UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 7

SEISMIC-REFRACTION MEASUREMENTS OF CRUSTAL STRUCTURE BETWEEN SANTA MONICA BAY AND LAKE MEAD*

by

John C. Roller** and John H. Healy**

DENVER, COLORADO

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Technical Letter
Crustal Studies-7
January 25, 1963

Dr. Charles C. Bates
Chief, VELA UNIFORM Branch
Advanced Research Projects Agency
Department of Defense
Pentagon
Washington 25, D. C.

Dear Dr. Bates:

Transmitted herewith are 10 copies of:

TECHNICAL LETTER NUMBER 7

SEISMIC-REFRACTION MEASUREMENTS OF CRUSTAL STRUCTURE BETWEEN SANTA MONICA BAY AND LAKE MEAD*

by

John C. Roller** and John H. Healy**

We intend to submit this report for publication in a scientific journal.

Sincerely,

L. C. Pakiser

L. C. Pakiser, Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-61.

** U. S. Geological Survey, Denver, Colorado.

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Abstract. A reversed seismic-refraction profile was recorded between Santa Monica Bay, California, and Lake Mead, Nevada, during November 1961. Depth to the Mohorovičić discontinuity was determined to be approximately 29 km at Santa Monica Bay, 36 km under the Transverse Ranges, 26 km under the Mojave Desert, and 30 km at Lake Mead.

Prominent events on the seismograms in the distance range 30 to 150 km are interpreted as reflections from the Mohorovičić discontinuity and from a crustal layer of intermediate velocity. These reflected events are used to make a detailed interpretation of crustal structure. The velocity of compressional waves in the mantle immediately below the Mohorovičić discontinuity was determined to be 7.8 km/sec. The velocity of compressional waves in the intermediate layer is near 7.0 km/sec. The apparent velocity of the direct arrival in the crustal rocks near the surface is 6.3 km/sec northeast of Santa Monica Bay, and 6.1 km/sec southwest of Lake Mead. The higher apparent velocity for the direct arrival from Santa Monica Bay seems to be

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the result of thinning toward the east of low-velocity rocks near the surface. These low-velocity near-surface rocks are Cenozoic sedimentary rocks and fractured and weathered granitic and metamorphic rocks. The velocity of S_g was determined to be 3.4 km/sec near Lake Mead.

A prominent phase with apparent velocity of 6.3 to 6.4 km/sec was recorded at distances beyond 200 km. This phase is identified as $\overline{P}$ and is interpreted as a reflection from the intermediate layer. Amplitude measurements support the conclusion that the $\overline{P}$ phase is a reflected arrival.

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INTRODUCTION

The U. S. Geological Survey recorded a reversed seismic-refraction profile between Lake Mead, Nevada, and Santa Monica Bay, California, in November 1961 (Fig. 1). Recordings were made at 38 positions along a line 413 km in length between the two shotpoints (Table 1). Three high-explosive charges, ranging from 2000 to 6000 lbs in weight, were fired at each shotpoint. The Santa Monica Bay shotpoint at lat 34°00.06'N and long 118°33.28'W was in water at a depth of about 100 ft. The water overlies a sedimentary section estimated to be 6000 ft thick. The Lake Mead shotpoint at lat 36°05.66'N and long 114°48.33'W was in water at a depth of about 160 ft. The water overlies a thin sedimentary section above the basement rocks. Ten seismic-recording units (Warrick and others, 1961) were used to make the recordings. Jackson and others (1963) have described the field procedures used in this study.

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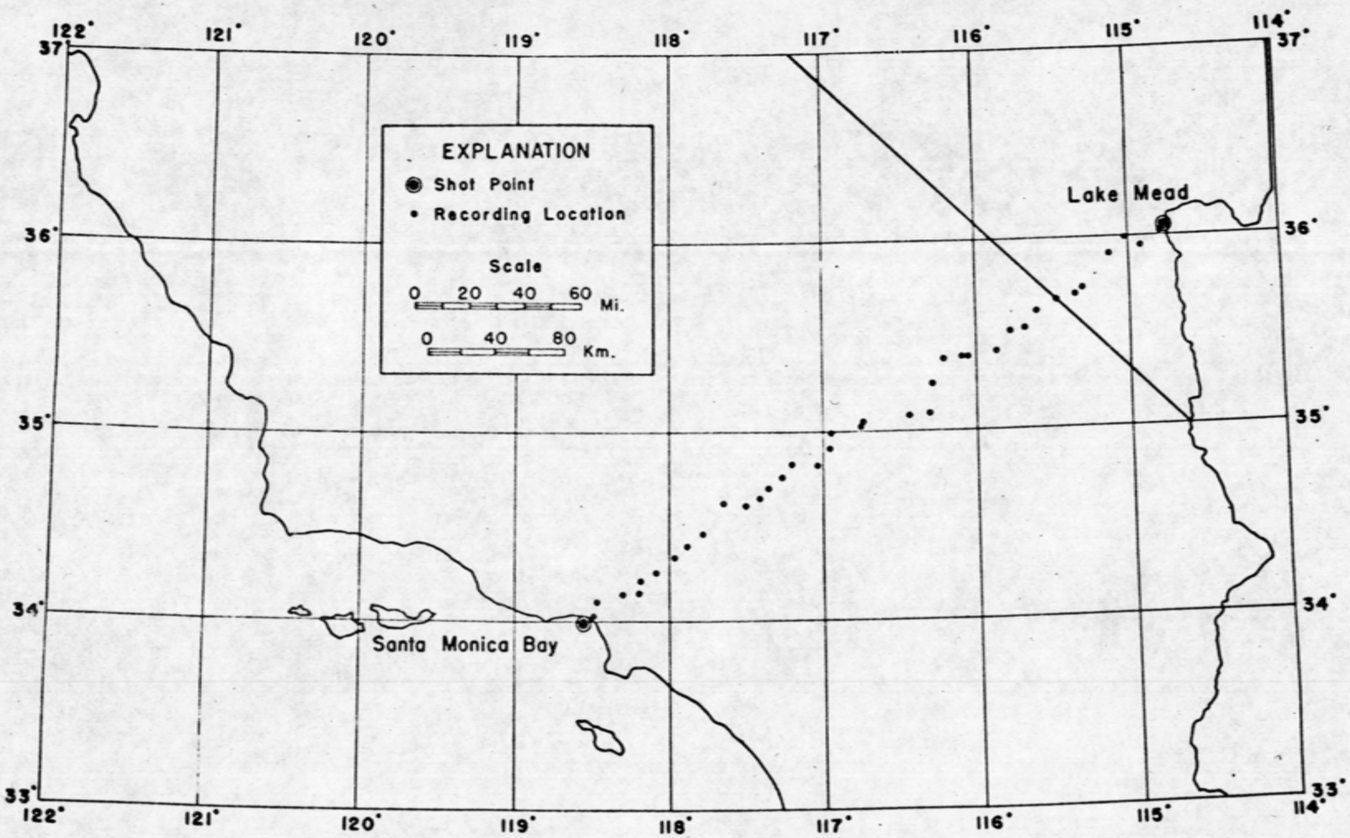

Figure 1.--Index map showing shotpoints and seismic recording locations.

Table 1.--Recording locations.

Shot: Lake Mead 1

Recording unit	End of Spread*	Latitude, North	Longitude, West	Elevation, ft
H	E	35°33.25'	115°40.75'	3530'
I	E	35°38.30'	115°36.68'	3420'
J	E	35°41.94'	115°29.58'	3130'
K	E	35°44.70'	115°23.24'	2890'
L	E	35°46.32'	115°20.60'	2890'
P	E	35°50.24'	115°15.71'	2990'
Q	E	35°58.23'	115°11.09'	2450'
R	E	36°01.82'	115°02.86'	1960'
S	W	35°58.93'	114°59.04'	2600'
T	E	36°04.66'	114°49.68'	1440'

* End of spread at which coordinates were measured. Spread length normally is 2.5 km.

Table 1.--Recording locations (continued).

