UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 5

CRUSTAL STRUCTURE ALONG THE COAST OF CALIFORNIA FROM SEISMIC-REFRACTION MEASUREMENTS*

by

J. H. Healy**

DENVER, COLORADO

This page intentionally left blank

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-5
November 9, 1962

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 5

CRUSTAL STRUCTURE ALONG THE COAST OF CALIFORNIA

FROM SEISMIC-REFRACTION MEASUREMENTS*

by

J. 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. 193-62.

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

This page intentionally left blank

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-5
November 9, 1962

CRUSTAL STRUCTURE ALONG THE COAST OF CALIFORNIA FROM SEISMIC-REFRACTION MEASUREMENTS*

by

J. H. Healy**

Abstract. Two reversed seismic-refraction profiles were recorded between Los Angeles and San Francisco in 1961. The three shotpoints were located in Santa Monica Bay, offshore near San Francisco, and at Camp Roberts, about halfway between Los Angeles and San Francisco.

The velocity of P_g along these profiles is 6.1 ± 0.1 km/sec, with possible exceptions near San Francisco and near Los Angeles, where the scatter in the arrival times indicates complex near-surface velocity variations. The velocity of P_n between Los Angeles and Camp Roberts is 8.2 ± 0.1 km/sec, and between Camp Roberts and San Francisco 8.0 ± 0.2 km/sec. There is no indication of an intermediate crustal layer in the traveltimes of first arrivals.

Computed depths to the Mohorovicic discontinuity, if the crust consists of a single layer, are: 35 km at Los Angeles, 23 km at Camp Roberts, and 23 km at San Francisco. Refractions from crustal layers of intermediate velocity need not appear as first arrivals, and in the extreme, the depth to the Mohorovicic discontinuity may be one-third greater than the thickness of a one-layer crust.

* Work performed under ARPA Order No. 193-62.

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

Amplitude measurements on seismograms from the drilled-hole shotpoint at Camp Roberts give the attenuation with distance for P_g as $r^{-1.74}$. The combined data for P_g from the two shotpoints in the ocean give the attenuation with distance as $r^{-2.13}$. The scatter in the measured amplitudes of P_n is too large to determine a rate of attenuation with distance, but the data indicate that attenuation in the 150 to 300 km range is less than r^{-3}.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-5
November 9, 1962

CRUSTAL STRUCTURE ALONG THE COAST OF CALIFORNIA FROM SEISMIC-REFRACTION MEASUREMENTS*

by

J. H. Healy**

Introduction. As part of the Geological Survey's study of crustal structure in the western United States, two seismic-refraction profiles were recorded along the coast of California in November 1961. The work was done as a part of the VELA UNIFORM program of the Advanced Research Projects Agency, Department of Defense. Seismograms recorded along these profiles provide information on the velocities of compressional waves in the crust and upper mantle and depths to the Mohorovicic discontinuity along a segment of the western continental margin of the United States. Seismograms were recorded at 45 places along these lines, and traveltimes were measured from shotpoints at Santa Monica Bay, Camp Roberts, and San Francisco (Fig. 1).

* Work performed under ARPA Order No. 193-62.

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

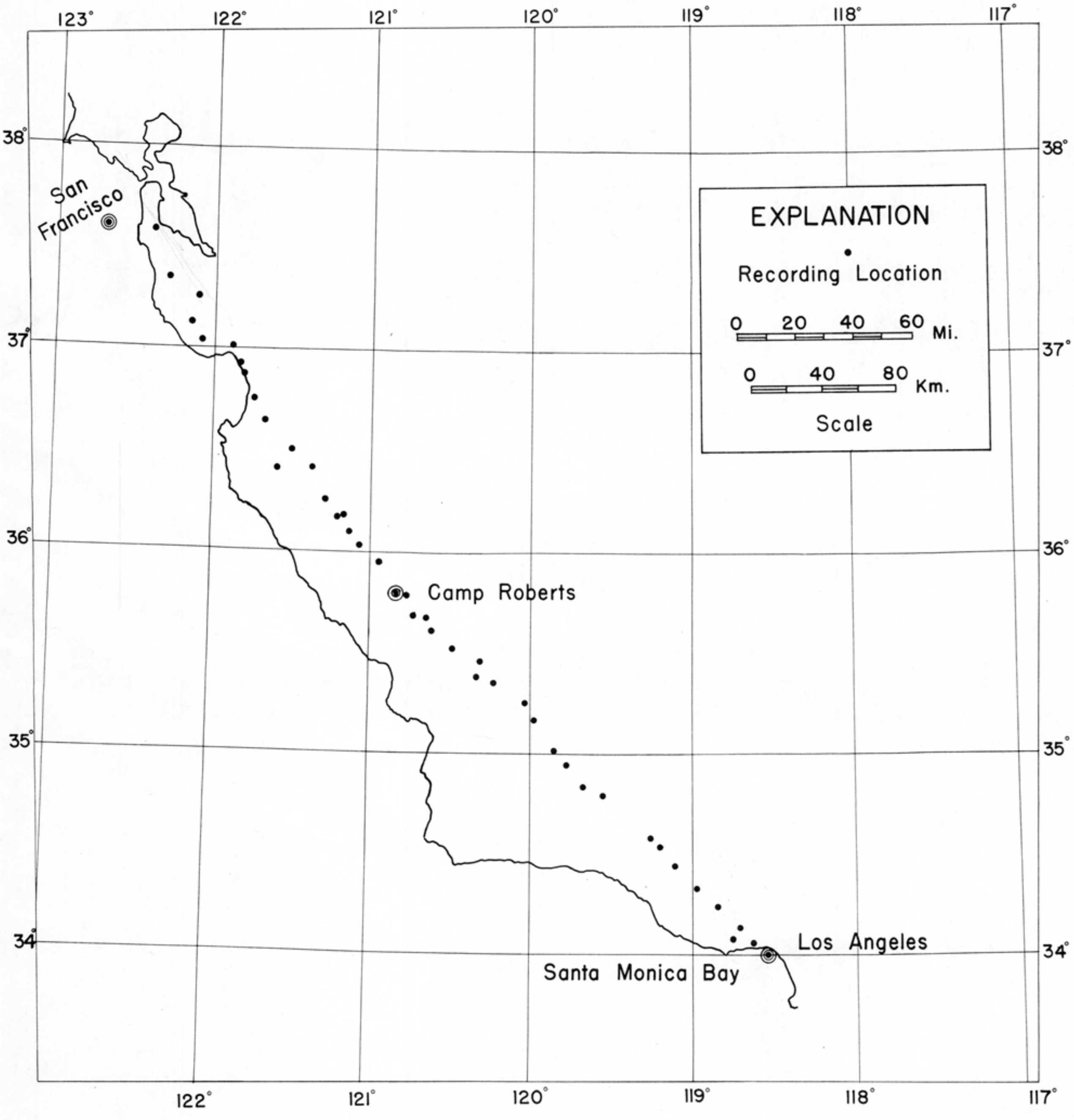

Figure 1 -- Location of shotpoints and recording positions.

