UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 19

CRUSTAL STRUCTURE IN THE EASTERN COLORADO PLATEAUS PROVINCE FROM SEISMIC-REFRACTION MEASUREMENTS*

by

John C. Roller**

DENVER, COLORADO

This page intentionally left blank

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-19
June 15, 1964

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 19

CRUSTAL STRUCTURE IN THE EASTERN COLORADO PLATEAUS PROVINCE FROM SEISMIC-REFRACTION MEASUREMENTS*

by

John C. Roller**

Sincerely,

L. C. Pakiser

L. C. Pakiser, Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-63.
** U. S. Geological Survey, Denver, Colorado.

This page intentionally left blank

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-19
June 15, 1964

CRUSTAL STRUCTURE IN THE EASTERN COLORADO PLATEAUS PROVINCE FROM SEISMIC-REFRACTION MEASUREMENTS*

by

John C. Roller**

ABSTRACT

A reversed seismic-refraction profile was recorded in the Colorado Plateaus Province from Hanksville, Utah, to Chinle, Arizona. The velocity of P_g is 6.2 km/sec, and the true velocity of P_n is 7.8 km/sec. Waves identified as reflections indicate that an intermediate layer in the crust has a velocity of approximately 6.8 km/sec. Thickness of the crust is 43 km at Chinle and 40 km at Hanksville. The P_n velocity in the Colorado Plateaus Province is the same as that in the Basin and Range Province, but is significantly lower than P_n in the High Plains of Colorado.

* Work performed under ARPA Order No. 193-63.
** U. S. Geological Survey, Denver, Colorado.

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-19
June 15, 1964

CRUSTAL STRUCTURE IN THE EASTERN COLORADO PLATEAUS PROVINCE FROM SEISMIC-REFRACTION MEASUREMENTS*

by

John C. Roller**

INTRODUCTION

The U. S. Geological Survey recorded a reversed seismic-refraction profile between Hanksville, Utah, and Chinle, Arizona, in June 1963 (Fig. 1). Seismic waves generated by four chemical explosions at Chinle and three at Hanksville were recorded on 67 seismograms along a line 296.23 km in length (Table 1, Fig. 1). Charges ranging in size from 2,000 to 10,000 lbs were fired in drill holes approximately 200 ft deep. Ten seismic-recording units (Warrick and others, 1961) were used to make the recordings with the field procedures described by Jackson and others (1963).

* Work performed under ARPA Order No. 193-63.
** U. S. Geological Survey, Denver, Colorado.