Shots: Lake Mead 2 - - Santa Monica 12

Recording unit	End of Spread*	Latitude, North	Longitude, West	Elevation, ft
H	W	35°01.58'	116°45.80'	1740'
I	W	35°05.46'	116°19.16'	1325'
J	W	35°05.36'	116°26.80'	1880'
L	W	35°15.70'	116°19.44'	1930'
P	W	35°22.98'	116°14.43'	1361'
Q	W	35°23.47'	116°07.44'	935'
R	W	35°23.77'	116°04.92'	1440'
S	W	35°24.94'	115°53.18'	3400'
T	W	35°31.85'	115°48.10'	3430'

* End of spread at which coordinates were measured. Spread length normally is 2.5 km.

Table 1.--Recording locations (continued).

Shots: Lake Mead 3 - - Santa Monica 13

Recording unit	End of Spread*	Latitude, North	Longitude, West	Elevation, ft
H	W	34°37.73'	117°39.60'	2870'
I	E	34°37.06'	117°29.60'	2802'
J	W	34°39.21'	117°25.26'	2735'
K	W	34°42.02'	117°22.28'	2682'
L	W	34°45.68'	117°18.00'	2575'
P	W	34°49.72'	117°13.44'	2575'
Q	W	34°49.02'	117°04.32'	2550'
R	W	34°55.33'	116°58.38'	2310'
S	W	34°59.86'	116°56.85'	2640'
T	W	35°02.22'	116°45.80'	1705'

* End of spread at which coordinates were measured. Spread length normally is 2.5 km.

Table 1.--Recording locations (continued).

Shot: Santa Monica 14

Recording unit	End of Spread*	Latitude, North	Longitude, West	Elevation, ft
H	W	34°02.68'	118°29.95'	305'
I	S	34°06.16'	118°28.38'	1230'
J	W	34°08.83'	118°19.89'	350'
K	S	34°09.64'	118°12.68'	745'
L	S	34°13.40'	118°11.36'	1950'
P	W	34°15.54'	118°06.15'	4600'
Q	W	34°20.60'	117°58.90'	5911'
R	W	34°25.58'	117°55.17'	4880'
S	W	34°28.54'	117°48.40'	3595'
T	E	34°31.50'	117°43.65'	3170'

* End of spread at which coordinates were measured. Spread length normally is 2.5 km.

GEOLOGY AND PHYSIOGRAPHY

The seismic profile extends from the Pacific Coast across the Transverse Ranges and the Mojave Desert, and terminates in the Basin and Range Province of Nevada. The complex geology of this region is characterized by a series of basins, ranges, and faults that generally strike northwest, normal to the line of profile. Major structures crossed by the profile are the Los Angeles Basin, the San Gabriel fault zone, the San Gabriel Mountains, the San Andreas fault zone, and numerous fault-block mountains of the Mojave Desert and the Basin and Range Province. The Los Angeles Basin is a broad syncline that contains up to 10,000 ft of Tertiary and Quaternary marine sedimentary rocks. It is bordered on the north and east by faulted and folded mountains (King, 1933). The San Gabriel Mountains are composed of Mesozoic felsic intrusives and Precambrian metamorphic rocks. The Basin and Range Province is characterized by a series of northwest trending fault-block mountains separated by basins filled with thick accumulations of Quaternary and Tertiary sedimentary deposits. The ranges are principally composed of Mesozoic and Tertiary felsic rocks, and Precambrian metamorphic rocks (Eardley, 1951; Ball, 1907; Bowyer and others, 1958; and,Hewett, 1956).

Average elevation of the seismic stations is 2500 ft above sea level. The greatest departures from the average elevation are in the San Gabriel Mountains where the highest station was at an elevation of 5900 ft, and near the coast where the elevation of the lowest station was 160 ft. The shotpoint elevations were -100 ft at Santa Monica Bay and 1200 ft at Lake Mead.

CHARACTERISTICS OF SEISMOGRAMS

Lake Mead and the Santa Monica Bay shotpoints both provided a relatively efficient conversion of explosive energy into seismic energy, and the quality of seismograms recorded along this profile is well above the average quality recorded in the California-Nevada region.

Lake Mead. The first arrivals (Table 2) for twelve seismograms recorded from Lake Mead to a distance of 140 km are the "direct" waves, and are designated P_g. The first energy can usually be determined without difficulty, although the first cycle of this phase is normally weak (Fig. 2).

A very strong secondary arrival recorded on the seismograms at distances of 50 to 120 km has been tentatively identified as a reflection from a layer with velocity of 7.8 km/sec, and is referred to as P_MP (Fig. 3). P_MP is the strongest event recorded in this distance range.

On some of the recordings a weaker event can be found between P_g and P_MP. It can be correlated as a reflection and/or refraction on recordings made near the critical distance (Fig. 3), and on the more distant recordings (Fig. 4) as a refraction from a crustal layer with velocity of about 7.0 km/sec. This arrival is referred to as P*.

Refractions from the Mohorovičić discontinuity (P_n) appear as strong first arrivals beyond 140 km. They can be definitely identified to a distance of 280 km (Fig. 4).

Table 2.--Arrival times of prominent phases.

Shot: Santa Monica 12 Charge Size - 6000 lbs

Unit	Dist., km	t_1 sec	a_f mμ	a_1 mμ	t_2 sec	a_2 mμ	t_3 sec	a_3 mμ	t_4 sec	a_4 mμ
H	199.9	32.68(2)			35.23		36.24(5)			
I	239.8	37.88(2)		1.7	42.07(5)	5				
J	228.0	36.26(2)		0.3	42.26	12				
L	248.2	39.02(2)			43.50(5)					
P	261.6	40.03(2)		0.2	45.63(5)	2.2				
Q	270.9	42.20(2)		0.5	47.16(5)	1.7				
R	274.3	42.40(2)		0.2	48.32(5)	2.0				
S	290.5	44.43(2)		0.1	49.35(5)	0.7				

Shot: Santa Monica 13 Charge Size - 4000 lbs

Unit	Dist., km	t_1 sec	a_f mμ	a_1 mμ	t_2 sec	a_2 mμ	t_3 sec	a_3 mμ	t_4 sec	a_4 mμ
H	108.3	19.66(1)		4.1	20.42(3)	1.8	21.43(4)	8		
I	116.7	20.20(1)		.25	21.21(3)	0.6	22.48(4)	21		
J	129.9				22.70(3)	2.0	23.70(4)	33		
L	142.2				25.23(3)	0.6	26.13(4)	12		
P	151.9	26.59(2)		.25			27.35(4)	4		
Q	163.3	28.00(2)		.25						
S	184.4	31.18(2)			32.45	6.7				
T	202.0	32.89(2)		3						

Table 2.--Arrival times of prominent phases (continued).

Shot: Santa Monica 14 Charge Size - 3000 lbs

Unit	Dist., km	t_1 sec	a_f mμ	a_1 mμ	t_2 sec	a_2 mμ	t_3 sec	a_3 mμ	t_4 sec	a_4 mμ
H	7.0	3.25(1)	211							
I	13.7	4.01(1)	68							
J	26.1	5.85(1)		113	7.55	414				
K	36.2	7.38(1)	2.4	29	9.65	39	10.48(3)	50	11.73(4)	45
L	41.7	8.30(1)	9.3	35	10.13	82	11.22(3)	145	11.93(4)	113
P	50.5	9.78(1)	4.3	27	11.54	44	12.14(3)	55	13.32(4)	117
Q	64.9	12.05(1)	1.2	11	13.96	17	14.43(3)	37	15.50(4)	38
R	75.1	13.56(1)	1.8	10	15.28	9.3	15.95(3)	42	16.97(4)	84
S	86.7	15.56(1)	1.6	17	17.24	37	17.86(3)	68	18.51(4)	84
T	93.3	16.27(1)		6.2	18.20	12	18.72(3)	42	19.41(4)	73

Table 2.--Arrival times of prominent phases (continued).