Field operations. Ten recording units were used in the field program. Each unit recorded the output of six vertical seismometers and two horizontal seismometers on photographic paper and magnetic tape. Where terrain permitted, the vertical seismometers were placed at 1/2-km intervals to form a 2 1/2-km spread approximately in line with the direction to the shotpoint. Timing was accomplished by recording the output of a WWV receiver, a calibrated chronometer, and the shot instant transmitted by radio from the shotpoint. A description of the instrumentation used has been given by Warrick and others (1961).

The shotpoints at San Francisco and Santa Monica Bay were in the ocean. Operations at both of these offshore shotpoints were conducted from a 70-foot shooting boat, the "Rise and Shine." Fifty-pound cans of Nitramon WW were banded together in groups of ten, primed, and dropped to the ocean floor along a guideline anchored to the bottom (Fig. 2). Two- to six-thousand pounds of explosives were accumulated in a pile at the end of the guideline in this manner, and then fired at a predetermined time.

The shotpoints in the ocean were marked by a system of buoys that were located with respect to coastal landmarks by radar and Loran equipment on the shooting boat. The location of the shotpoints for succeeding shots was accomplished by reference to the system of buoys and by fathometer readings to detect the cavity in the ocean floor caused by earlier shots. The error in location of the offshore shotpoints is estimated to be about 200 meters.

Figure 2 -- Marine offshore shotpoint ocean floor charge loading. As the release hook is disengaged, charge follows the weighted stationary line to the ocean floor.

Shots fired at Camp Roberts, California, were in drilled holes and ranged in size from 2,000 to 10,000 pounds.

Geologic setting. The recordings were made west of the San Andreas fault in a complex geologic setting along the coast of California. King (1959) has summarized the major geologic features and some of the outstanding geologic problems of this region. Only a few aspects of the geology, which may provide insight into problems in interpretation, will be discussed in this paper. The San Andreas fault is recognized as a major tectonic feature with large right-lateral strike slip. The length of the San Andreas and its probable displacement of tens and perhaps hundreds of kilometers suggest that the zone of slippage penetrates into the mantle rocks. It seems reasonable to expect that a fault of this size would produce major changes in crustal structure in the vicinity of the fault zone. In addition to the complications introduced by the San Andreas fault zone, it is probable that the whole coastal province has been fractured by a complex of faults that are only partly revealed by surface geology. Such faulting can cause irregularities in boundaries within the crust, lateral changes in crustal velocities, and anomalous absorption of seismic energy.

The area crossed by these profiles includes large bodies of deformed rocks of Tertiary age lying on a basement of Mesozoic or older rocks. The basement rocks include plutonic bodies similar in composition and age to the rocks of the Sierra Nevada batholith and metamorphic rocks of which the major unit is the Franciscan formation. The diverse rock types and complex structures of the region undoubtedly account for some of the anomalous arrival times that were observed on these profiles.

Accuracy of the data. Timing accuracy of 0.01 second was maintained during recording, and this accuracy is compatible with the precision of timing strong arrivals on the seismograms.

The recording positions were determined by plotting the position on the best available topographic maps. Where topographic maps of the 15-minute or 7-1/2-minute Geological Survey series were available, positions were located to within 0.1 km; where maps were old or inadequate, the positions may be in an error by 1 km with respect to the shotpoint. The accuracy of the apparent velocities, as determined from the traveltime plots, is estimated to be within 0.1 km/sec, except at positions near San Francisco where a much larger error is possible. No attempt was made to compute the probable error in apparent velocities by statistical techniques. The author feels that such determinations are not valid unless there are sufficient data to evaluate causes of error, and to demonstrate that the mean of the error distribution is zero. In this particular set of data, the first motion could not be positively identified beyond 125 km, and it is probable that the mean of the error distribution for P_n arrival times is not zero.

The apparent velocities reported in this paper were determined by visually fitting straight lines to the traveltime data, taking into consideration the quality or degree of certainty of the individual arrivals as well as the scatter in the plotted times. The range of possible error was estimated by shifting straight-line segments on the traveltime plot to determine the range in apparent velocities that might, in the interpreter's judgment, be consistent with the data.

Traveltime data. Profile San Francisco to Camp Roberts (Fig. 3, Table 1a)--First arrivals at recording positions between 25 and 75 km south of the shotpoint at San Francisco are erratic, and time delays from an arbitrary 6.1 km/sec apparent-velocity line are greater than 1 sec. These variations in arrival time are further supported by a recording in Golden Gate Park, 25 km northeast of the shotpoint. In Golden Gate Park, first motion was recorded at 4.5 sec, which leads the arrival time 25 km directly east of the shotpoint at the same distance by almost a second. All possible sources of error have been examined in this distance range. First motion is easily recognizable on all recordings except on the recording 33 km from the shotpoint. Distances and timing were rechecked, and no errors were found.

Time variations of this magnitude over such short distances can only be explained by large changes in the velocity of rocks within a few km of the surface. A possible explanation of the