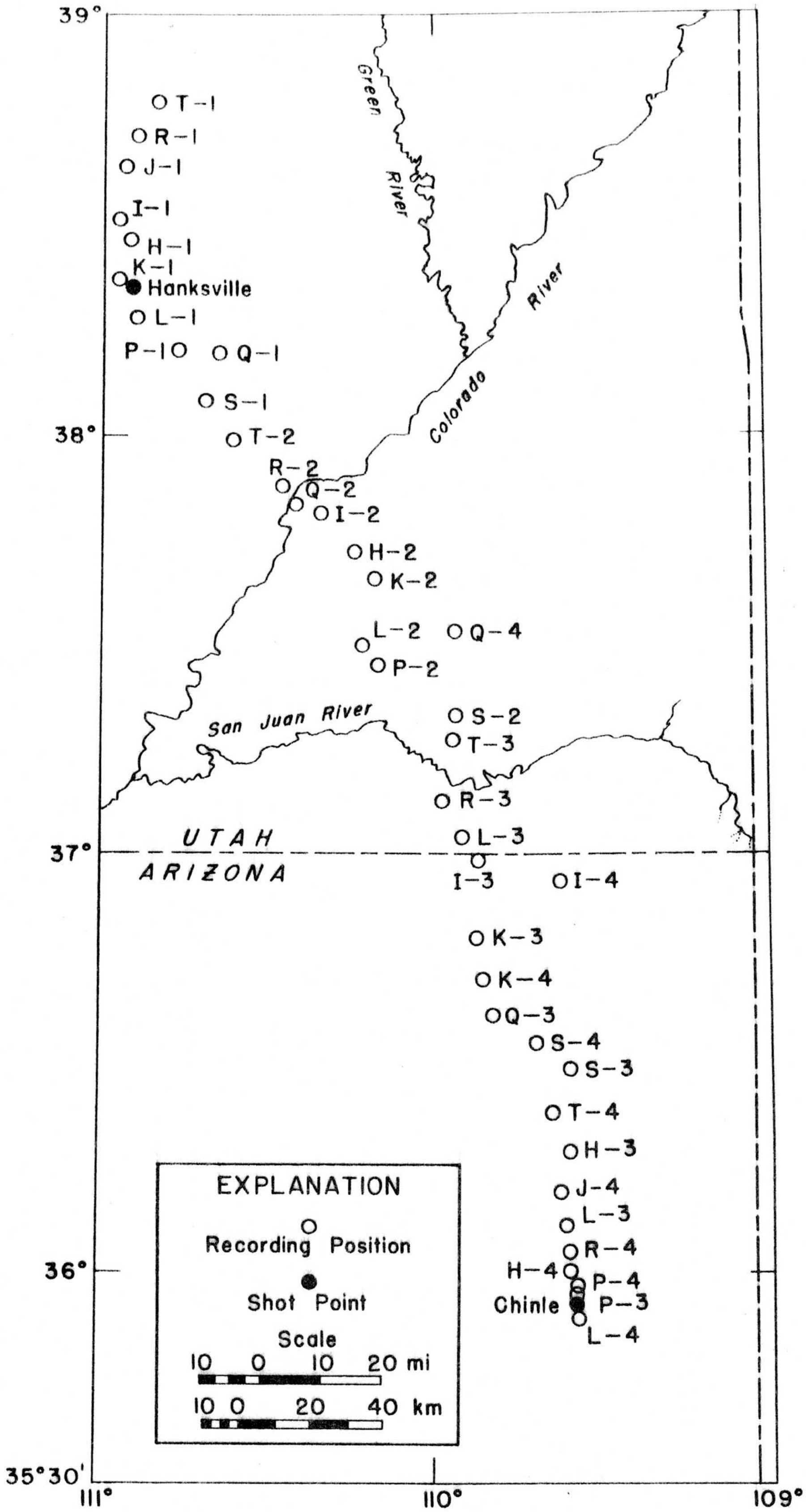

Figure 1.--Index map showing locations of shotpoints and recording positions. Location numbers refer to Chinle shot numbers.

Table 1.--Shotpoint and recording locations

	Latitude, North	Longitude, West	Elevation, Meters
Hanksville shotpoint	38°21.99'	110°55.44'	1480
Chinle shotpoint	35°54.64'	109°34.44'	1860

Shot: Hanksville 2, 2,000 lbs, Chinle 1, 6,000 lbs

Unit	Latitude, North	Longitude, West	Elevation, Meters
H	38°27.72'	110°53.38'	1400
I	38°30.59'	110°55.20'	1550
J	38°38.26'	110°54.48'	1950
K	38°21.97'	110°55.54'	1480
L	38°17.28'	110°52.34'	1570
P	38°12.18'	110°44.79'	1700
Q	38°11.77'	110°37.86'	1590
R	38°41.47'	110°52.15'	2070
S	38°04.58'	110°39.62'	1790
T	38°47.78'	110°48.45'	2130

Shot: Hanksville 3, 2,000 lbs, Chinle 2, 4,000 lbs

Unit	Latitude, North	Longitude, West	Elevation, Meters
H	37°43.80'	110°15.00'	1580
I	37°48.79'	110°20.95'	1540
J	37°49.82'	110°28.98'	1170
K	37°39.90'	110°11.40'	1520
L	37°30.00'	110°14.16'	1800
P	37°27.66'	110°11.25'	1600
R	37°54.60'	110°27.82'	1320
S	37°20.34'	109°57.00'	2160
T	37°59.00'	110°36.85'	1640

Table 1.--Shotpoint and recording locations (continued)

	Latitude, North	Longitude, West	Elevation, Meters
Shot: <u>Hanksville 4, 10,000 lbs, Chinle 3, 2,000 lbs</u>			
<u>Unit</u>			
H	36°18.24'	109°36.45'	1740
I	36°58.68'	109°52.25'	1520
J	37°03.08'	109°54.65'	1510
K	36°47.43'	109°53.07'	1660
L	36°07.00'	109°34.78'	1700
P	35°57.25'	109°34.54'	1900
Q	36°37.20'	109°50.25'	1610
R	37°07.47'	109°58.68'	1700
S	36°30.15'	109°36.36'	1700
T	37°16.26'	109°56.58'	1700
Shot: <u>Chinle 4, 2,000 lbs</u>			
<u>Unit</u>			
H	36°00.15'	109°36.13'	1820
I	36°56.79'	109°37.52'	1490
J	36°11.16'	109°37.80'	1770
K	36°41.88'	109°50.85'	1580
L	35°54.19'	109°35.07'	1860
P	35°58.67'	109°34.71'	1860
Q	37°33.42'	109°53.43'	2070
R	36°03.37'	109°36.43'	1800
S	36°32.85'	109°42.33'	1710
T	36°22.77'	109°39.33'	1680

All coordinates are for the seismometer at the west end of the spread.