Shot: Lake Mead 1 Charge Size - 2000 lbs

Unit	Dist., km	t_1 sec	a_f mμ	a_1 mμ	t_2 sec	a_2 mμ	t_3 sec	a_3 mμ	t_4 sec	a_4 mμ
H	98.8	17.11(1)					18.99(4)			
I	88.9	15.21(1)	2.1	36	16.03(3)	30	17.48(4)	70		
J	75.9	13.03(1)	1.1	12.5	14.23(3)	79	15.95(4)	115		
K	66.7	11.52(1)			13.32(3)		14.78(4)			
L	60.2	10.59(1)	6.0	41			14.13(4)	103		
P	50.0	8.97(1)	9.0	83						
Q	35.4	6.69(1)	25	330						
R	22.8	4.45(1)								
S	17.7	3.59(1)	30	380						
T	2.0	.96(1)	46	440						

Table 2.--Arrival times of prominent phases (continued).

Shot: Lake Mead 2 Charge Size - 4000 lbs

Unit	Dist., km	t_1 sec	a_f mμ	a_1 mμ	t_2 sec	a_2 mμ	t_3 sec	a_3 mμ	t_4 sec	a_4 mμ
H	211.8	32.65(2)		15	33.95(6)	3.3	36.41(5)	11		
I	174.2	27.66(2)								
J	183.3	28.91(2)		5			32.07(5)	16		
L	163.1	26.51(2)	0.5	4			28.16(4)	7		
P	149.4	24.95(2)	0.2	6			26.43(4)	10		
Q	140.0	23.61(1)					24.74(4)			
S	121.3	20.50(1)	0.2	1.9	21.39(3)	24	22.10(4)	16		
T	107.7	18.40(1)					19.89			
Shot: Lake Mead 3	Charge Size - 6000 lbs									
H	303.6									
I	293.3	48.70(2)					49.90(5)	4		
J	283.9	48.02(2)								
K	277.2	41.36(2)		2.8			46.87(5)	4		
L	271.2	40.04(2)								
P	261.5	38.70(2)		1.4	40.4(6)		44.09(5)	1.0		

Table 2.--Arrival times of prominent phases (continued)

Shot: Lake Mead 3   Charge Size - 6000 lbs (continued)

Unit	Dist., km	t_1 sec	a_f mμ	a_1 mμ	t_2 sec	a_2 mμ	t_3 sec	a_3 mμ	t_4 sec	a_4 mμ
Q	247.3	37.57(2)								
R	233.2	35.10(2)					39.42(5)			
S	226.7	34.80(2)		4	36.10(6)		38.76(5)	8		
T	208.8	32.40(2)		1.4	34.73	14	36.03(5)	10		

$t_{1,\ 2,\ 3,\ 4}$ = time of prominent phase on the seismogram.

a_f = amplitude of first upward motion in millimicrons.

$a_{1,\ 2,\ 3,\ 4}$ = maximum peak-to-peak amplitude of phase in millimicrons.

(1) phase identified as P_g

(2) " " " P_n

(3) " " " $P_I P$

(4) " " " $P_M P$

(5) " " " $\overline{P}$

(6) " " " P*

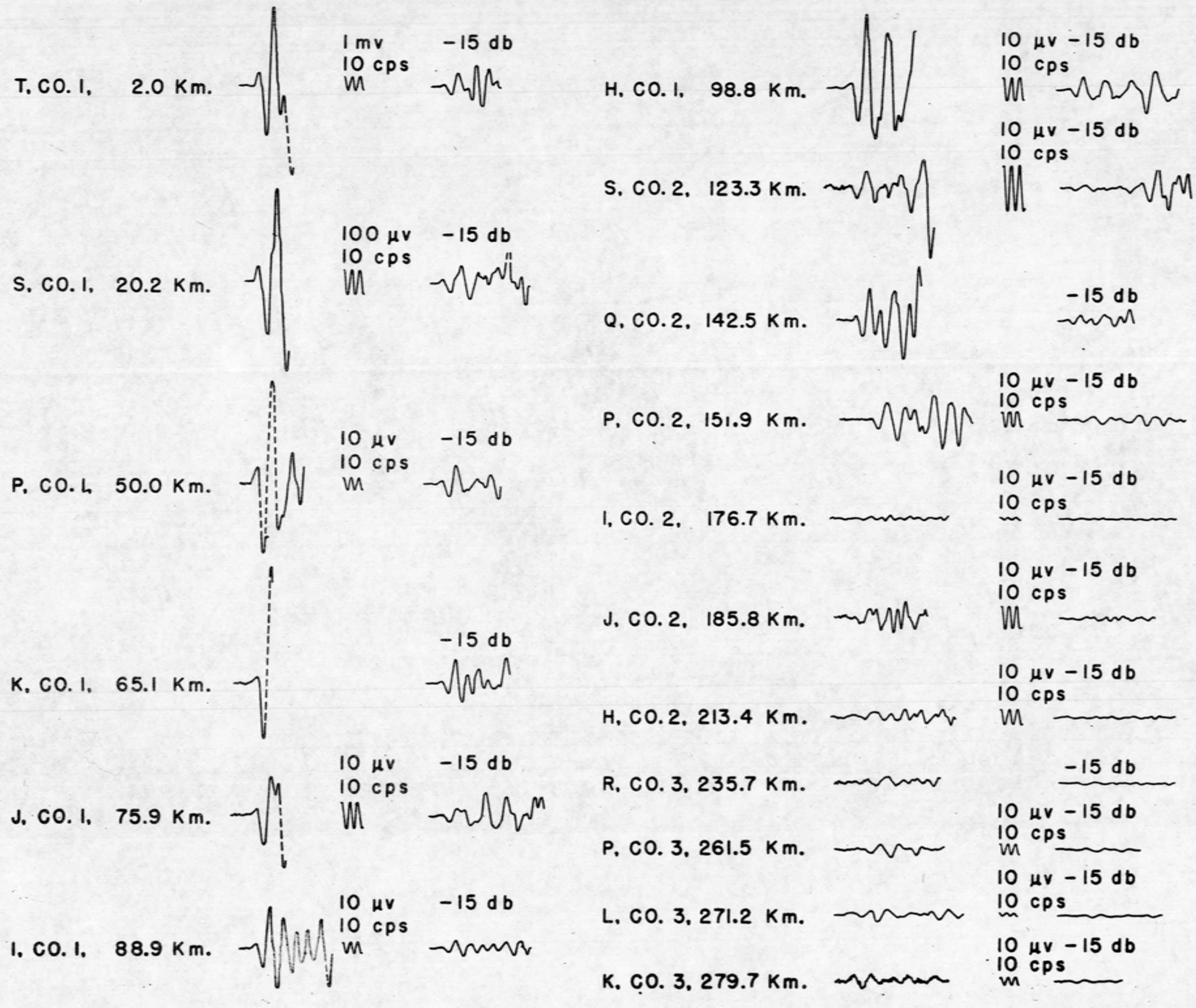

Figure 2.--First motion from shots in Lake Mead as recorded at various distances.