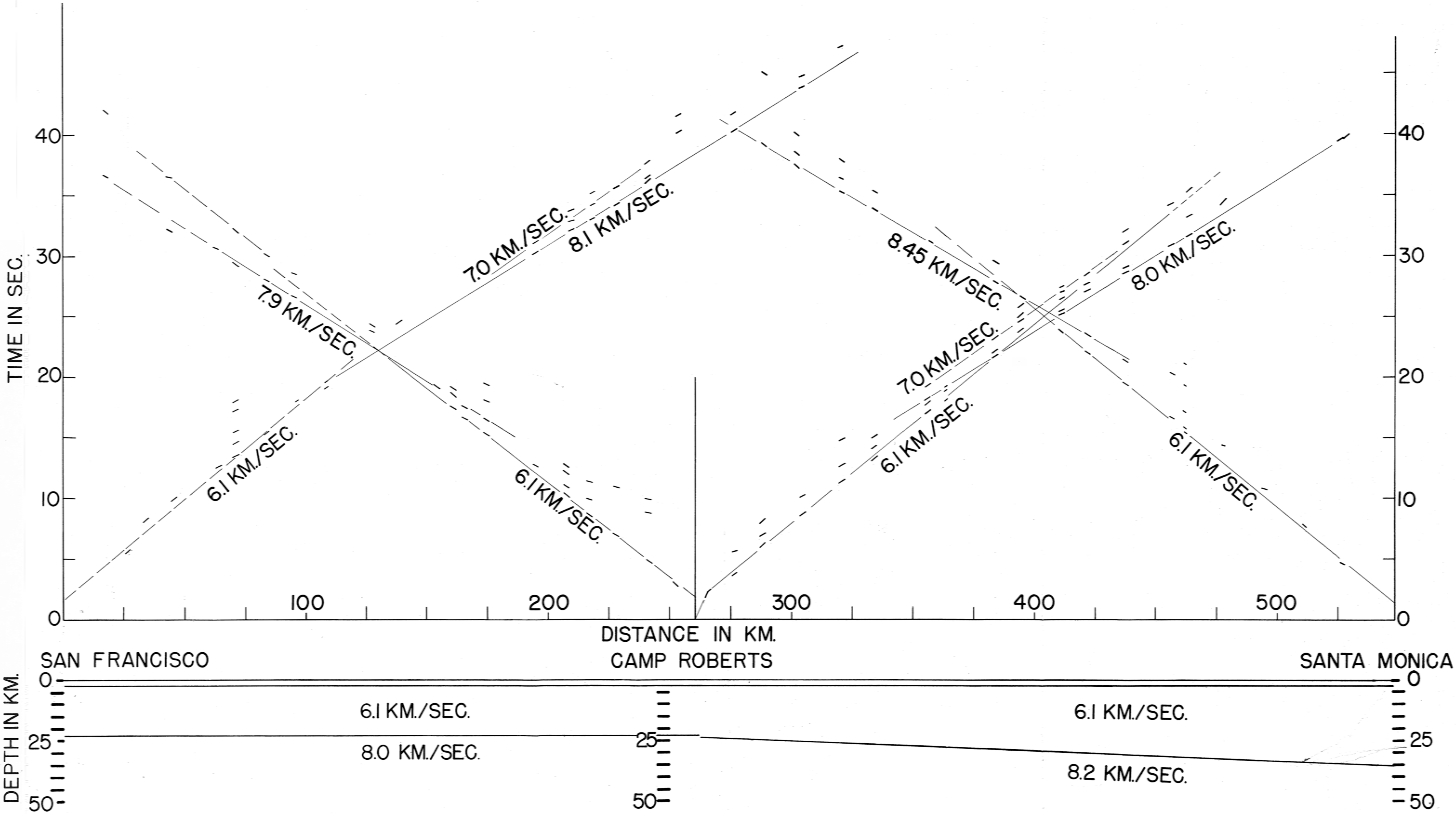

Figure 3 -- Traveltime curve between Santa Monica Bay and San Francisco.

Table 1a.--Times of first arrivals.

Profile: Camp Roberts - San Francisco
Latitude of S.P.: 36°47.38'
Longitude of S.P.: 120°49.98'

Distance to recording unit, km	Latitude	Longitude	Time of First arrival, sec
6.5	35°50.90'	120°50.85'	2.62
20.1	35°56.66'	120°57.30'	4.69
33.3	36°01.42'	121°04.05'	6.86
44.2	36°05.78'	121°08.85'	8.41
51.5	36°09.22'	121°11.36'	10.00
66.5	36°15.58'	121°17.65'	12.35
82.1	36°23.50'	121°21.95'	15.14
93.6	36°22.98'	121°34.45'	16.47
99.2	36°23.72'	121°38.70'	17.36
104.6	36°32.42'	121°32.35'	19.03
131.4	36°43.18'	121°44.43'	23.76
149.4	36°52.46'	121°49.30'	20.16
163.5	36°59.30'	121°53.00'	28.78
177.7	37°01.52'	122°05.78'	27.91
187.9	37°06.64'	122°08.82'	29.15
196.4	37°14.00'	122°06.18'	30.565
214.9	37°19.52'	122°16.75'	32.05
242.9	37°34.54'	122°24.40'	36.44

Table 1b.--Times of first arrivals (continued).

Profile: San Francisco - Camp Roberts
Latitude of S.P.: 37°36.08'
Longitude of S.P.: 122°41.55'

Distance to recording unit, km	Latitude	Longitude	Time of First arrival, sec
25.4	37°34.54'	122°24.40'	5.49
47.7	37°19.52'	122°16.75'	9.78
82.9	37°01.52'	122°05.73'	15.21
98.8	36°59.30'	121°53.00'	17.90
129.3	36°43.18'	121°44.43'	22.90
140.0	36°38.36'	121°40.37'	24.425
179.2	36°23.50'	121°21.95'	29.79
194.1	36°15.58'	121°17.65'	30.10
210.2	36°09.56'	121°09.90'	32.055
217.0	36°05.78'	121°08.85'	32.94
227.4	36°01.42'	121°04.05'	34.11
240.5	35°56.66'	120°57.30'	35.91
275.1	35°40.80'	120°44.89'	40.07
303.5	35°31.40'	120°29.34'	43.715

Table 1c.--Times of first arrivals (continued).

Profile: Camp Roberts - Santa Monica Bay
Latitude of S.P.: 35°47.46'
Longitude of S.P.: 120°49.98'

Distance to recording unit, km	Latitude	Longitude	Time of First arrival, sec
4.4	35°46.81'	120°47.10'	1.85
17.6	35°40.05'	120°43.50'	3.56
42.9	35°31.40'	120°29.34'	8.51
61.8	35°26.31'	120°18.15'	11.19
72.5	35°21.08'	120°14.38'	13.09
96.7	35°13.51'	120°01.25'	16.90
105.4	35°09.34'	119°58.06'	17.93
121.9	35°01.69'	119°51.86'	21.56
132.8	34°57.38'	119°46.98'	23.42
149.5	34°50.35'	119°40.15'	25.13
159.9	34°47.21'	119°34.17'	26.97
178.3	34°42.26'	119°23.37'	28.50
194.3	34°34.22'	119°16.67'	32.62
202.1	34°32.20'	119°13.39'	31.58
215.5	34°26.88'	119°07.05'	34.11
235.0	34°19.36'	118°58.50'	41.09
251.3	34°13.51'	118°50.55'	41.80
264.3	34°08.17'	118°43.45'	39.44
269.1	34°04.40'	118°45.18'	39.62

Table 1d.--Times of first arrivals (concluded).

