La Jolla, Santa Barbara, Tinemaha and Haiwee, in Southern California. The velocities of propagation of eight principal phases were determined. Thicknesses of three layers above a depth of about 40 k.m. in the earth's crust were calculated.

PURPOSE OF INVESTIGATION:

This investigation was carried out at the Seismological Laboratory of the California Institute of Technology during the summer of 1940, for the purpose of determining seismic travel times and the depths of crustal layering in a limited geological province in Southern California. For a number of years, in the routine work at the Seismological Laboratory, differences in phase velocities along wave paths in different geological provinces have been known to exist. This paper represents an effort to determine the average velocity of propagation for the eight most easily identified phases of four shocks occurring in the northern end of the Peninsular Ranges of Southern California, and to calculate the approximate thicknesses of the crustal layering in that geological province.

ACKNOWLEDGEMENTS:

This work was carried out under the direct supervision of Dr. Charles F. Richter. Much generous advice was given by Dr. Beno Gutenberg, whose earlier work* was an invaluable model. Much help was also given the author by Mr. R.E. Rogers.

(* B.Gutenberg: "Travel Time Curves at Small Distances, and Wave Velocities in Southern California" Gerlands Beiträge zur Geophysik, vol. 35, p. 6-50,1932).

SOURCE OF DATA:

The data was obtained from the records of the Seismological Laboratory, Pasadena, California, which is maintained and operated by the California Institute of Technology as the central station of a coordinated group. Auxiliary stations in Southern California (from which records were obtained) are maintained at Mount Wilson, Riverside, Santa Barbara, La Jolla, Tinemaha,and Haiwee. Records from the Auxiliary Station at Palomar were incomplete, and were not used.

At all these stations the minute-marks on the seismograms are coördinated directly with time signals of the U.S.Naval Observatory automatically recorded on one seismogram of each station three to five times daily. This method of time control gives an accuracy within 2/10 second.

All stations are equipped with horizontal component Wood-Anderson torsion seismometers with electromagnetic damping and optical recording*. The general direction of the instruments is N-S and E-W, but significant deviations from these directions occur in the case of torsion seismometers with short free periods; therefore in general it is not possible to use azimuths givén by the seismograms. The free periods of these

(*Bull. Seismo. Soc. of America XV, 1925)

SOURCE OF DATA: (Cont'd.)

instruments were near o.8 sec.; the magnification for short waves near 3000, and the damping ratio nearly critical. Also at Pasadena are long period instruments of the same type, with free periods near 10 seconds, and a magnification of 300 - 500 for short waves. At all stations, vertical seismographs of the Benioff type* with critical electromagnetic damping and galvanometric-optical recording were used. Also at Pasadena are Benioff type horizontal-motion seismometers which are short period instruments (T_0 = 1.0 Sec., T_1 = 0.25 and 2.0 sec.), crtically damped, and a strong motion Benioff type seismometer with wave magnification of about 100,000, period of about 1 sec., and little less than critically damped. For this investigation, measurements in all cases were taken from records made by the short period instruments. The location of the stations and epicenters may be seen in Figure I. Data on the stations and epicenters are given in Table I.

(* Bull. Seis. Soc. Am. XXII, 156, 1932)

LIST OF STATIONS

TABLE I

STATION	LONGITUDE NORTH °	'	LATITUDE WEST °	'	HEIGHT m.	FOUNDATION	ABBREVIATION
Pasadena	34	08.9	118	10.3	295	Weathered granite	P
Mt. Wilson	34	13.5	118	03.4	1742	Weathered granite	MW
Riverside	33	59.6	117	22.4	250	Weathered granite	R
Santa Barbara	34	26.6	119	42.8	100	Alluvium	S
La Jolla	32	51.8	117	15.2	8	Consolidated detrital material	LJ
Tinemaha	37	05.7	118	15.5	1180	Basalt	T
Haiwee	36	08.2	117	58.6	1100	Loosely cemented tuff	H
Boulder City	35	58.8	114	50.0	776	Fractured monzonite	B

Four shocks with epicenters in the region of the northern end of the Peninsular Ranges were selected for study. These were shocks whose arrivals were strong at all stations of the system, whose epicenters were in the desired region, and whose records at all stations were undisturbed by mechanical defects of recording. Epicenters of these shocks were first located for the routine reports of the laboratory, by Mr. R.E.Rogers who used either the method of comparing the travel times with those of previously located earthquakes or the perpendicular bisector method applied to the arrival times of the first P wave (not the $\overline{P}$ phase).

Epicentral locations were checked by the author. The method of perpendicular bisectors to find the epicenter, which is known to first approximation by comparison with travel times of shocks of known location or by macroseismic evidence, has been described by B. Gutenberg* and is as follows:

The velocity of $\overline{P}$ waves is known to be near 5.6 km/sec in Southern California **

(* B. Gutenberg :op cit.)
(** H.O.Wood and Charles F.Richter, Bull.of the Seis. Soc. of Am. XXI, 28, 1931).

SOURCE OF DATA (Cont'd.)

Take at least two pairs of stations which have nearly the same times of arrival of the $\overline{P}$ waves. If the $\overline{P}$ waves arrive at one of the pair of stations (x) seconds later than at the other, the second station of the pair will be 5.6(x) km. nearer to the epicenter than the first. One may then mark a point which is 5.6(x) km. from the second station on the line between the second station and the approximate epicenter. The true epicenter then must be on the perpendicular bisector of the line segment from that point to the first station. A second pair of stations gives a second perpendicular bisector, whose intersection with the first perpendicular bisector is a second approximation to the true epicenter. If necessary, this method may be repeated, using this better approximation to the true epicenter.