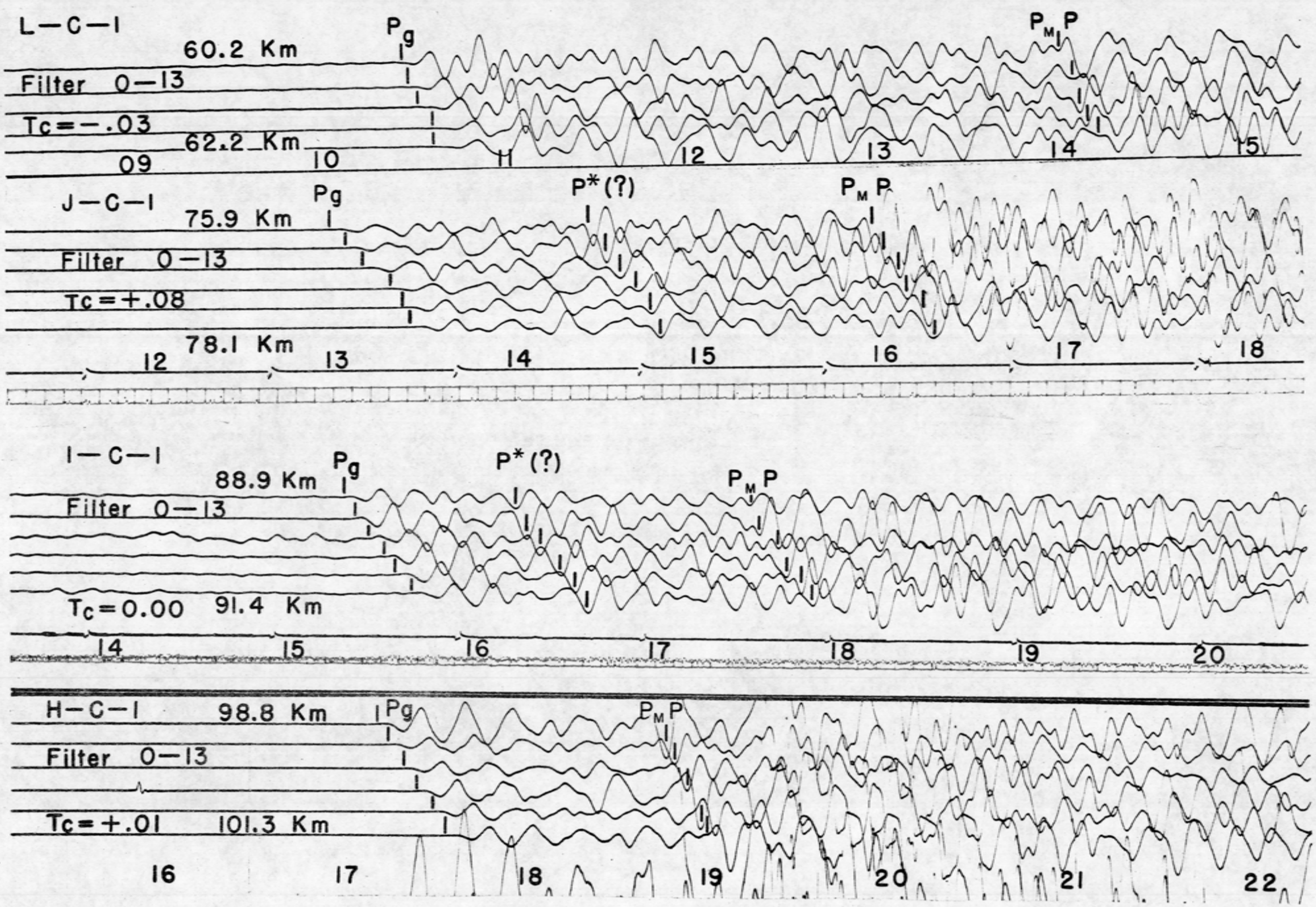

Figure 3.--Seismograms recorded at short distances from Lake Mead shotpoint.

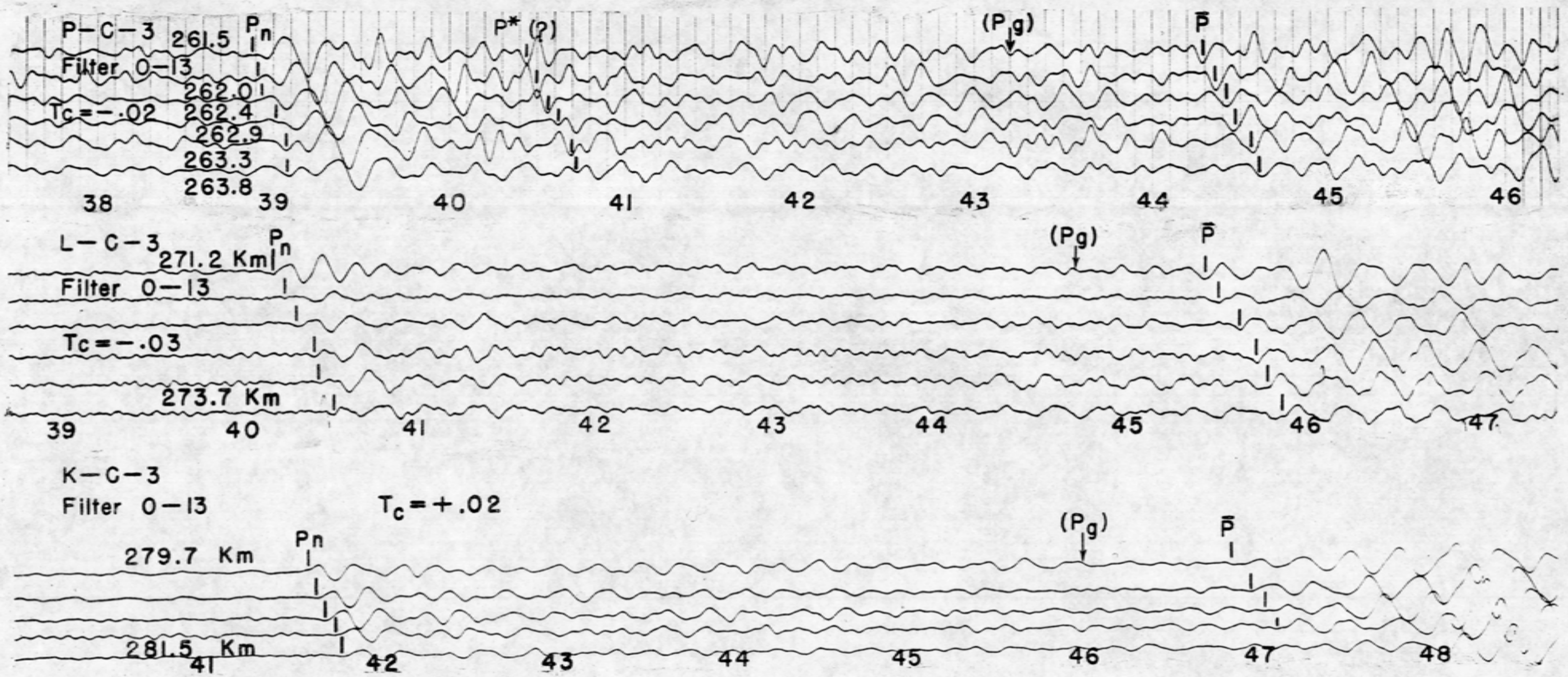

Figure 4.--Distant seismograms recorded from Lake Mead shotpoint.

A large-amplitude wave train that follows P_n by several seconds is identified as $\overline{P}$ (Fig. 4). This event has an apparent velocity of 6.3 km/sec (Fig. 5), and its traveltime branch is delayed approximately 1 sec with respect to the projection of P_g. No clear event can be identified as P_g beyond the cross-over distance of P_g to P_n (Fig. 4).

Another event on some of the recordings in the 140 to 280 km range occurs at a time appropriate for a refraction from the 7.0 km/sec layer, but it is not continuous and the scatter of arrival times about the 7.0 km/sec line is large. This event generally has a higher frequency than P_n.

A shear wave (S_g) that travels with velocity of 3.4 km/sec was identified to a distance of 150 km from Lake Mead.

There are many other events on the seismograms that cannot be correlated between recording positions.

Santa Monica Bay. The seismograms recorded from shots in Santa Monica Bay are very similar to those recorded from shots in Lake Mead.

First arrivals on 12 seismograms (Table 2) recorded in the distance range 7 to 116.7 km are identified as P_g. The amplitude of P_g falls off very rapidly where the profile crosses the San Andreas fault zone at a distance of approximately 90 km from the Santa Monica Bay shotpoint, and P_g disappears into the noise at a distance of about 20 km beyond the fault zone.

Between 120 and 200 km from Santa Monica Bay, the time of the first recognizable energy on the seismograms is later than the time appropriate for P_g.