GEOLOGY AND PHYSIOGRAPHY

The Colorado Plateaus Province is a large elevated crustal block that is bordered on the south and west by the Basin and Range Province, and on the north and east by the ranges of the Rocky Mountains. The Colorado Plateaus is characterized by many high plateaus separated by deep, steep-walled canyons. The area traversed by this profile is a semi-desert containing sparse vegetation and very few inhabitants.

The main geological features of the Colorado Plateaus are the large structural basins separated from uplifts by large monoclinal flexures. Rock strata within the basins and in the uplifts are flat lying or dip very gently. Clusters of intrusive mountains and many igneous dikes and volcanic cones are widely distributed over the central and eastern portion of the province. These structural and volcanic features are for the most part of Mesozoic and Cenozoic age, and they show that the region has been tectonically active during these eras. The Colorado Plateaus Province was not deformed to the same extent as the surrounding areas although it was uplifted as a great block in perhaps the Pliocene or even Pliestocene epoch (Gilluly, 1963). It can be regarded as a stable area only when compared with the complex deformational features of the adjoining provinces.

The salient geologic features of the province have been summarized by King (1959) and Eardley (1962). Individual features or areas crossed by the seismic profile have been described by a number of workers. Of particular interest among these are the study of the Henry Mountains by Hunt (1953), the San Rafael Swell by Gilluly (1929), and the recent map of the Shiprock quadrangle by O'Sullivan and Beikman (1964).

The seismic profile starts near Hanksville, Utah, in a large structural basin, proceeds southward across the east flank of the intrusive Henry Mountains, crosses the Monument Uplift, the Comb Monocline near the Utah-Arizona border, and ends near Chinle, Arizona, in the Black Mesa Basin (Fig. 2). With the exception of the steep-dipping flexure of the Comb Monocline, the rock strata along the profile are nearly flat lying. The elevation along the profile ranges from 3500 ft (1070 meters) above sea level in the bottom of Glen Canyon on the Colorado River to 6200 ft (1890 meters) on the higher plateaus, and averages 5600 ft (1710 meters) along the entire profile. The elevations of the shotpoints are 4700 ft (1480 meters) at Hanksville and 6000 ft (1860 meters) at Chinle.

INFORMATION ON THE SEISMOGRAMS

The efficiency of the Hanksville shotpoints in converting explosive energy into seismic energy was poor, and the efficiency of the Chinle shotpoint was fair. However, because of the very low background noise at most of the recording positions, useable seismograms were obtained to a distance of 300 km from the Hanksville shotpoint and 335 km from the Chinle shotpoint. The maximum seismic background noise at many of the recording locations was less than 0.5 millimicron with an average frequency of 5 cps.