The method of locating epicenters by means of the perpendicular bisector method applied to first arrivals is less exact than the method described by Gutenberg, However, since values of velocity of the $\overline{P}$ phase differed from each other by less than could probably be introduced by differences in wave path, it was assumed that the additional error introduced by this further approximation is small.

Locations of the epicenters are shown in Figure I.

Origin times of the shocks were calculated in the following way. The $\overline{P}$ wave was identified by means of its short period, which was distinctive at distances less than about 375 km. Dividing the differences in distances to the stations by the differences in corresponding arrival times of $\overline{P}$ gave quotients which were averaged to a first approximation of the velocity of $\overline{P}$. Dividing the distances to the stations by this value of the velocity gave quotients which were averaged to give a first approximation of the origin time. In the last operation, only distances greater than 100 km. were used in the calculations. Differences between the arrival times and this supposed origin time then gave values of the travel-time of $\overline{P}$, which in turn when divided into the distances to the station, gave values for the velocity of propagation of $\overline{P}$, which were consistent with themselves. The list of shocks is shown in Table II.

The travel times of all measurable phases, tabulated in Table III, were then plotted. In figure 2, plotted versus their epicentral distances are the travel times of all measured phases. Unidentified phases are shown in black. The identified phases, which include P_n, P_a, P_b and $\overline{P}$ and the corresponding transverse waves, are shown in colors.

TABLE II - LIST OF SHOCKS

SHOCK	DATE	LONGITUDE NORTH °	'	LATITUDE WEST °	'	TIME OF ORIGIN (P.S.T.)
Terwilliger Valley TV-A	Mar.25,1937	33	28	116	35	08:49:04.0
Terwilliger Valley TV-B	May 12, 1939	33	28	116	35	11:25:03.4
San Jacinto SJ	Feb. 28, 1940	33	08	116	05	09:28:06.5
Arlington A	Nov. 7, 1939	33	54	117	21	10:52:07.5

TABLE III
TERWILLIGER VALLEY "A"

STATION	Δ (km)	Corr. to Direct Reading (min)	Corr. to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	Amplitude (mm) E	Amplitude (mm) Z	Remarks
Pasadena	165.4	+0	7.7	27.9	0.4	0.3			
				28.6	0.6	3.0			P_n
				29.5	0.5	2.5			P_a
				30.5	0.4	5.0			P_1
				31.3	0.5	16.0			
				32.8	0.6	28.0			
				34.9	0.5	25.			
				39.1	0.5	-			
				40.5	0.5	-			
				42.4	0.6	12.0			
				46.6	0.7	27.0			S_b
				49.8	0.6	-			S_n
				51.3	0.7	55.0			$\bar{S}$
				52.3	0.7	55.0			Later phases off record.
				57.2	-				
Mt. Wilson	160.2	- 03	33.2	28.0	0.3			2.0	P_n
				28.8	-			7.5	
				29.4	0.3			50.0	$\bar{P}$ poorly defined - large amplitudes.
				31.5	0.3			50.0	
				40.1	0.5			-	
				71.2	0.5			10.0	
				78.7	0.7			2.5	
Riverside	93.8	- 11	25.1	17.0	0.6			5.0	P_a Strong deflection Back lash on all late phases.

TABLE III
TERWILLIGER VALLEY "A"

STATION	Δ (km)	Corr. to Direct Reading (min)	Corr. to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	Amplitude (mm) E	Amplitude (mm) Z	Remarks
Santa Barbara	309.1	- 03	41.6	45.9		0.2			P_n
				46.9					P_b
				48.9		0.5			
				49.6		2.0			
				57.4					P) Group is characterized by distinct change in period and amps.
				62.3			10.	10.0	) " "
				68.4					) " "
				72.2		30.			) " "
				85.6					) " "
				88.7		50.			) " "
				96.0		12.			S)
				101.0		10.			) Group is characterized by larger period & variable amplitudes.
				133.4					) " "
				146.4					) " "
				155.9					) " "
La Jolla	91.2	- 07	34.1	16.5					P_a Later amplitudes are off record.
Tinemaha	430.4	+ 4	8.4	60.4	0.5			1.5	P_n Microseismic amp. on horizontal component
				61.1	0.3			1.0	
				62.1	0.4		0.5	1.5	
				64.4	0.6		1.0		
				66.6	0.3		1.0		
				68.4	0.5		2.5		

TABLE III

TERWILLIGER VALLEY "A"

STATION	Δ (km)	Corr. to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Tinemaha (cont'd.)				71.9	0.5		1.0		
				73.9					
				74.4	0.7		6.0		P_a
				76.5	0.8		8.0		
				79.4	0.7		17.0		$\bar{P}$
				81.4	0.5		5.0		
				82.5	0.5		5.0		
				85.5	0.5		10.0		
				99.4					
				108.0	0.6		15.0		S_b
				124.4	0.5		8.0		
				126.6	0.6		25.0		S_a Short period, large ampl.
				128.0	0.4		6.0		
				130.0	0.9		60.0		)
				134.1	1.9		18.0		) Increase in amplitude
				149.0					
				155.0					Increase in period.
				174.1	3.0				
Haiwee	322.1	- 17	20.8	47.0			0.1		P_n
				48.7	0.6		0.5		P_b
				53.3	0.5		2.0		
				54.4	0.6		2.0		
				56.3	1.0		3.0		P_a
				57.4	1.0		1.5		
				58.1	0.5		1.6		
				60.1	0.6-0.7		10.0		$\bar{P}$