Profile: Santa Monica Bay - Camp Roberts
Latitude of S.P.: 34°00.06'
Longitude of S.P.: 118°33.28'

Distance to recording unit, km	Latitude	Longitude	Time of First arrival, sec
19.1	34°04.40'	118°45.18'	4.57
21.6	34°08.17'	118°43.45'	4.815
36.3	34°13.51'	118°50.55'	7.64
52.6	34°19.36'	118°58.50'	10.75
71.7	34°26.88'	119°07.05'	14.32
85.5	34°32.20'	119°13.39'	15.38
92.7	34°35.22'	119°16.67'	16.57
109.6	34°42.26'	119°23.37'	19.35
127.6	34°47.21'	119°34.17'	21.90
138.3	34°50.35'	119°40.15'	23.69
154.7	34°57.38'	119°46.98'	26.37
165.6	35°01.69'	119°51.86'	27.64
182.2	35°09.34'	119°58.06'	30.44
190.0	35°13.51'	120°01.25'	30.99
215.1	35°21.08'	120°14.38'	33.61
225.9	35°26.31'	120°18.15'	35.14
244.6	35°31.40'	120°29.34'	37.18
260.4	35°36.94'	120°37.30'	38.90
271.2	35°40.05'	120°43.50'	40.09

observed time delays is the contrast in velocity between Cenozoic sedimentary rocks and the older granitic and metamorphic rocks in the area, or the velocity contrast between the metamorphic Franciscan formation and granitic basement rocks. Cameron (1961), in a study of earthquakes in northern California, reported strong arrivals through the Franciscan at a velocity of 5.1 km/sec, and a velocity through rocks below the Franciscan of 5.95 km/sec.

The scatter in velocities makes it impossible to determine the velocity of P_g without short refraction profiles. An apparent velocity of 6.1 km/sec with an intercept time of 1.7 sec fits the data reasonably well, and four spreads at distances between 82 and 113 km support the 6.1 km/sec apparent velocity. This velocity will be adopted in interpreting the traveltime data.

From 113 to 195 km, the line of the profile ran near the shore at Monterey Bay and then down Salinas Valley, where high seismic noise prevented the recording of satisfactory seismograms.

Between 195 and 255 km, clear arrivals were recorded at six locations. This part of the traveltime curve can be fitted by apparent-velocity lines ranging between 7.8 and 8.2 km/sec. The best fit is an apparent velocity slightly less than 8.1 km/sec. The intercept times for these apparent velocities are between 5.1 and 6.2 sec, with the 8.1 km/sec line giving an intercept time of 5.7 sec. At 275 km, a clearly-recorded arrival falls on the 8.1 km/sec apparent-velocity line, and at 302 km, a questionable arrival falls on this line. These distant recordings support the 8.1 km/sec apparent velocity.

Profile Camp Roberts to San Francisco (Fig. 3, Table 1b)--Good first arrivals were recorded on six spreads from 0 to 60 km from the shotpoint at Camp Roberts. A 6.1 km/sec apparent velocity fits the six arrival times with a maximum departure from the line of 0.2 sec, and the estimated error in velocity is less than 0.1 km/sec. Between 85 and 110 km, four spreads have erratic arrival times. First motion could not be determined in this range, but the recorded arrivals are strong and show clear line-up across the seismograms. From 110 to 175 km, the recordings were made in Salinas Valley or near the coast at Monterey Bay, and the high noise level prevented the recording of useable seismograms. Between 175 and 240 km, 5 units recorded clear arrivals. The seismograms from these units show erratic arrival times, and it is not possible to determine a precise apparent velocity.

Erratic arrival times were also recorded at these locations from the shotpoint at San Francisco. A more detailed study of near-surface velocities is needed for a refined interpretation of this section of the profile.

Profile Camp Roberts to Santa Monica Bay (Fig. 3, Table 1c)--Between 5 and 100 km southeast of the shotpoint at Camp Roberts, seven units recorded good arrivals. Traveltimes of these arrivals can be fitted with an apparent-velocity line of 6.1 km/sec. The maximum residual from this line is 0.3 sec. Between 120 and 205 km, six units recorded well-defined arrivals. Traveltimes of these arrivals can be approximately fitted to an apparent-velocity line of 8.1 km/sec with an intercept time of 6.3 sec. However, the scatter in the arrival times indicates a possible error as large as 0.2 km/sec in the apparent velocity. South of 200 km from the shotpoint the profile extended into the densely-populated areas of southern California, where it was difficult to find quiet recording locations. One good recording was made at 270 km, and it shows clear arrivals falling on the 8.1 km/sec line.

Profile Santa Monica Bay to Camp Roberts (Fig. 3, Table 1d)--The arrival times at positions out to about 80 km from the shotpoint in Santa Monica Bay revealed a scatter similar to that found near the shotpoint at San Francisco. On the profile from Santa Monica Bay to Camp Roberts, it would be possible to fit times of first arrivals in the distance range 10 to 75 km with an apparent velocity of 5.5 ± 0.2 km/sec, and arrivals in the distance range 75 to 135 km with an apparent velocity of 6.3 to 6.5 km/sec. However, these traveltimes might also represent seismic waves traveling in an underlying layer with a true velocity of 6.1 km/sec and then upward through near-surface rocks of low velocity and varying thickness. The delays would thus be related to the complex geology in this region, as they are near San Francisco. Although the refraction data available do not justify a selection between these two possible interpretations, an arbitrary 6.1 km/sec apparent velocity was drawn through these traveltimes. Between 80 and 160 km, five traveltimes fall reasonably close to the apparent-velocity line of 6.1 km/sec. Between 165 and 300 km, the arrival times recorded at five spreads fall within 0.1 sec of an 8.45 km/sec apparent velocity.

Secondary arrivals. Strong secondary arrivals were recorded on all profiles. From 0 to 100 km, many events with apparent surface velocities appropriate for reflections were recorded on individual seismograms, and between 50 and 300 km events that could represent refractions from intermediate layers were found. Considerable effort to correlate these events between adjoining seismograms met with limited success. Two sets of arrivals that indicate a possible 7.0 km/sec layer, and a number of isolated events that are probably reflected arrivals, are shown on the traveltime graph (Fig. 3).

Interpretation of traveltimes. The traveltime data (Table 1) were fitted with straight-line velocity segments (Table 2).

These numerical approximations provide a reasonable fit to the traveltime data except at points near San Francisco. The region near San Francisco has been studied in more detail by a group at the University of California (A. S. Ryall, written communication), and their work confirms the structural complexity of the region.

Because there is no clear indication of crustal layers of intermediate velocity in the traveltime data, the simplest model that is consistent with the times of first arrivals is a one-layer crust with a thin low-velocity layer at the surface. The intercept times of P_g range between 1.3 and 1.7 seconds, with an average of 1.5 sec. A uniform surface layer 2.6 km thick with a velocity of 3.0 km/sec would have this average intercept time and will be accepted as a reasonable first approximation to the near-surface velocity structure.

Table 2.--Traveltimes for P_g and P_n

from first arrivals

Profile	P_g	P_n
San Francisco to Camp Roberts	$T_{pg} = 1.7 + \Delta/6.1$ sec	$T_{pn} = 5.7 + \Delta/8.05$ sec
Camp Roberts to San Francisco	$T_{pg} = 1.5 + \Delta/6.1$ sec	$T_{pn} = 5.7 + \Delta/7.9$ sec
Camp Roberts to Santa Monica	$T_{pg} = 1.3 + \Delta/6.1$ sec	$T_{pn} = 6.25 + \Delta/8.05$ sec
Santa Monica to Camp Roberts	$T_{pg} = 1.6 + \Delta/6.1$ sec	$T_{pn} = 7.8 + \Delta/8.45$ sec

Using the assumed near-surface layer, the traveltimes in Table 2, and the assumption of a one-layer crust, the depth to Mohorovicic discontinuity is 23 km at San Francisco, 23 km at Camp Roberts, and 35 km at Los Angeles (Table 3). The velocity of P_n between San Francisco and Camp Roberts is 8.0 km per sec with an estimated maximum error of 0.2 km/sec. The velocity of P_n between Camp Roberts and Los Angeles is 8.2 km/sec with an estimated error of 0.1 km/sec.