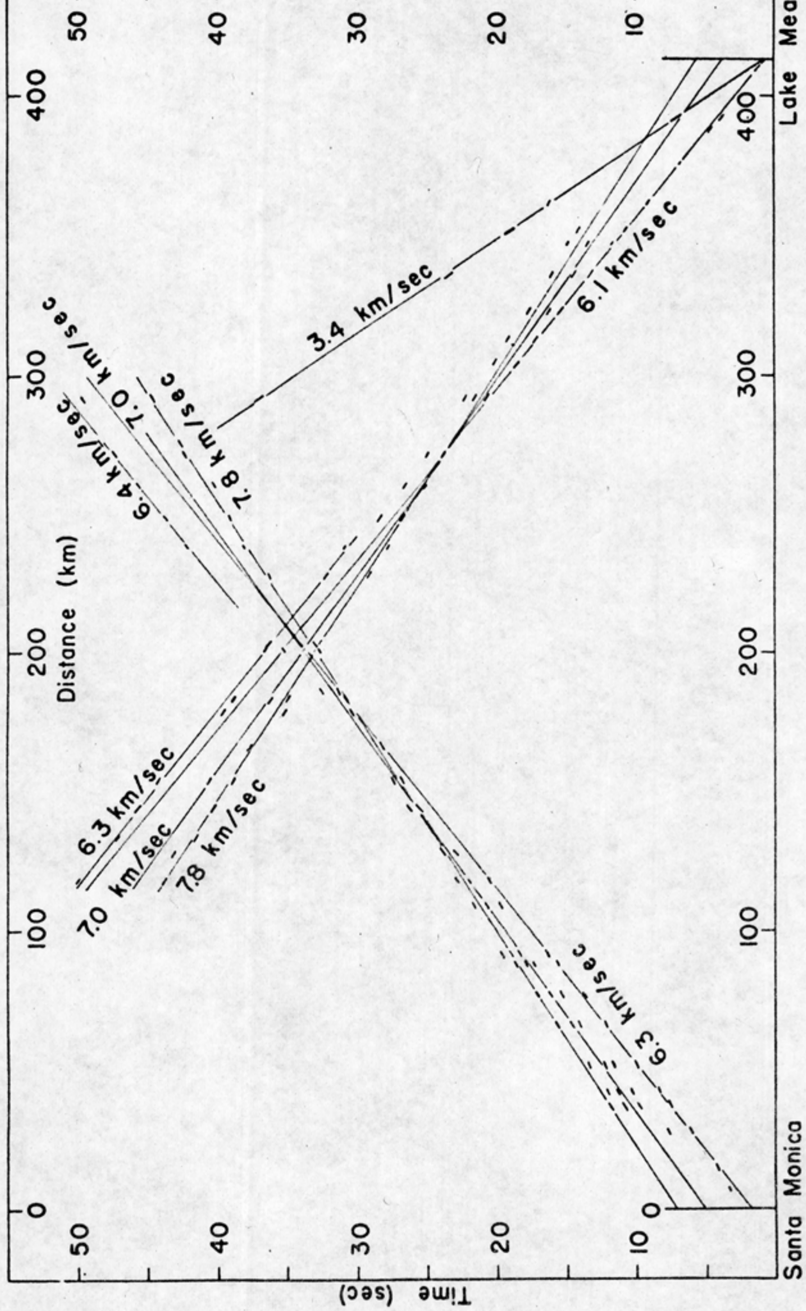

Figure 5.--Traveltime curve between Santa Monica Bay, California, and Lake Mead, Nevada.

P_n is clearly recorded as the first arrival on nine seismograms made in the range between 200 and 300 km from Santa Monica Bay.

The large-amplitude wave identified as $\overline{P}$, with velocity of about 6.4 km/sec, is prominent on the seismograms, and the arrival times of this phase are later than traveltimes of the extension of P_g beyond the cross over to P_n. This wave train is similar to $\overline{P}$ observed by others (Romney, 1959; Shurbet, 1960), although the velocity of 6.4 km/sec is higher than previously reported. This phase has the same velocity as a phase observed by Diment, Stewart, and Roller (1960), which was interpreted as possibly being P_g reflected once from the earth's surface as a result of a slight increase of velocity with depth.

P_MP arrivals were also recorded from Santa Monica Bay in the distance range 50 to 150 km.

TIME OF FIRST ARRIVALS

The first waves from the Lake Mead shotpoint to reach recording positions to a distance of 140 km, fit the line $T = 0.6 + \Delta/6.1$. Most of the arrivals fall within 0.1 sec of this line, and the largest deviation is 0.3 sec. In the distance range 140 km to 280 km from Lake Mead, first arrivals fit the line $T = 5.5 + \Delta/7.8$. Most of the arrivals fall within 0.2 sec of this line, and the largest deviation is 0.3 sec.

The first waves from Santa Monica Bay shotpoint to reach recording positions to a distance of 120 km, fit the line $T = 1.7 + \Delta/6.3$. All of the points, with the exception of one, fall within 0.2 sec of this line. From 120 km to the P_g-P_n crossover, the true first arrivals are too weak to be picked. The first waves from Santa Monica Bay shotpoint to reach recording positions in the distance range 200 to 290 km fit the line $T = 7.1 + \Delta/7.8$. All arrivals fall within 0.2 sec of this line.

DEPTH CALCULATIONS FROM REFRACTION DATA

Using only first arrivals and assuming that apparent velocities on the traveltime curves are true velocities, calculated depth to the Mohorovičić discontinuity is 31.3 km for the one-way profile from Santa Monica Bay to Lake Mead; for the one-way profile from Lake Mead to Santa Monica Bay, depth to the Mohorovičić discontinuity is 24.8 km.

Press (1960) reported a thickness of 23 km for the 6.1 km/sec layer along a line from the Nevada Test Site to Corona, California. This was interpreted to overlay a medium with velocity of 7.66 km/sec. A thickness of 26.7 km for this layer was reported along a line from the Nevada Test Site to Kingman, Arizona, by Diment, Stewart, and Roller (1961). The central point of that line is close to Lake Mead.

If we assume that the 7.0 km/sec layer indicated by the secondary events is a discrete layer, the crustal thicknesses are increased to 33.4 and 27.8 km, respectively (Table 3). A velocity of 3.0 km/sec has been assumed for the near-surface material.

REFLECTIONS

An event of large amplitude follows P_g by a few seconds at distances of 75 to 145 km from the Santa Monica Bay shotpoint, and at distances of 50 to 120 km from the Lake Mead shotpoint. The apparent velocities across the spreads and the positions on the traveltime plot support the conclusion that this event is a reflection from the Mohorovičić discontinuity. An attempt was made to pick and correlate as many of these events as possible (Figs. 6 and 7).

Three prominent events were found in the distance range 36 to 150 km from the Santa Monica Bay shotpoint. The most prominent of these is the reflection from the Mohorovičić discontinuity (P_MP); a second prominent event is interpreted as a reflection from the top of the intermediate layer (P_IP). The third event is a weak forerunner of the intermediate-layer reflection and has not been identified.

Table 3.--Computed crustal models.

Layer	From Santa Monica Bay: Velocity (km/sec)	From Santa Monica Bay: Thickness (km)	From Lake Mead: Velocity (km/sec)	From Lake Mead: Thickness (km)
1	3.0	2.9	3.0	1.0
2	6.3	28.4	6.1	23.8
3	7.8	- -	7.8	- -
Total depth to M-discontinuity 31.3			Total depth to M-discontinuity 24.8	

Layer	From Santa Monica Bay: Velocity (km/sec)	From Santa Monica Bay: Thickness (km)	From Lake Mead: Velocity (km/sec)	From Lake Mead: Thickness (km)
1	3.0	2.9	3.0	1.0
2	6.3	23.9	6.1	19.0
3	7.0	6.6	7.0	7.8
4	7.8	- -	7.8	- -
Total depth to M-discontinuity 33.4			Total depth to M-discontinuity 27.8	