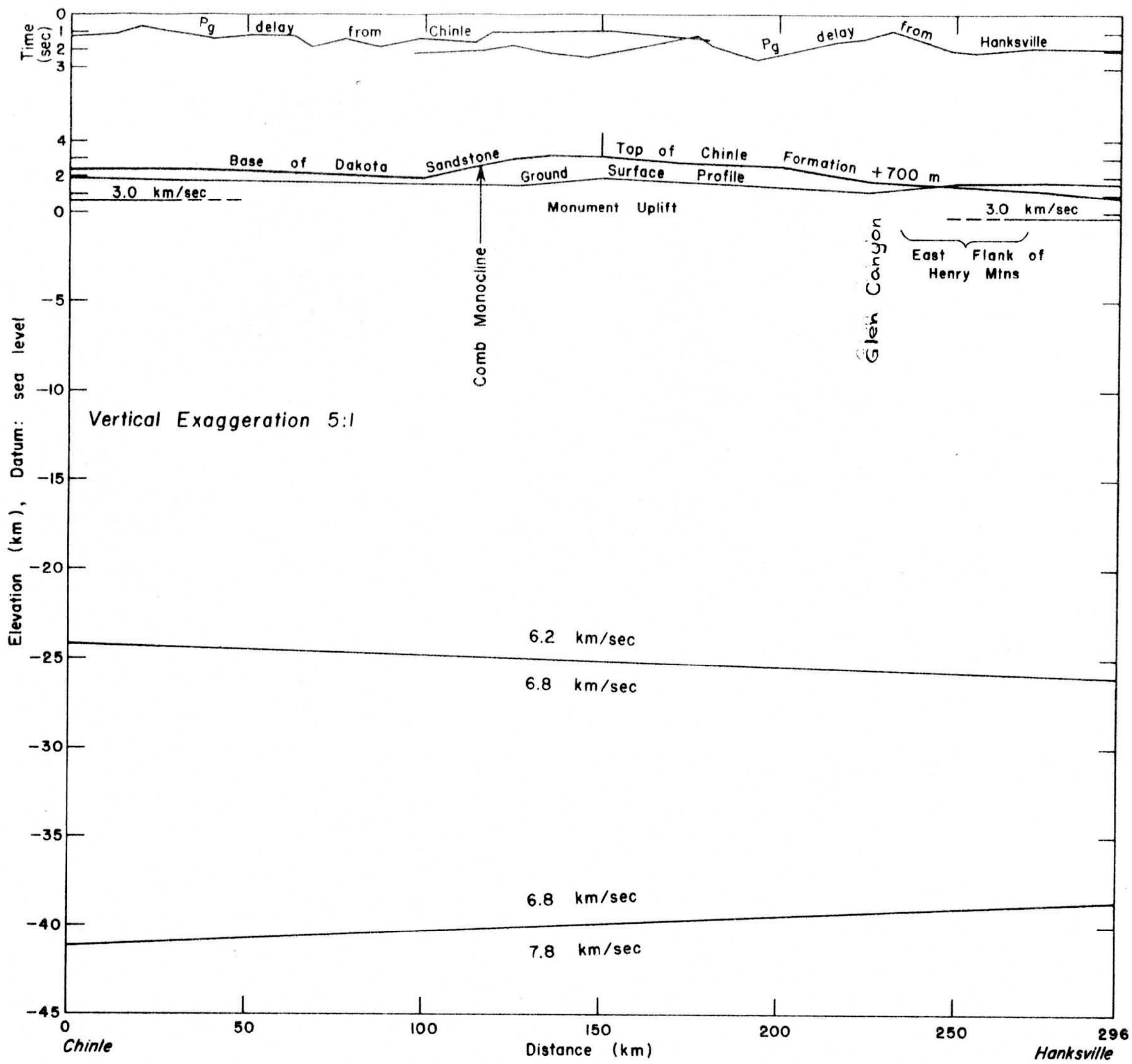

Figure 2.--Crustal structure in the Colorado Plateaus Province, with surface elevations, geologic structure, and P_g delay times. Geologic crossection taken from O'Sullivan (1963) and Hunt (1953).

The first arrivals on the seismograms recorded from the Hanksville shotpoint define a three-segment time-distance curve (Fig. 3). The first arrivals on 2 close-in seismograms in the distance range from 0 to 12.5 km define a line with an apparent velocity of 3.0 km/sec. This is the velocity of the seismic waves in the near-surface sedimentary rocks. An apparent velocity for P_g, the direct wave in the crust, of 6.25 km/sec is defined by 16 recordings in the distance range from 12.5 to 220 km. The P_g arrival times minus $\Delta/6.0$ km/sec are plotted in Figure 2 for both the Hanksville and Chinle shotpoints with geologic, structural, and topographic data along the line. These reduced or delay times show a scatter of 0.65 sec from Chinle and 0.90 sec from Hanksville. The only obvious correlations between the P_g arrival times and the geologic structure or topography are at Comb ridge on the Chinle arrival times, where the average delay decreases approximately 0.5 sec, and across Glen Canyon on the Hanksville arrival times. The remainder of the scatter seems to be the random result of inhomogenities in the sedimentary rocks or upper crust, and not necessarily related to the gross structure or topography. Although the first motion is usually weak and emergent, the arrival times can usually be determined to within ± 0.1 sec.

From 237 km to 295 km the first arrivals define a line with an apparent velocity of 7.85 km/sec. This is the velocity of P_n, the refracted wave from the top of the mantle. First arrivals on these recordings are very weak; however, the velocity should not be in error by more than ± 0.1 km/sec if we assume that the arrivals as picked are within one cycle of the true first arrivals.