The effect of intermediate layers. To illustrate the effect of masked intermediate layers, it is convenient to adopt simplified traveltime models without dip. Various velocity models with intermediate layers that are consistent with two traveltime segments can be devised (Table 3). One traveltime model matches approximately the crustal structure at Camp Roberts without dip; it has a thin low-velocity layer at the surface and two branches of the traveltime curve, one with a velocity of 6.1 km/sec and an intercept time of 1.5 sec, and a second with a velocity of 8.1 km/sec and an intercept time of 6.0 sec. The second traveltime model has no low-velocity layer at the surface; it has only two traveltime branches, one with a velocity of 6.1 km/sec and an intercept time of zero, a second with a velocity of 8.1 km/sec and an intercept time of 6.0 sec.

Any layer, whose velocity line passes through the intersection of the 6.1 and 8.1 km/sec lines could be present at depth and avoid detection in analysis of first arrival times. Furthermore, it is possible that the energy associated with such a masked layer might not be detectable as secondary arrivals.

Table 3.--Effect of intermediate layers on crustal thickness illustrated with simplified traveltime models.

Layer	Intercept time	Compressional-wave velocity, km/sec	Depth to bottom of layer, km
1	0 sec	3.0	2.58
2	1.5	6.1	22.98
3	6.0	8.1	
1	0	3.0	2.58
2	1.5	6.1	16.72
3	3.83	7.0	26.12
4	6.0	8.1	
1	0	6.1	27.814
2	6.0	8.1	
1	0	6.1	19.46
2	3.13	7.0	31.99
3	6.0	8.1	
1	0.000	6.10	3.73
2	0.122	6.13	5.92
.			
.			
.			
49	5.878	8.05	37.00
50	6.000	8.1	

Working on this principle, a model was constructed by inserting an intermediate layer of 7 km/sec velocity, for which there is some evidence on the traveltime curve, with an intercept time adjusted so that this layer passes through the critical distance at the critical time. This intermediate layer increases the depth from 23 to 26 km (Table 3). By continuing this process of adding intermediate layers, all of which have intercept times and velocities such that they pass through the critical distance at the critical time, it is possible to devise a model that will yield the approximate maximum depth consistent with a two-branch traveltime curve (Fig. 4, Table 3).

A program was written for the Geological Survey's Burroughs 220 computer to compute the structure for a model with 50 layers. When 50 layers are inserted such that they have equal increments of intercept time and all pass through the intersection of P_g and P_n, the series of layers converges to a continuous-velocity function that was computed by Slichter (1932). In Slichter's solution, all of the rays emerge at a common point. The velocity-depth function for this model is:

$$v = V_0 \cosh \frac{\pi z}{X_c}$$

where:

V_0 is the velocity at zero depth,

v is the velocity at depth z,

and,

X_c is the critical distance.

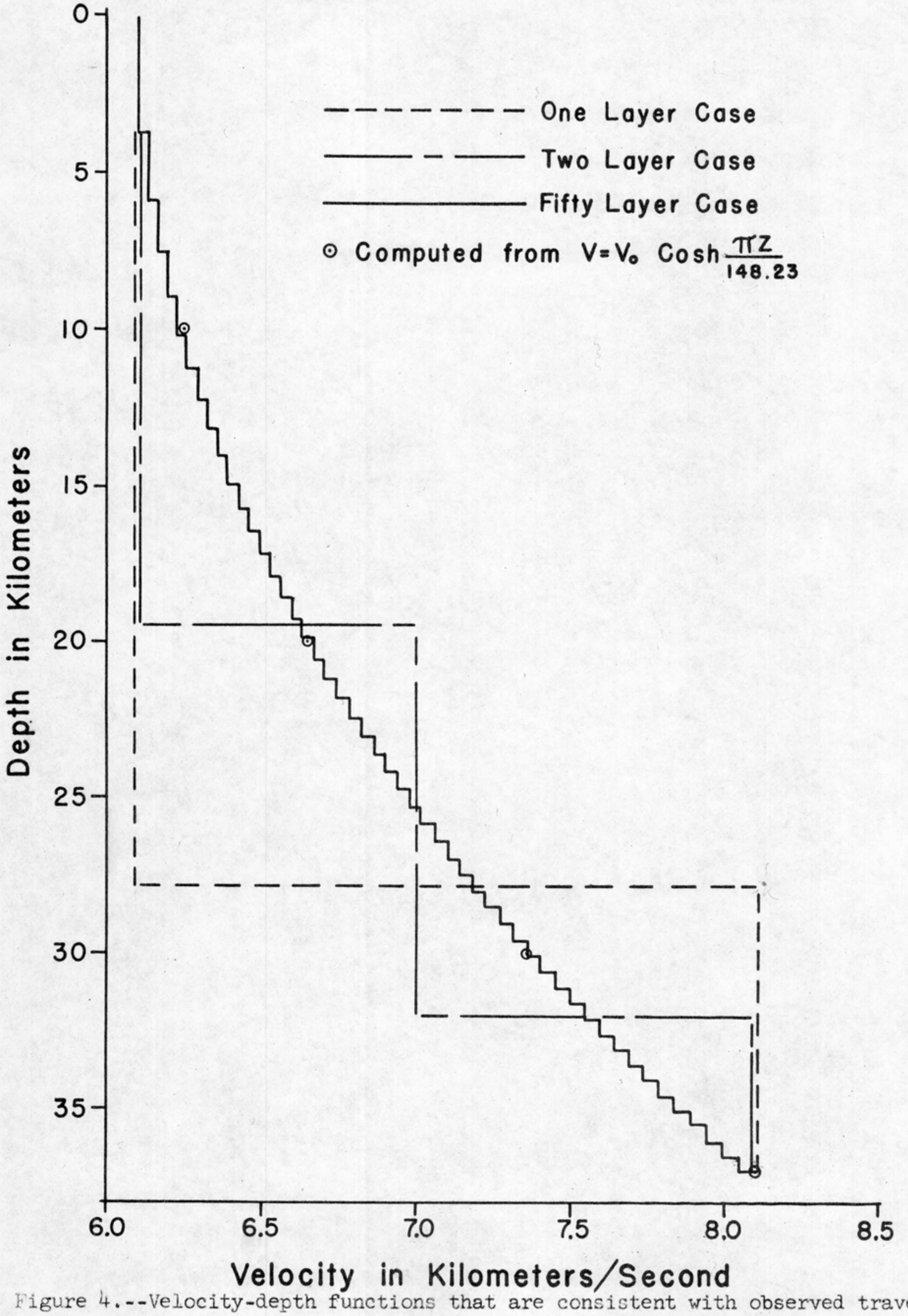

Figure 4.--Velocity-depth functions that are consistent with observed traveltimes.