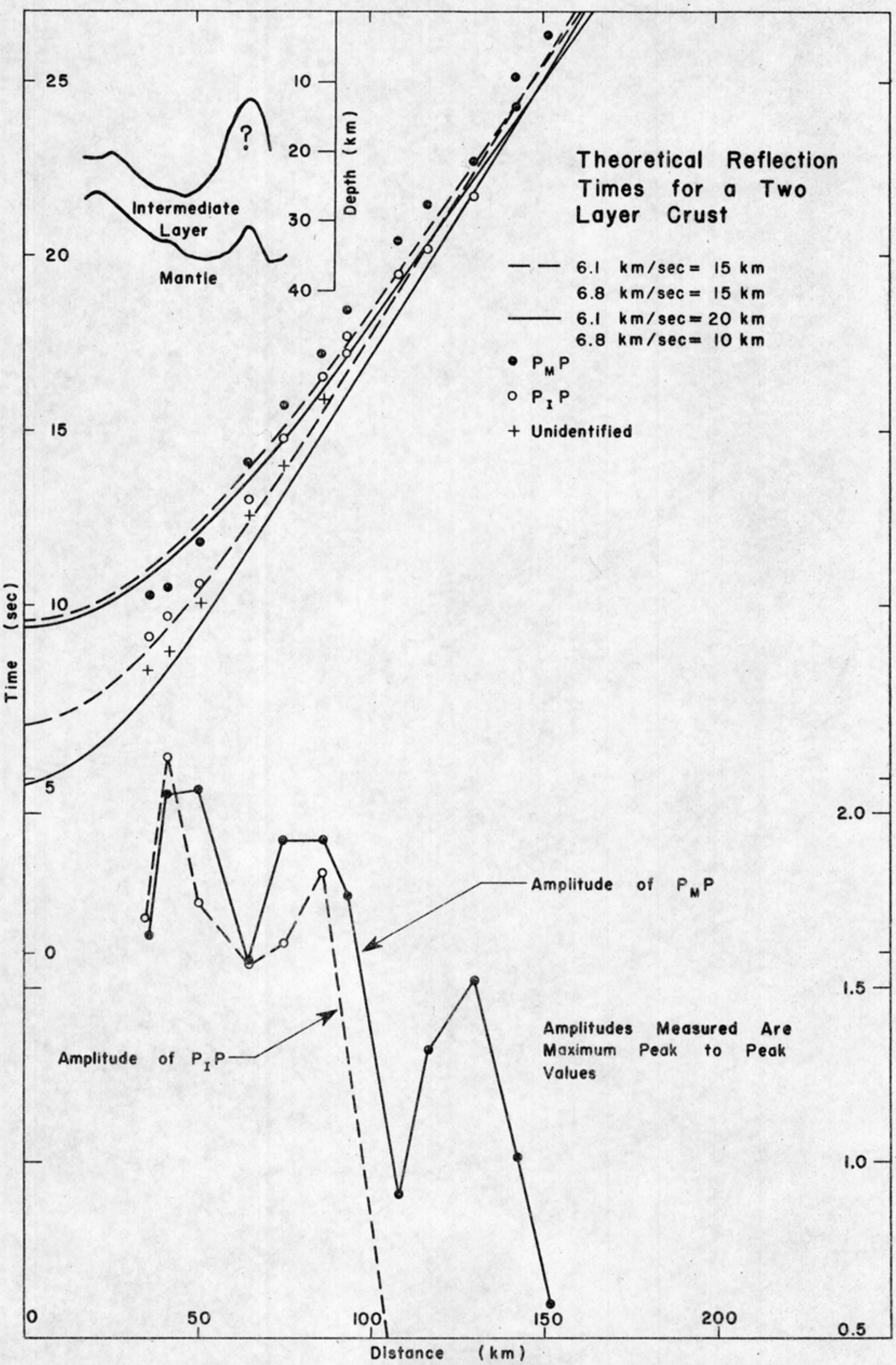

Figure 6.--Traveltimes and amplitudes of reflections recorded from Santa Monica Bay shotpoint.

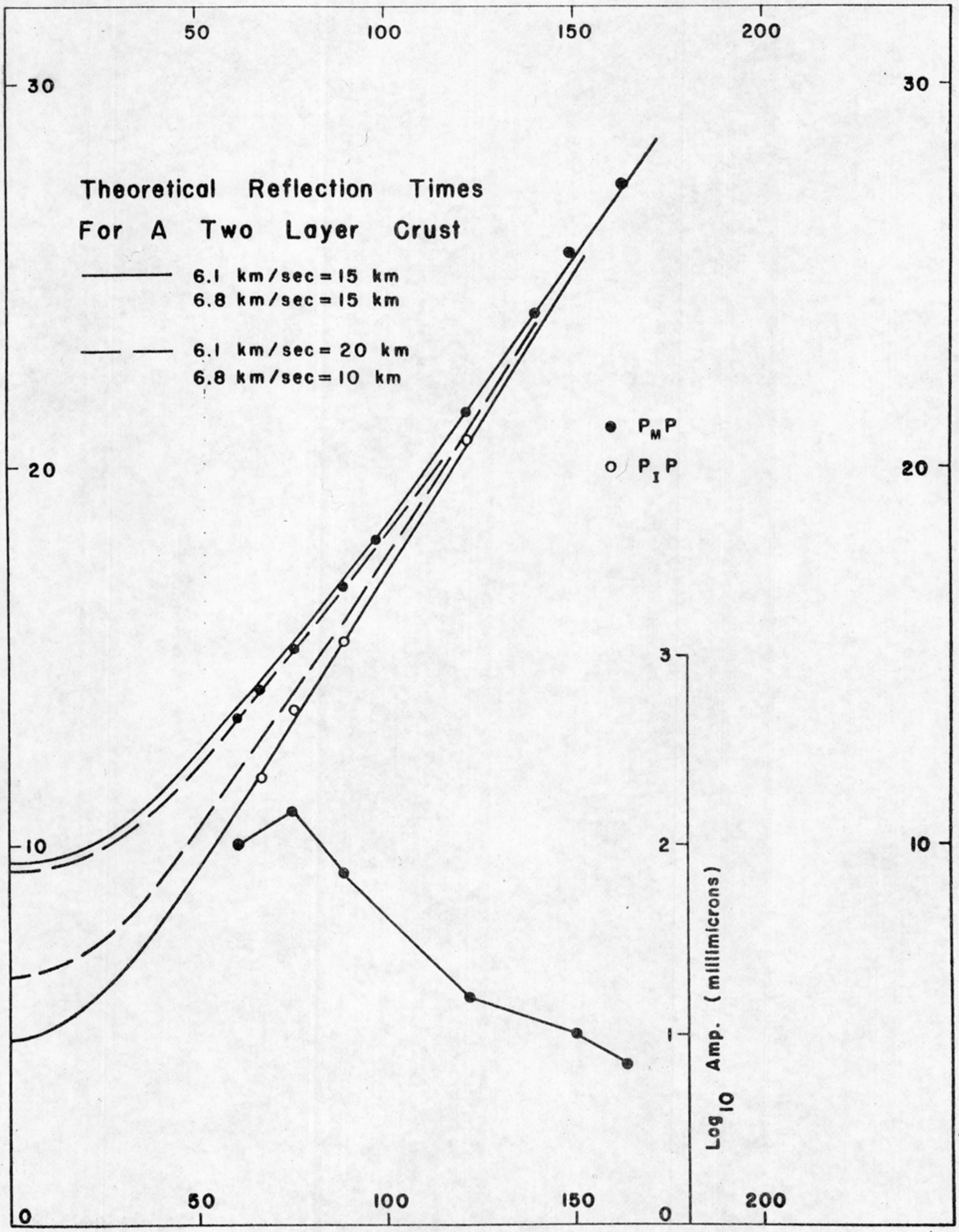

Figure 7.--Traveltimes and amplitudes of reflections recorded from Lake Mead shotpoint.

At recording locations where a clear P_g arrival was received, relative deviations of the time of arrival of P_g from the line $0.6 + \Delta/6.1$ was used to determine a correction for the near-surface low-velocity rocks. At locations where P_g was not recorded, the correction for the near-surface low-velocity material was estimated from the nature of the recording location and from the P_n arrivals. Reflections recorded in the Los Angeles area do not fit theoretical reflection curves for any flat-layer model, and an approximate method based upon an assumption that the thickness ratio of granitic crust to intermediate layer remains constant as the depths change (Fig. 6) was used to compute the position of the crustal boundaries from the reflection data.