TABLE III
TERWILLIGER VALLEY B

STATION	△ (km)	Correction Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Pasadena	165.4	– 0	11.7	28.1	0.4		0.1		P_n
				29.0	0.5		1.0		P_a
				29.8	0.2		0.7		
				30.3	0.4		1.5		P
				31.9	0.5		0.5		
				33.6	0.5		1.5		
				36.4	0.5		1.0		
				43.2	0.3		0.5		
				46.2					
				47.1	0.7				S_b
				49.1	0.5		7.0		S_a
				50.4					S_n
				51.1	0.3		5.0		S
				51.7	0.5		8.0		
				52.9	0.5		8.0		
				53.5	0.6		8.0		
				59.3	0.7		1.5		
				67.8	0.7		1.5		
				71.0	1.0				
				73.1	0.6		1.0		
				77.6	0.8		1.5		
				80.1	0.7		0.5		
				112.9	1.0				
				142.9	1.0				
				157.2	0.9				

TABLE III
TERWILLIGER VALLEY B

STATION	△ km)	Corr. to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Mt. Wilson	160.2	+ 0	19.8	28.4	0.3	0.2			P_a
				28.7	0.5	0.5			
				29.6	0.3	0.8			$\overline{P}$
				31.0	0.4	0.3			
				32.3		large			
				33.2	0.3	2.0			
				43.2	0.5	1.3			
				45.7	0.6	2.0			
				46.1					S_b
				46.6	0.5	2.0			
				47.6	0.4	2.5			S_a
				49.0	0.3	11.0			S_n
				49.9	0.3				$\overline{S}$
				51.3	0.5	6.0			
				55.4	0.5	3.0			
				60.5		2.0			
				63.5	0.6	5.0			
				65.8	0.3				
				69.4	0.5				
				84.6	0.5	8.5			
				93.4	0.6	0.6			
Riverside	93.8	0	0	17.4	0.4		1.5		$\overline{P}$ possibly P_b
				18.7	0.1				
				19.7					P_n
				28.9					S_a
				29.2	0.5		4.0		$\overline{S}$
				29.7	0.3		15.0		
				31.8	0.7		18.0		S_b
				34.8	0.7		4.0		S_n

TABLE III
TERWILLIGER VALLEY B

STATION Y	Δ (km)	Corr. to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Riverside (cont'd)	93.8	0	0	37.2					
				37.6	0.7		5.0		
				51.6	0.5		2.0		
				58.1	0.7		1.0		
Santa Barbara	309.1	+ 0	5.5	46.3	0.5			0.45	P_b
				54.1					P_a
				56.3	0.6			1.0	Possibly $\overline{P}$
				57.5	0.4			2.0	$\overline{P}$
				64.0	0.4			2.5	
				72.3	0.7			1.0-2.5	
				81.3	0.6			2.0	S_n
				84.5	0.9			1.0	
				89.9	0.5			2.5	
				90.9					S_a
				93.3	0.4			5.0	
				97.4	0.3			4.0	$\overline{S}$
				101.4	1.2			2.2	
				104.1	0.9			3.0	
				105.9	0.7			2.0	
				111.9	0.6			1.0	
				113.1	0.6			2.6	
				114.8	1.0			2.0	
La Jolla	91.2	- 0	13.6	17.0	0.2		8.0		$\overline{P}$ possibly P_b
				19.5	0.6		1.0		P_n
				22.5	0.5		3.0		
				27.8	0.5		2.0		S_a possibly $\overline{S}$
				28.9	0.4		30.0		$\overline{S}$

TABLE III
TERWILLIGER VALLEY B

STATION	Δ (km)	Corre. to Direct (min)	Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
La Jolla (cont'd)	91.2	-0	13.6	31.3	0.6		30.0		S_b
				32.0	0.6		32.0		
				35.5	0.4		20.0		
				43.5	0.6		8.0		
				48.0	0.6		8.0		
				50.3	0.6		8.0		
				53.4	0.8		2.5		
				57.4	0.5		5.0		
Tinemaha	430.4	+ 0	7.5	60.1	0.6			0.5	P_n
				61.9	0.4			0.5	
				65.3	0.4			0.5	
				70.8	0.6			1.0	
				72.4	0.7			2.5	
				75.7					P_a
				78.4	0.4			2.3	P
				82.4	0.5			2.3	
				85.3					
				87.6	0.6			2.4	
				93.7	0.6			2.6	
				103.1	0.6			2.4	
				107.1	0.5			0.6	S_n
				109.1	0.8			-	S_b
				110.3	0.8			1.3	
				111.1	0.8			1.3	
				116.1	0.6			1.3	
				120.6	0.5			1.5	
				124.8	0.5			1.9	S_a
				125.7	.			.	

TABLE III
TERWILLIGER VALLEY B

STATION	Δ (sec)	Correction to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Tinemaha (cont'd)	430.4	+ 0	7.5	129.4	0.4			0.7	
				130.6					
				131.5	0.5			2.5	
				134.3	0.6			2.5	$\bar{S}$
				136.7	0.5			2.4	Possibly $\bar{S}$
				140.2	0.8			1.0	
				144.4	0.5			1.0	
				146.5	0.7			1.0	
				149.2	0.6			2.5	
				153.1	1.4	(0.5)		2.5	
Haiwee	322.1	+ 0	5.5	47.3	0.7	(0.4)		0.5	P_n
				51.2	0.5			2.0	
				55.4	0.6		0.2	4.0	
				59.4	0.4	0.6		4.0	$\bar{P}$
				60.9	0.5			7.0	
				63.0	0.5		0.3		
				65.9	0.7			3.0	
				68.6	0.7			3.0	
				70.9	0.6			3.0	
				74.6	0.6				
				76.8	0.6				
				79.6	0.4				
				83.3	0.6			2.5	S_n possibly S_b
				84.1	0.5				
				85.8	0.6				
				89.1	0.5				
				90.7	0.4				
				94.1	0.6			1.0	S_a
				95.8	0.6			4.0	
				98.2	0.4				