Computations such as these give an estimate of the minimum and maximum crustal thickness consistent with the observed two-branch first-arrival traveltime curve. For the example, based on a two-branch traveltime curve, crustal thickness for a one-layer crust is 27.8 km and for a 50-layer crust the thickness is 37.0 km (Fig. 4, Table 3). The objection may be raised that the continuous increase of velocity with depth associated with the 50-layer case is not physically reasonable; neither is the more usual assumption of a crust of uniform velocity. The true physical model must lie somewhere between these two extremes, which give maximum and minimum crustal thicknesses, assuming, of course, that velocity is either constant or increases with depth.

Amplitudes. A determination of amplitude was made on all seismograms on which the first energy was sufficiently above noise to permit a reliable measurement. Two parameters were measured: the amplitude of the first motion and the maximum amplitude, peak-to-peak, in the first few cycles. Amplitudes were scaled to a 2,000-pound charge on the assumption that amplitude is a linear function of charge size.

The results from the shotpoints in water were plotted separately from the drilled-hole shotpoint at Camp Roberts. From the Santa Monica Bay and San Francisco shotpoints, the amplitude of the first motion decays as $r^{-1.74}$ to a distance of 130 km (Fig. 5). Results from Camp Roberts show a decay as $r^{-2.13}$ (Fig. 6). When measurements

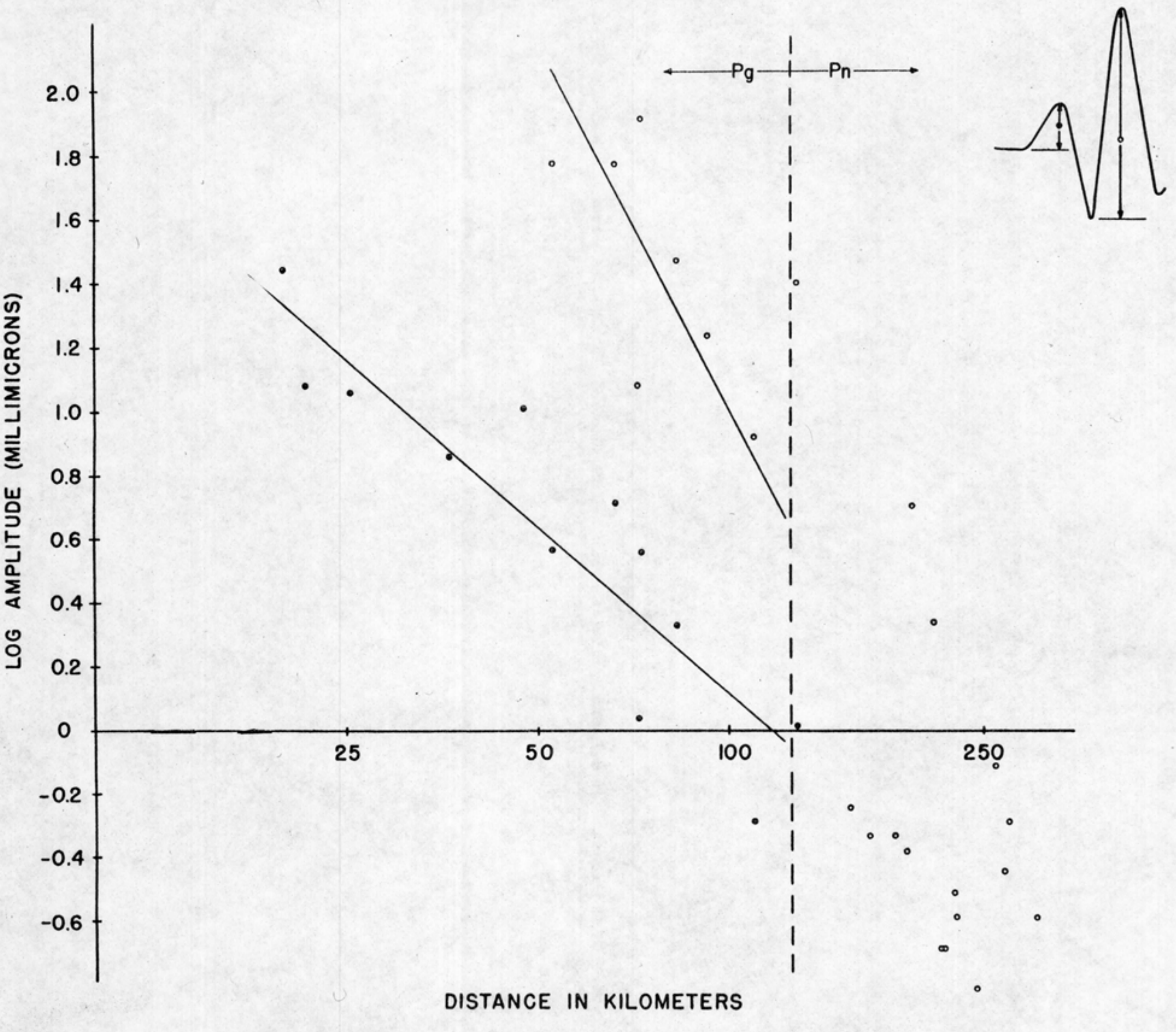

Figure 5.--Amplitudes from shotpoints at San Francisco and Los Angeles.