Structures in the crustal boundaries seem to be related to the Transverse Ranges in southern California. Although the details of structure in the crustal boundaries are in doubt because of interpretational uncertainties which include proper phase correlation and near-surface corrections, a number of significant points are illustrated. First, the reflections indicate structure which has not been revealed by the refraction data. Second, the quality of the recordings indicates that a carefully-designed experiment using closely-spaced recording units, with shotpoints separated by about 100 km, would provide a fairly precise picture of variations in crustal boundaries in this region. Third, it is apparent that the refraction method, as presently used, tends to average crustal thicknesses along the length of the profile without revealing important local variations in the crustal boundaries.

The reflections recorded from the Lake Mead shotpoint fit the theoretical curves for a flat-layer crust with a total thickness of about 30 km and an intermediate layer 10 km thick.

AMPLITUDES

Amplitudes of prominent phases were measured and tabulated with arrival times (Table 2). Two amplitudes were measured for first arrivals: the amplitude of the first upward (compressional) motion, and the maximum peak-to-peak amplitude for the phase. On other arrivals, only the maximum peak-to-peak amplitude for the phase was measured. An average frequency of 5 cps was used to reduce the amplitudes as measured on the seismogram to amplitudes of ground motion.

The largest amplitudes on seismograms recorded between 50 and 150 km are those of the P_MP reflections from the Mohorovičić discontinuity. No attempt has been made to compare the amplitude of this event with theoretical amplitudes, but the high ratio of the amplitude of P_MP to the amplitude of the "direct" arrivals supports the interpretation that these events are reflections.

Amplitudes of P_g (Figs. 8 and 9) display strong attenuation with distance, and are reduced to the noise level between 120 and 140 km from the source. Individual amplitudes of P_g show considerable scatter about any line which would correspond to an inverse-power fall-off with distance. There is a suggestion in the pattern of the

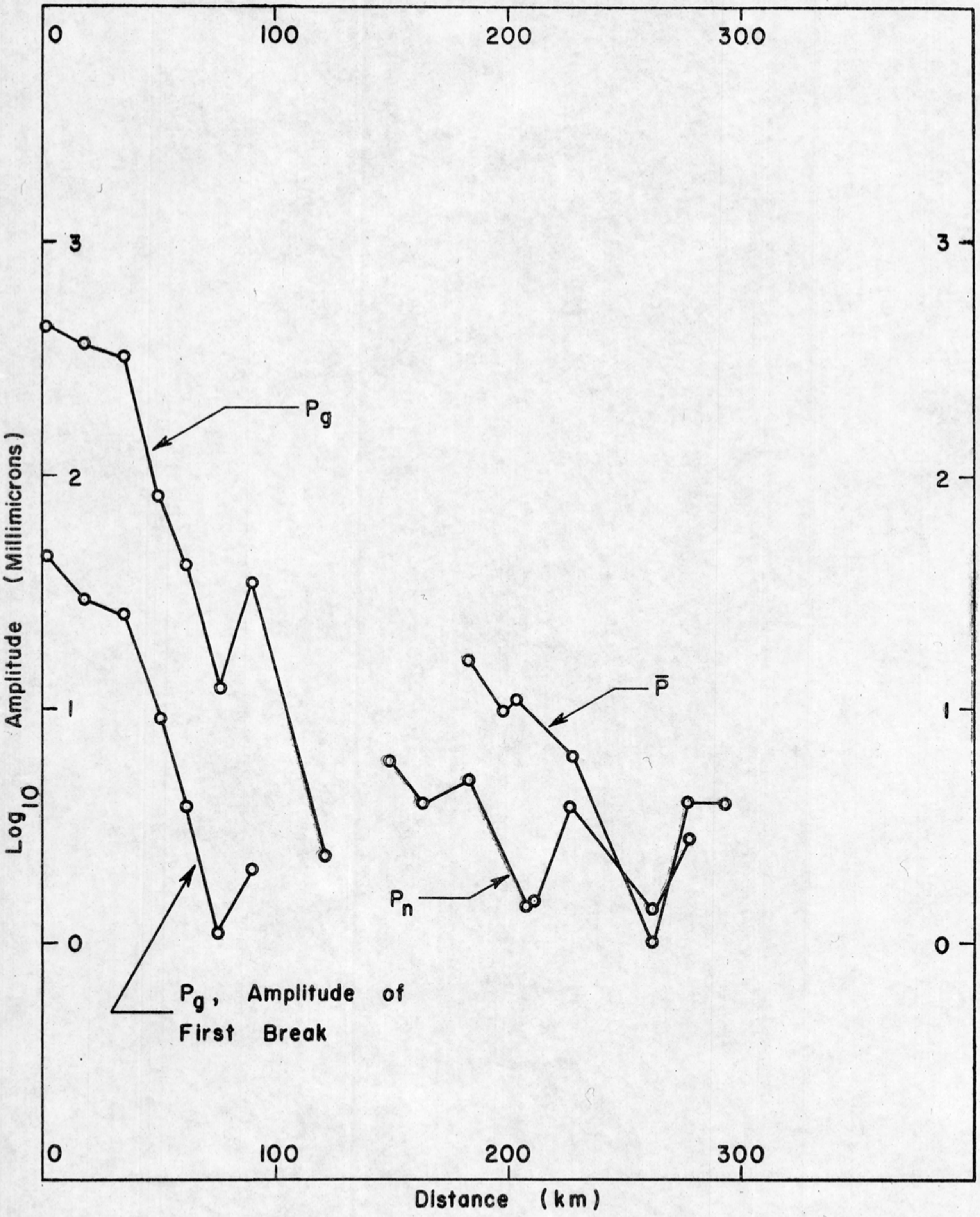

Figure 8.--Amplitudes from shots at Lake Mead.