TABLE III
TERWILLIGER VALLEY B

STATION	△ (sec)	Correction to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Haiwee (cont'd.)	322.1	+ 0	5.5	99.8	0.5			5.0	
				101.6	0.5			9.0	$\overline{S}$
				102.1	0.6			8.0	
				110.1	0.5			5.0	
				112.3	0.7				
				115.6	0.6			3.0	
				117.1	0.5				
				118.1	0.6			3.0	
				119.9	0.6			5.0	
				124.3	0.5			1.5	
				128.1	0.7			4.0	
				131.6	0.6			3.0	
				133.3	0.6			2.0	
				136.1	0.5 (0.6)			2.0	
				138.6	0.7 (0.8)			1.5	
				143.6	0.6			0.6	
Boulder	329	− 0	0.1	53.1					
				54.0	0.5				
				57.6	0.4			0.5	P_a
				59.5	0.3			0.6	
				61.0	0.4			0.6	$\overline{F}$
				62.8	0.4			0.5	
				70.6	0.5			0.5	
				76.6	0.3			0.5	
				79.5	0.5			0.4	
				89.6	0.5			0.6	
				90.1	0.8			1.0	
				91.7	0.8			2.5	

TABLE III

TERWILLIGER VALLEY B

STATION	(km)	Corr. to Direct Reading (min)	Corr. to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	Amplitude (mm) E	Amplitude (mm) Z	Remarks
Boulder (cont'd.)	329	-0	0.1	94.9	0.3			1.0	
				97.3	0.5			1.5	S_a
				100.3	0.8			1.8	

TABLE III
SAN JACINTO

STATION	△ (km)	Correction to Direct Reading (min)	Correction to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	Amplitude (mm) E	Amplitude (mm) Z	Remarks
Pasadena	225	+ 0	6.3	35.0	0.4				P_n, possibly P_b
				36.4	0.2				
				36.8	0.3				
				37.3	0.6			0.5	
				38.3	0.3			12.0	
				38.8					
				39.5	0.5			16.0	$\frac{P}{P}_a$
				41.5	0.2			21.0	
				43.3	0.7			20.0	
				45.4	0.6			20.0	
				47.4	0.4			12.0	
				48.0	0.5			15.0	
				50.7	0.5			15.0	
				51.5	0.3			15.0	
				53.1	0.5			20.0	
				54.6	0.3			10.0	
				56.3	0.4			15.0	
				58.3	0.5			18.0	
				59.3	0.7			20.0	
				59.8	0.3			10.0	
				61.1	0.7			20.0	S_b
				62.1	0.3			18.0	
				62.9	0.5			10.0	S_n
				63.1	0.3			6.0	
				63.9					
				65.3	0.6				$\frac{S}{S}_a$
				71.3	0.3				
				71.8	0.6				
				77.3	0.7			10.0	
				81.8	0.7				
				83.0	0.7			20.0	
				83.9	0.5			20.0	

TABLE III
SAN JACINTO

STATION	Δ (sec)	Corr. to Direct Reading (min)	Corr. to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	Amplitude (mm) E	Amplitude (mm) Z	Remarks
Mt. Wilson	220	+ 0	3.8	34.7	0.5				P_n possibly P_b
				37.1	0.3				
				37.7	0.2	0.7			
				39.2	0.4	0.7		40.0	
				39.7	0.2				
				40.5	0.4			40.0	$\bar{P}$
				41.0	0.3			18.0	
				41.3	0.3			40.0	
				42.8	0.5			40.0	
				45.6	0.5			42.0	
				46.9	0.4			25.0	
				48.0	0.6			25.0	
				49.2	0.6	0.7		50.0	
				52.9	0.6	0.7			
				55.8	0.5			48.0	
				56.8	0.5	0.7			
				59.8	0.6	1.0			S_b
				60.7	0.4			15.0	
				61.4	0.5	0.7			S_n
				62.2	0.6	1.5			
				62.8	0.5	5.0			
				64.8	0.6			40.0	S_a
				67.8	0.7			40.0	
				69.8	0.3			53.0	$\bar{S}$
				73.5	0.3	1.5			
				82.9	0.5			30.0	
				87.3	0.5			20.0	
				89.0	0.5			20.0	
				91.8	0.6				
				94.3	0.6			40.0	
				97.8	0.6				

TABLE III

SAN JACINTO

STATION	$\triangle$ (sec)	Corr. to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Riverside	152	-0	06.8	25.5	0.5			2.5	P_b
				26.3	0.3			1.5	P_n
				26.9	0.3			10.0	P_a
				27.8	0.3			30.0	$\bar{P}$
				29.3	0.5			33.0	
				31.2	0.3			30.0	
				33.1	0.4			25.0	
				34.7	0.3				
				35.4	0.3				
				36.7	0.5			12.5	
				41.7	0.5				
				42.6	0.5			35.0	
				44.1	0.7			30.0	S_b
				45.0	0.3			35.0	S_a
				48.9	0.3			35.0	
				53.8	0.6			35.0	
				56.2	0.5			30.0	
				64.3	0.5			20.0	
				73.5	0.7			20.0	
				77.0	0.7			15.0	
				83.7	0.5			10.0	
				95.8	0.5			9.0	
				100.5	0.7			6.0	