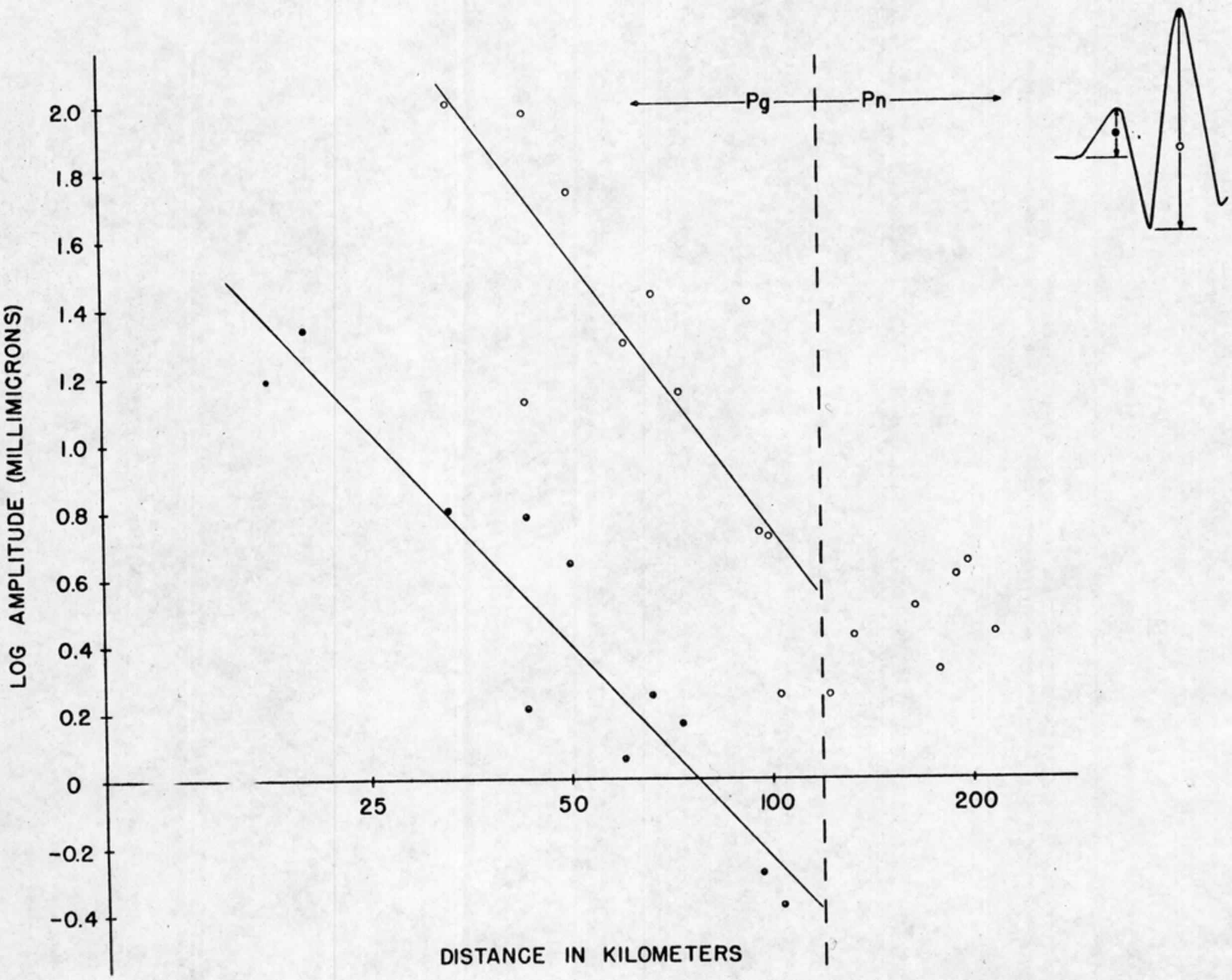

Figure 6.--Amplitudes from shotpoints at Camp Roberts, California.

are made of the maximum amplitude in the first few cycles, the corresponding attenuation rates are $r^{-3.84}$ from Camp Roberts and $r^{-2.68}$ from the offshore shotpoints.

The scatter in the amplitudes of P_n arrivals is large, and an attenuation rate cannot be determined from the data. P_n may actually increase in amplitude with distance over the range of 135 to 250 km.

The scatter observed in the amplitudes is about what would be expected from variations in "ground factor" (Gutenberg, 1957). Other sources of error are the use of a linear-scaling relation between amplitudes and charge sizes, and interference patterns in the arrivals which make it impossible to make measurements on the same phase on each seismogram. The difference in the rate of attenuation between the water shotpoints and the drilled-hole shotpoint is an indication of the magnitude of scatter in the amplitude measurements. The data available are not adequate for an evaluation of the causes of this scatter.

If the rate of amplitude attenuation for P_g between 0 and 125 km is extended to greater distances, where P_g is a secondary arrival, the P_g phase would be masked by the background "reverberation" or the arrival of phases with larger amplitudes. This fact raises questions about the nature of the phases that have been identified as P_g at large distances on earthquake seismograms. Either the amplitude attenuation of P_g with distance is a function of source depth or there is a different mode of propagation for the distant P_g phase as compared with the "direct" P_g at near distances. It is suggested that the secondary phase identified as $\overline{P}$ by early investigators is not the "direct" wave but is probably a phase reflected from a boundary within the crust.

<u>Comparison with earlier results</u>. Byerly (1939) reported speeds of $\overline{P}$ and P_n for central California of 5.61 km/sec and 8.02 km/sec. He also found evidence for two intermediate layers with velocities of 6.72 and 7.24 km/sec. Byerly established the $\overline{P}$ velocities using stations and earthquakes in the vicinity of San Francisco. The P_n velocities and velocities of the intermediate layers were established by using data from the southern California and the central California networks of seismic stations. Thus his $\overline{P}$ velocity will be valid for the localized region around San Francisco, and his P_n and intermediate velocities are a rough average of these velocities over California.

Ryall (1962) reported that the speed of P_n under the University of California network in central California is 7.81 km/sec and that the crust thins toward the coast.

Cameron (1961) studied traveltimes in northern California and reported a crustal structure consisting of a "sedimentary" layer 3 km thick of velocity 5.1 km/sec; a granitic layer 21 km thick of velocity 5.95 km/sec; and a basaltic layer 5 km thick of velocity 6.93 km/sec. The total depth to the Mohorovicic discontinuity was determined to be 29 km, and the velocity of P_n

was determined to be 7.98 km/sec. The traveltimes of P_n from this structure with a surface-source are approximated by the equation:

$$T_{Pn} = 6.2 + \Delta/7.98.$$

R. Hamilton (oral communication) reports an apparent speed of P_n for seismic waves traveling north from Salinas, California, of 8.08 km/sec. Tatel and Tuve (1955) reported a crustal thickness of 23 km along the coast of California.

An early study of crustal structure in southern California from earthquake seismograms (Gutenberg, 1944) reported the following velocities: $\overline{P} = \Delta/5.577$, $P_y = 1.2 + \Delta/6.047$, and $P_n = 6 + \Delta/8.06$ (in coastal areas). In contrast to Byerly's work in central California, $\overline{P}$ and P_y were usually picked at distances where they occurred as secondary arrivals. The assumption that the phase $\overline{P}$, with a velocity of 5.577 km/sec, was a direct arrival through the crustal layers near the surface had to be abandoned when it was shown that the first arrivals from blasts had a velocity near 6 km/sec (Gutenberg, 1951).

Richter (1958) describes the changes in the interpretation of the observed traveltimes in southern California that resulted from this contradiction.