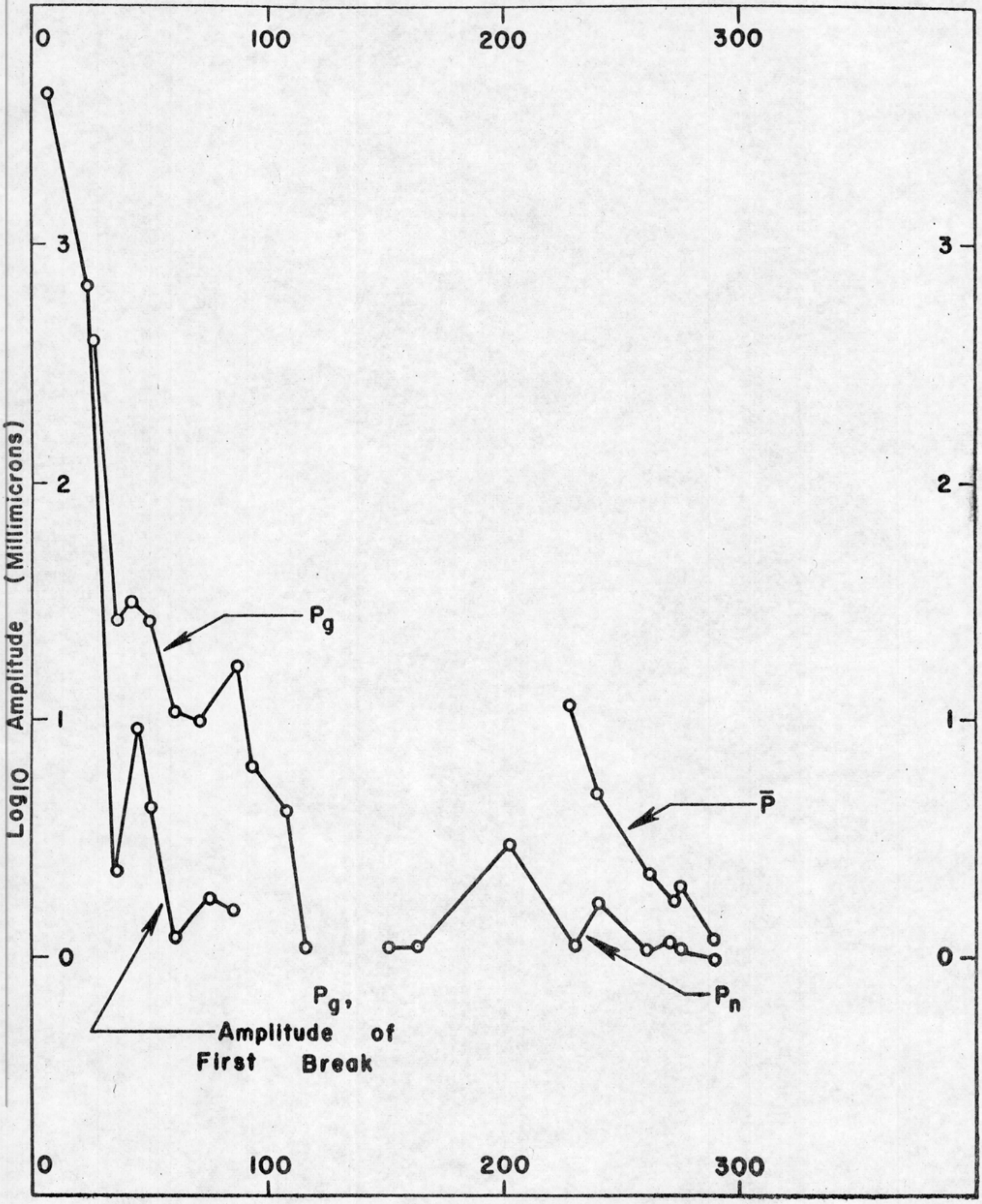

Figure 9.--Amplitudes from shots at Santa Monica Bay.

plotted points that part of this scatter may be the result of an amplitude-distance relationship that does not correspond to any simple power law. For example, both curves indicated an increase in amplitude at about 95 km. Such a pattern might be the result of a velocity gradient in the crustal zone through which P_g is propagating.

CONCLUSIONS

Along the part of the profile that crosses the Mojave Desert, two-way refraction coverage indicates that the Mohorovičić discontinuity is a flat surface at a depth of about 26 km. If the events picked as reflections have been correctly identified, they indicate a slight thickening of the crust to about 30 km at Lake Mead, and a thickening to about 40 km under the Transverse Ranges; the crust thins toward the coast to about 33 km at Santa Monica Bay (Fig. 10). In the opinion of the authors, the general form of the interpretation presented in Figure 10 is correct; however, details of crustal structure at the ends of the profile are based on the interpretation of reflection data and may be seriously in error. If this identification of the reflections is supported by further work, the detailed interpretation of crustal structure presented here illustrates a powerful technique for future exploration of the earth's crust.

Velocity of compressional waves in the crust below the near-surface low-velocity material is 6.1 ± 0.1 km/sec in this region. Apparent velocities of the $\overline{P}$ arrival of 6.3 to 6.4 km/sec indicate that the velocity in the granitic crust increases to between 6.3 and 6.4 km/sec

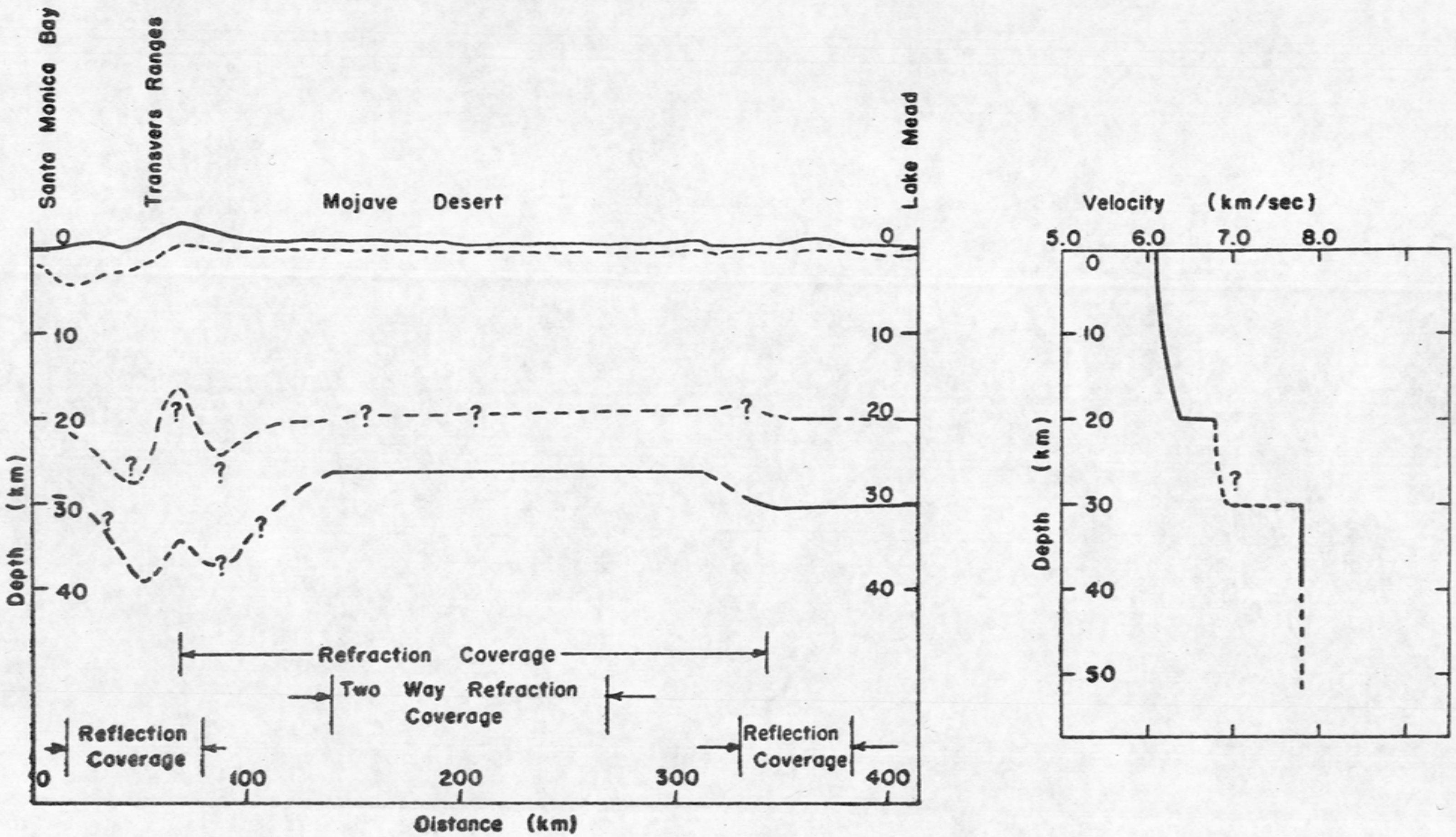

Figure 10.--Model of crustal structure.

immediately above the intermediate layer. Although there is no evidence for an intermediate layer in the traveltimes of first arrivals, a large number of weaker secondary phases, both reflections and refractions, suggest the existence of an intermediate layer with a velocity between 6.8 and 7.0 km/sec.

Amplitudes of P_n were determined in the distance range 140 to 290 km. As in the case of P_g, scatter in the plotted amplitudes prevents the determination of the rate of attenuation with distance, and there is a suggestion that the observed scatter is not entirely the result of random local variations.

In the distance range 220 to 300 km, $\bar{P}$ is the strongest phase on the seismograms. $\bar{P}$ is first identified as a clear phase at about 220 km, where the amplitude of the event is more than an order of magnitude greater than the projected amplitude for P_g as measured at near distances, and between 220 and 300 km the amplitude of $\bar{P}$ decreases sharply with distance. These properties suggest that the event is a reflection. The apparent velocity of $\bar{P}$ between 6.3 and 6.4 km/sec requires the reflecting horizon to be above the intermediate layer, and it seems reasonable to conclude that this event is a wide-angle reflection from the top of an intermediate crustal layer. Either a single or double reflection equivalent to the phase P_IP or P_IPP_IP would fit the observed traveltimes. The conclusion that $\bar{P}$ is not the "direct" wave is in agreement with the conclusion reached by a number of other authors (Richter, 1958; Healy, 1963; Ryall and Stuart, 1963).

The nature of velocity variation in the intermediate layer is unknown, but existence of reflections from the Mohorovičić discontinuity and the long-range refraction data suggest a fairly sharp transition between the intermediate layer and the upper-mantle rocks with velocity of 7.8 km/sec.

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