TABLE III
SAN JACINTO

STATION	Δ (sec)	Corr. to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Santa Barbara	365	-0	25.0	54.5	0.5			2.5	P_b
				56.6					
				59.6	0.5			1.0	
				61.2	0.4			1.0	
				65.3					
				66.1	0.3			2.5	Possibly $\overline{P}$
				68.1	0.4				$\overline{P}$
				71.1	0.5			2.0	
				71.6	0.4			5.0	
				74.6	0.5			2.0	
				80.3	0.4			1.5	
				87.5	0.5			2.5	
				90.8	0.7				S_n
				101.0	0.7			1.5	
				105.5	0.4			2.0	
				106.4	0.5			2.5	S_a
				108.0	0.7			3.0	
				108.5	0.5			3.5	
				112.2	0.3			2.5	$\overline{S}$
				115.6	0.6			2.5	Possibly $\overline{S}$
				120.5	0.5			5.0	

TABLE III
SAN JACINTO

STATION	Δ (km)	Correction to Direct Reading (min)	Correction to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	Amplitude (mm) E	Amplitude (mm) Z	Remarks
La Jolla	114	+ 0	5.4	20.4	0.4			2.0	P_b possibly P_a
				20.9	0.3			15.0	$\bar{P}$
				21.8	0.3			4.0	P_n
				22.4	0.2			5.0	
				23.5	0.3		14.0		
				24.7	0.1			5.0	
				26.9	0.3			2.8	
				28.4	0.2			3.5	
				28.9	0.6		7.0		
				30.0					
				32.2	0.5			5.7	
				33.9	0.3		50.0		$\bar{S}$ possibly S_a
				35.6	0.6		12.0		S_b
				38.1	0.5		40.0		
				39.5	0.3		23.0		S_n
				44.5	0.5		15.0		
				48.8	0.5			5.7	
				50.4	0.6		15.0		
Tinemaha	478	− 0	12.6	66.1	0.5			Small	P_n
				70.4	0.7			"	P_b
				79.4	0.3			0.5	
				81.9	0.6			2.0	
				82.1	0.2			0.7	
				83.9	0.5			2.0	P_a
				87.4	0.3			1.5	$\bar{P}$
				88.9	0.6			2.0	
				90.5	0.5			2.0	
				92.3	0.5			2.0	
				96.4	0.5			2.0	
				99.4	0.6			2.0	
				107.9	0.6			2.0	

TABLE III
SAN JACINTO

STATION	△ (km)	Corr. to Direct Reading (min)	Corr. to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Tinemaha (cont'd.)	478	- 0	12.6	116.5	0.6			2.5	S_n
				119.9	0.7			2.5	S_b
				124.5	0.7			2.0	
				139.2	0.7			1.0	S_a
				140.9	0.5			3.0	
				142.9	0.7			4.0	
				144.6	0.6			5.0	
				146.4	0.6			4.5	
				153.5					
				156.5	0.5			2.5	
				158.2	0.5			2.5	
				161.1	0.6			-	
				165.0	0.6			2.5	
				172.7	0.6			2.0	
Haiwee	371	+ 0	1.5	55.2	-			-	P_b microseismic ampt.
				56.5	0.3				
				60.4	0.5				
				61.6	0.8			0.4	
				64.2	0.4			1.0	
				64.7	0.5			3.0	P_a
				65.4	0.5			2.5	
				68.6	0.3			2.5	$\bar{P}$ emergent
				69.9	0.5			3.0	
				71.6	0.6			2.5	
				75.3	0.7			2.5	
				83.7	0.5			2.0	
				85.1	0.5			2.0	
				89.0	0.7			2.5	
				93.3	0.6			2.5	S_n 1 sec. early

TABLE III
SAN JACINTO

STATION	△ (km)	Corr. to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Haiwee (cont'd.)	371	+ 0	1.5	102.5	0.3			1.0	
				110.2	0.5			6.0	
				118.6	0.6			5.0	
				123.2	0.6			5.0	
				128.0	0.7			4.0	
Boulder	331	+ 0	0.2	59.7	0.3				
				65.2	0.5				
				97.9	0.3				S_a
				101.5	0.7				Sharp amplitude increase
				107.2	0.7				

TABLE III

ARLINGTON

STATION	Δ (km)	Correction to Direct Reading (min)	Correction to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	Amplitude (mm) E	Amplitude (mm) Z	Remarks
Pasadena	82.0	+ 0	1.8	14.8	0.3			0.2	P_a
				15.8	0.3		1.0	30.0	$\overline{P}$ possibly P_b
				16.8	0.3	23.0			
				17.5	0.2	30.0			
				18.2	0.5	29.0	2.5	-	
				20.1	0.5			30.0	
				21.6	0.3			26.0	
				22.3	0.6	30.0			
				22.8	0.4		1.8		
				23.5	0.4	30.0			
				24.1	0.5		2.6		
				25.3	0.3		2.0		$\overline{S}$ possibly S_a
				26.1	0.5		12.5		
				27.5	0.3		7.0		
				28.8	0.4		6.0		S_b
				31.1	0.6		15.0		
				32.8	0.4		3.5		S_n
				45.5	0.5				
				51.9	0.6				
				62.3	0.7				
				64.6	0.7			30.0	
				66.8	0.6				
				77.8	0.5			20.0	
				84.2	0.7			20.0	
				86.8	0.5			7.5	
				92.8	0.6			7.0	
				100.9	0.6			7.5	

TABLE III
ARLINGTON

STATION	Δ (km)	Correctionto Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Mount Wilson	75.0	-0	20.8	13.6	0.4			0.2	P_a
				14.5	0.4		2.5		P
				15.0	0.3	5.0			P_b
				15.5	0.1		6.0		
				16.7	0.3				P_n
				20.4	0.2				
				21.7	0.5		3.0		
				23.2	0.3			92.0	$\bar{S}$ possibly S_a
				24.2	0.5		62.0	110.0	
				25.4	0.4		55.0		
				26.3	0.4		67.0		
				27.8	0.2		27.0		
				28.6	0.5		20.0		
				31.0	0.5		20.0		S_n
				34.7	0.6		15.0		
				42.7	0.5		6.0		
				45.2	0.3				
				49.2	0.7		5.0		
				51.7	0.5				
				66.2	0.5		2.0	45.0	
				79.2	0.6		1.6	45.0	
				96.5	0.6		1.0	30.0	
				102.0	0.7			5.0	
				103.2	0.7			18.0	