The phase identified by Gutenberg (1944) as P_y has a traveltime that is very close to the traveltime of P_g reported in this paper, and the traveltime of P_n reported by Gutenberg is a fair average of the traveltimes of P_n along the coast of California. It is unfortunate that the 5.577 $\overline{P}$ velocity measured by Gutenberg (1944) was so close to the 5.61 $\overline{P}$ velocity determined by Byerly (1939). As it appears now, Byerly's measurements were correct, but were representative of an anomalous low-speed region in the vicinity of San Francisco. Gutenberg's measurements followed a secondary phase that was not an extension of the first arrival at near distances. This apparent agreement between the two investigators supported the idea that the direct-wave velocity was close to 5.6 km/sec over most of California. When the difficulty concerning the $\overline{P}$ velocity is recognized, these early results compare favorably with modern seismic-refraction data.

Because no single geophysical method provides an unambiguous solution to crustal structure, Press (1960) recommended the combined use of seismic-refraction, gravity, and surface wave phase-velocity data. Evernden (1954) measured the phase velocity of Rayleigh waves across a triangular net near San Francisco, and Press (1957) determined crustal thickness as 30 km from Evernden's data on the assumption that the crust is similar to the standard continental crust taken to have a thickness of 35 km. Using this same method with data from the California Institute of Technology network of stations in southern California, Press (1956) computed a crustal thickness of 35 km. This value for southern California agrees with the crustal thickness determined from refraction measurements, but the central California value gives a crustal thickness about 7 km greater than that determined from refraction measurements. Recognition of the fact that the measured velocities near San Francisco in the crust and in the mantle are somewhat lower than the average continental values will force the use of a thinner crust to fit the phase-velocity data. The San Andreas fault, which separates the triangle over which the phase velocities were measured from the line of the refraction profile, might account for a sudden change of crustal structure between the location of the phase velocity measurements and the location of the refraction measurements. These factors appear to be adequate to account for the discrepancy in crustal thickness as determined from refraction measurements and phase velocity data at San Francisco.

The gravity anomalies along the refraction profile express the complex geology and topography of the region; however, a compilation of the free-air gravity anomaly indicates that the average free-air anomaly is near zero. An average free-air anomaly of zero, of course, implies that the region on the average is in isostatic equilibrium. Once this conclusion has been reached, further analysis, using an average Bouguer anomaly, is meaningless because the difference between the free-air anomaly and the Bouguer anomaly is a function only of the topography and an assumed density. Further information about the detailed structure of the crust might be gained by study of the shape of the Bouguer anomaly in the coastal region, but such a study is beyond the scope of this paper. Tsuboi (1956) made a preliminary effort to analyze the shape of the gravity anomaly along the coast of California and determined a depth of 24 km to the Mohorovicic discontinuity at the coast.

Summary. Two seismic-refraction profiles were successfully recorded in a difficult area along the coast of California between San Francisco and Los Angeles. The successful completion of this project demonstrates the feasibility of conducting crustal refraction studies in densely-populated regions.

The velocity structure is complex near San Francisco. The data suggest that metamorphic and sedimentary rocks with velocities of 5.6 km/sec or lower overlie, in irregular masses, crustal rocks with velocities near 6.1 km/sec. The velocity of P_n determined between San Francisco and Camp Roberts is 8.0 km/sec; however, the irregular near-surface velocity structure in the vicinity of San Francisco introduces uncertainties into this measurement. For about 150 km in either direction from Camp Roberts, California, the velocity of P_g is 6.1 km/sec. In southern California the velocity of P_g is confused by complex near-surface geology. Rocks with a velocity of 6.1 km/sec, underlying irregular basin structures filled with low-velocity sediments adequately explain the traveltime data.

The depth to the Mohorovicic discontinuity increases from about 23 km at Camp Roberts to 35 km at Los Angeles. This dip is confirmed by the apparent speeds of P_n recorded along the profile, and a true velocity of 8.2 km/sec is indicated for the P_n phase. The evidence for intermediate velocity layers in the crust in this region is not conclusive; however, it seems likely that there is some increase in velocity with depth. The presence of intermediate layers could increase the computed depth to the Mohorovicic discontinuity by 3 to 5 kilometers.

Amplitude measurements for the P_g phase show an attenuation with distance as $r^{-1.74}$ from the drilled-hole shotpoint and $r^{-2.13}$ from the water shotpoints.

REFERENCES

Byerly, P., Near earthquakes in central California, _Bull. Seism. Soc. Am._, _29_, 427-462, 1939.

Cameron, J. B., Earthquakes in the northern California coastal region (Part 1), _Bull. Seism. Soc. Am._, _51_, 203-221, 1961.

Cameron, J. B., Earthquakes in the northern California coastal region (Part 2), _Bull. Seism. Soc. Am._, _51_, 203-221, 1961.

Evernden, J. F., Direction of approach of Rayleigh Waves and related problems (Part 2), _Bull. Seism. Soc. Am._, _44_, 159-182, 1954.

Gutenberg, B., Traveltimes of principle P and S phases over small distances in southern California, _Bull. Seism. Soc. Am._, _34_, 13-32, 1944.

Gutenberg, B., Traveltimes from blasts in southern California, _Bull. Seism. Soc. Am._, _51_, 5-12, 1951.

Gutenberg, B., Effects of ground on earthquake motion, _Bull. Seism. Soc. Am._, _47_, 221-250, 1957.

King, P. B., The evolution of North America, _Princeton University Press_, 1959.

Press, F., The determination of crustal structure from the phase velocity of Rayleigh waves (Part I), _Bull. Geol. Soc. Am._, _67_, 1647-1658, 1956.

Press, F., The determination of crustal structure from the phase velocity of Rayleigh waves (Part II), _Bull. Seism. Soc. Am._, _47_, 2-3, 1957.

REFERENCES (Continued)

Press, F., Crustal structure in the California-Nevada region, *J. Geophys. Res.*, *65*, 1039-1051, 1960.

Ryall, A. S., The Hebgen Lake, Montana, earthquake of August 18, 1959: P Waves, *Bull. Seism. Soc. Am.*, *52*, 235-271, 1962.

Richter, C. F., Elementary Seismology, *W. H. Freeman and Company, San Francisco*, *286*, 1958.

Slichter, L. B., The theory of the interpretation of seismic travel-time curves in horizontal structures, *Physics*, *3*, 273-295, 1932.

Tatel, H. E., and M. A. Tuve, Seismic exploration of the continental crust *in* Crust of the Earth (Poldervaart, ed.), *Geol. Soc. Am., Special Paper* *62*, 35-50, 1955.

Tsuboi, C., Crustal structure in northern and middle California from gravity and pendulum data, *Bull. Geol. Soc. Am.*, *67*, 1956.

Warrick, R. E., D. B. Hoover, W. H. Jackson, L. C. Pakiser, and J. C. Roller, The specification and testing of a seismic-refraction system for crustal studies, *Geophysics*, *26*, 820-824, 1961.