TABLE III
ARLINGTON

STATION	Δ (km)	Correction to Direct Reading (min)	Correction to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	Amplitude (mm) E	Amplitude (mm) Z	Remarks
Riverside	9	-0	09.0	6.0	0.3	24.0			Possibly $\bar{P}$
				7.9	0.3	16.0			
				10.0	0.3	77.0			
				11.0	0.3	25.0			
				20.0		18.0			
				23.5		13.0			
				40.1	0.4	2.0		49.0	
				45.0	0.6			40.0	
				49.0	0.5			27.0	
				53.0	0.6			20.0	
				69.0	0.7			20.0	
				74.0	0.5			20.0	
				75.5	0.7			11.0	
				79.0	0.7			13.0	
				82.6	0.6			18.0	
Santa Barbara	226	-0	5.5	35.4	0.5			1.0	P_n possibly P_b
				37.6	0.5			2.0	
				38.6	0.5	0.5			
				40.1	0.5			2.0	P_a
				41.1	0.4	0.6		2.5	$\bar{P}$
				42.7	0.5			5.0	
				43.5	0.3		0.8	6.0	
				48.0	0.4			7.0	
				49.7	0.5			6.0	
				50.9	0.4	1.0			
				51.7	0.3			7.0	
				53.7	0.5			8.0	

TABLE III
ARLINGTON

STATION	Δ (km)	Corr. to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Santa Barbara (cont'd)	226	- 0	5.5	56.5	0.6	1.2			
				58.6	0.6			8.0	
				61.3	0.5	2.0		8.0	
				64.9	0.3			12.0	S_n
				66.9	0.5	6.0			
				68.8	0.5			18.0	S_a
				69.6	0.5	7.0			
				70.8	0.3			20.0	$\overline{S}$
				72.8	0.6			16.0	
				75.3	0.5			17.0	
				76.2	0.5			24.0	
				77.7	0.5	5.0			
				88.2	0.9	3.0			
				92.6	0.5			6.0	
				94.2	0.7	4.0			
				96.6	0.7			5.0	
La Jolla	115	+ 0	4.5	22.3	short				P_n
				22.7	0.3	0.2		2.0	
				24.2	0.7	2.5			
				25.2				11.0	
				26.7				10.0	
				29.6	0.3	2.5			
				30.9	0.6	2.0			
				35.9				10.0	S_b
				37.6	0.4	3.5			
				38.0				21.0	
				38.6		12.0			
				42.9				36.0	
				51.0				16.0	
				68.8	0.6	5.0			

TABLE III
ARLINGTON

STATION	Δ (km)	Correction to Direct Reading (min)	(sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	E	Z	Remarks
Tinemaha	361	+ 0	5.0	52.0	0.3		0.4		P_n
				59.7	0.7	1.0	2.5		
				63.9	0.6	1.5	2.5		P_a
				65.6	0.5	1.5	1.0		$\bar{P}$
				68.0	0.7	1.0			
				70.5	0.7	1.0			
				73.0	0.6		1.0		
				86.0	0.6		1.0		
				99.0	0.8		1.2		
				101.0	0.7	1.5			
				102.2	0.6		2.5		
				103.5	0.4	2.0			
				104.0	0.5		2.5		
				105.4	0.7	2.6			S_a
				109.4	0.8		2.5		
				112.7	0.7	2.4			
				116.2	0.5		1.5		
				118.5	0.3		0.7		
				113.5	0.5		2.0		$\bar{S}$
				127.5	0.7	1.5			
Haiwee	251	+ 0	21.8	38.9	0.2			0.3	P_n possibly P_b
				40.6	0.7			2.3	
				41.8	0.4			14.0	
				43.0	0.6			23.0	
				44.0	0.5			17.0	P_a
				45.1	0.3			13.0	
				46.4	0.4			8.0	$\bar{P}$
				47.9	0.5			15.0	
				51.8	0.6			17.0	

TABLE III
ARLINGTON

STATION	Δ (km)	Correction to Direct Reading (min)	Correction to Direct Reading (sec)	Travel-Time (sec)	Period (sec)	Amplitude (mm) N	Amplitude (mm) E	Amplitude (mm) Z	Remarks
Haiwee (cont'd)	251	+ 0	21.8	55.9	0.6			10.0	
				59.1	0.5			8.0	
				62.2	0.5			7.0	
				64.3	0.5			7.5	
				72.3	0.7			29.0	
				74.8	0.5			23.0	S
				77.4	0.5			20.0	Possibly E
				78.4	0.3			5.0	
				79.4	0.6			7.5	
				80.3	0.6			11.0	
				81.8	0.5			12.5	
				85.7	0.5			13.0	
				98.3	0.7			6.0	
				103.3	0.5			5.0	
				105.7	0.6			8.0	

VELOCITY AND CHARACTER OF PRINCIPAL PHASES:

When the data had been plotted, other principal phases were then identified, and their velocities measured from the graph shown in Figure 2. $\bar{P}$ was the first arrival at distances less than 50 km. It may be identified at distances greater than 100 km. and less than about 400 km. as the phase with the distinctively short period. The period of the $\bar{P}$ phase, over that range of distance, was consistently about 0.3 sec. The periods of phases arriving at about the same time were usually about 0.5 sec. $\bar{P}$ has the travel-time equation:

$$t = \frac{\text{distance from focus}}{5.4}$$

which for distanses greater than about 100 km. approximates:

$$t = \frac{\Delta}{5.4}$$

P_a was the first arrival at distances greater than about 50 km. and less than about 115 km. At distances greater than about 150 km. it is the large amplitude P wave which just precedes the small period $\bar{P}$ wave. The travel-time equation of P_a is:

$$t = 0.5 + \frac{\Delta}{7.2}$$

where is equal to the distance from the epicenter and t is equal to the travel-time

P_b is the first arrival at distances greater than 115 km. and less than about 225 km. It is a persistent phase of moderate length period. Its travel-time equation is:

$$t = 5.7 + \frac{\Delta}{7.2}$$

VELOCITY AND CHARACTER OF PRINCIPAL PHASES: (Cont'd.)

P_n is the first arrival at distances greater than about 225 km. It is a long period phase, and has an approximate travel-time formula as follows:

$$9.0 + \frac{\Delta}{8.2}$$

S-group phases corresponding to the above compressional P-waves have been identified. These represent transverse waves which travel along approximately the same paths as the P-group compressional phases.

$\bar{S}$ is a short period phase of the S-group. It is much harder to distinguish than $\bar{P}$, but also has a distinctively short period. It is the first arrival of the S-group for distances less than 90 km. It has the travel-time equation, as follows:

$$t = \frac{\Delta}{3.1}$$

S_a is the first large amplitude phase of the S-group, at distances greater than 200 km. It is the first arrival of the S-group at distances greater than 90 km., and less than 135 km. Its travel-time equation is approximately:

$$t = 1.2 + \frac{\Delta}{3.4}$$

S_b is the first arrival of the S-group at distances greater than 135 km. and less than 325 km. It is a long period wave that at distances greater than about 250 km. appears to be a member of the small

VELOCITY AND CHARACTER OF PRINCIPAL PHASES: (Cont'd.)

amplitude waves at the end of the P-group. Its travel-time equation is:

$$t = 9.2 + \frac{\Delta}{4.3}$$

S_n is a long period persistent phase, which is identified only with difficulty in the record. It is the first of the S-group to arrive at distances greater than 325 km. Its equation is:

$$t = 15.0 + \frac{\Delta}{4.7}$$

Other phases of the P-group are probably due to reflection. Some of them are:

P_4 is an early short period phase in P-group:

$$t = 15.2 + \frac{\Delta}{6.5}$$

P_6 is a persistent amplitude increase of moderate period:

$$t = 1.6 + \frac{\Delta}{5.0}$$

P_7 is a persistent phase of fairly short period:

$$t = 13.6 + \frac{\Delta}{4.80}$$

Phases of the S-group which occur with and after those that have been identified are either direct transverse or surface waves. Periods of these waves are so long and the number of the phases so great that no attempt has been made to identify them.

FOCAL DEPTH:

Depth of focus was calculated by the formula suggested by Gutenberg.*

"If we use only short distances, the depth of focus "h" is given within the limit of error or the observations by the formula

$$h^2 = (tv)^2 - \Delta^2$$

where "t" is the travel-time of the P waves, "v" their mean velocity and "Δ" the distance. On the other hand we can express "t" by the travel-time for the depth of focus zero and the difference "d".

$$t = \frac{\Delta}{v} + d$$

Combining these two formulas we have:

$$h^2 = vd\ (vd + 2\Delta)$$

or approximately in mose cases

$$h^2 = 2\ vd\Delta$$ "

With the above formula, the focal depth has been calculated for all cases where distance to the epicenter is less than 100 km. The results of these calculations are shown in Table IV.

* (B.Gutenberg: op. cit.)

TABLE IV - FOCAL DEPTHS

SHOCK	STATION		FOCAL DEPTH, (h = 2 vd)
TV-A	LJ	91.2	21.2
	R	93.8	20.6
TV-B	LJ	91.2	32.2
	R	93.8	32.7
A	R	9.	20.3
	MW	75.0	9.3

THICKNESS OF LAYERS:

According to the formulae suggested by Gutenberg (op. cit.), "if the velocities of a certain kind of waves (either longitudinal or transversal) in successive layers are given by V_1, V_2, V_3, ... V_n, we can calculate the thickness d_1, d_2, d_3 ... of these layers, assuming constant velocity in each of them, in the following way:

For the first layer, we have:

$$2d_1 - h = \frac{\Delta^* \left(\frac{1}{V_1} - \frac{1}{V_2} \right)}{\sqrt{\frac{1}{V_1^2} + \frac{1}{V_2^2}}}$$

Where Δ^* is the distance where the travel time curves of the two corresponding waves intersect, h is the depth of focus.

For each following layer we have, where i is the angle of incidence:

$$\sin i_1 : \sin i_2 : \sin i_3 : \ldots : 1 = V_1 : V_2 : V_3 : \ldots : V_n$$

$$D_n = (2d_1 - h) \tan i_1 + 2d_2 \tan i_2 + 2d_3 \tan i_3 + \ldots + 2d_{n-2} \tan i_{n-2}$$

$$t_n = \frac{2d_1 - h}{V_1 \cos i_1} + \frac{2d_2}{V_2 \cos i_2} + \frac{2d_3}{V_3 \cos i_3} + \ldots + \frac{2d_{n-2}}{V_{n-2} \cos i_{n-2}},$$

If t' is the travel-time to a distance Δ' of the wave with its deepest point in the layer n, we calculate:

$$D_n = \Delta' - \Delta_n \qquad T_n = t' - t_n$$

$$d_{n-1} = \frac{(V_n T_n - D_n) \cos i_{n-1}}{2 \left(\frac{V_n}{V_{n-1}} - \frac{V_{n-1}}{V_n} \right)}$$

THICKNESS OF LAYERS: (Cont'd.)

Assuming that $\bar{P}$, P_2, P_b and P_n, as well as the corresponding S-waves, are caused in this way, the following thicknesses of layers and corresponding wave velocities have been found.

For the first layer, the calculations of the P-wave layers showed that 2d = h + 13.55. Assuming that the focus is situated within this top layer, focal depth calculations, of which results are shown in Table IV, indicate that the focus is probably near the maximum depth in the layer. Thus if one assumes that the depth of focus is 13.5 km., the layering may be calculated with results as indicated in Table V.

TABLE V - THICKNESS OF LAYERS

Data from Longitudinal Wave				Data from Transversal Wave						
Thickness of Layer (km)	Depth of Layer (km) Top	Btm.	Velocity (Long.) V_p (km/sec.)	Thickness of Layer (km)	Depth of Layer (km) Top	Btm.	Velocity (Transv.) V_s (km/sec.)	Mean Lower Depth (km)	$\frac{V_p}{V_s}$	Poisson's Ratio
13.6	0	- 13.6	5.4	15.35	0	- 15.4	3.1	14.5	1.74	0.254
6.6	13.6	- 20.2	5.8	9.33	15.4	- 24.7	3.4	22.5	1.71	0.242
20.3	20.2	- 40.5	7.2	19.2	24.7	- 43.9	4.3	42.2	1.68	0.225
	40.5	- -	8.2		43.9	- -	4.7	-	1.74	0.254

VERTICAL SECTION
(ASSUMING DEPTH OF FOCUS IS 13.5 KM.)

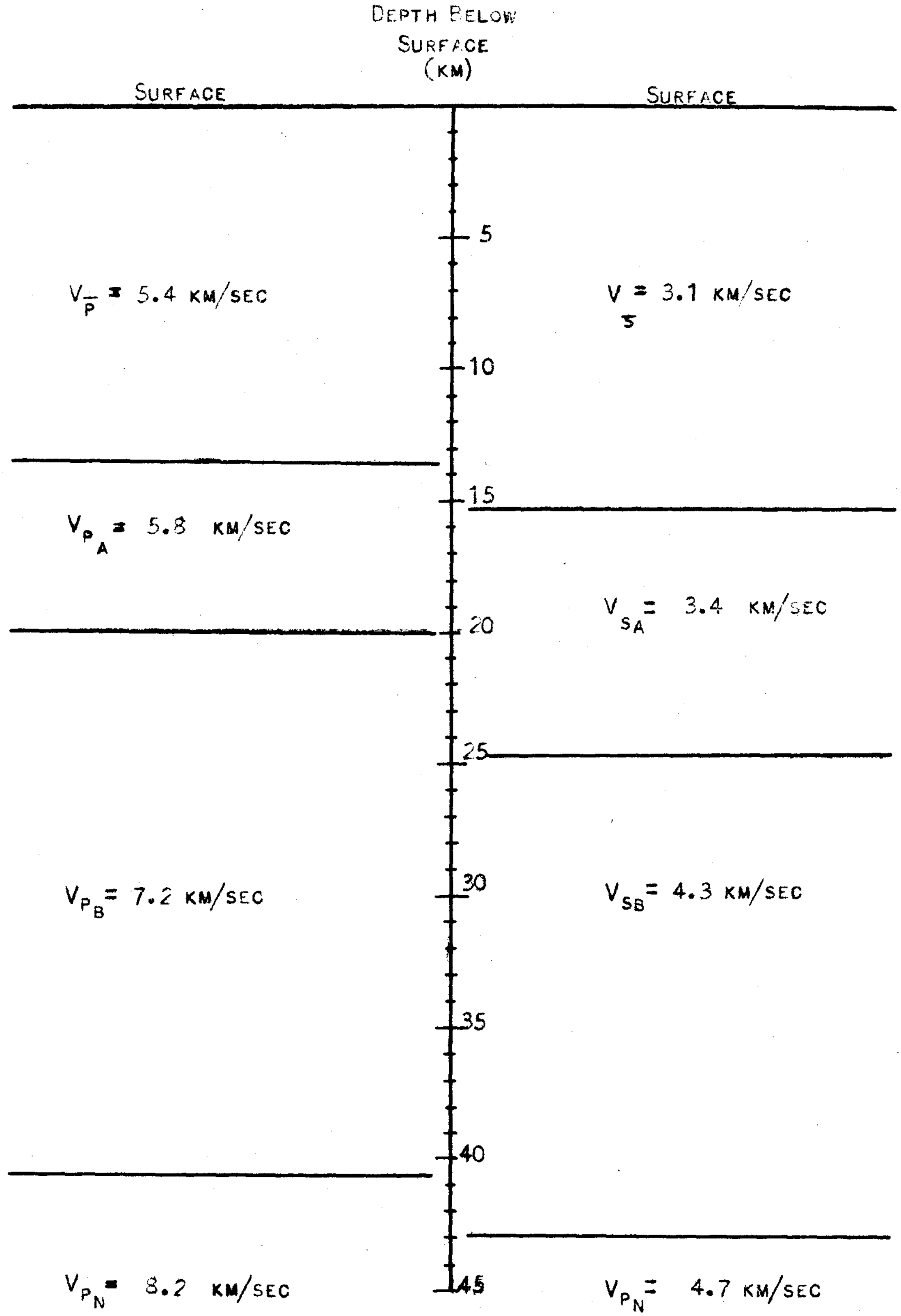

FIG 3 THICKNESS OF LAYERS