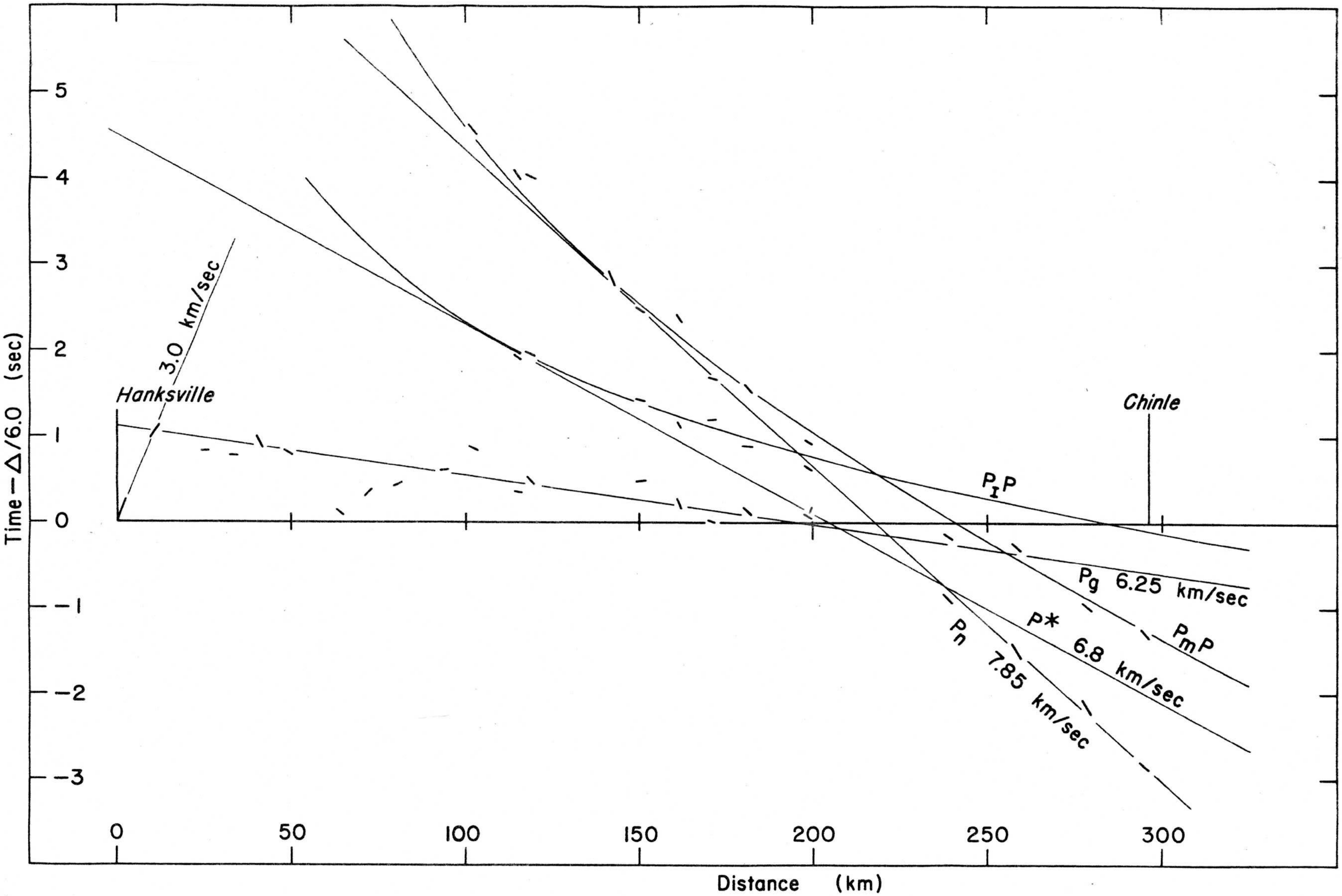

Figure 3.--Reduced time-distance curve from the Hanksville shotpoint.

Two groups of secondary arrivals have been identified as reflected events. Secondary arrivals on 7 recordings in the distance range from 115 to 200 km have been identified as reflections from an intermediate layer in the crust (P_IP) with a velocity of approximately 6.8 km/sec. These events are similar to those found in the Basin and Range Province (Roller and Healy, 1963).

Another group of arrivals on 13 recordings in the distance range from 102 to 295 km have been identified as reflections from the Mohorovicic discontinuity (P_MP). Many other secondary events can be seen on the individual seismograms, but cannot be correlated between seismograms.

First arrivals from the Chinle shotpoint can be plotted on a three-segment time-distance curve (Fig. 4). Near the shotpoint the first arrivals on one seismogram define a line with an apparent velocity of 3.0 km/sec. First arrivals on 20 seismograms in the distance range from 4 to 219 km define an apparent P_g velocity of 6.2 km/sec. The first arrivals on 9 seismograms define an apparent P_n velocity of 7.8 km/sec. This would give a true P_n velocity of 7.7 to 7.9 km/sec assuming that the 7.8 km/sec P_n velocity from Chinle is correct. The large amount of good quality data from Chinle would seem to make this assumption valid.

The P_n velocity on this profile is less than the P_n velocity of 8.0 km/sec found by Ryall and Stuart (1963) on a long unreversed profile that crosses the Colorado Plateaus in an easterly direction.

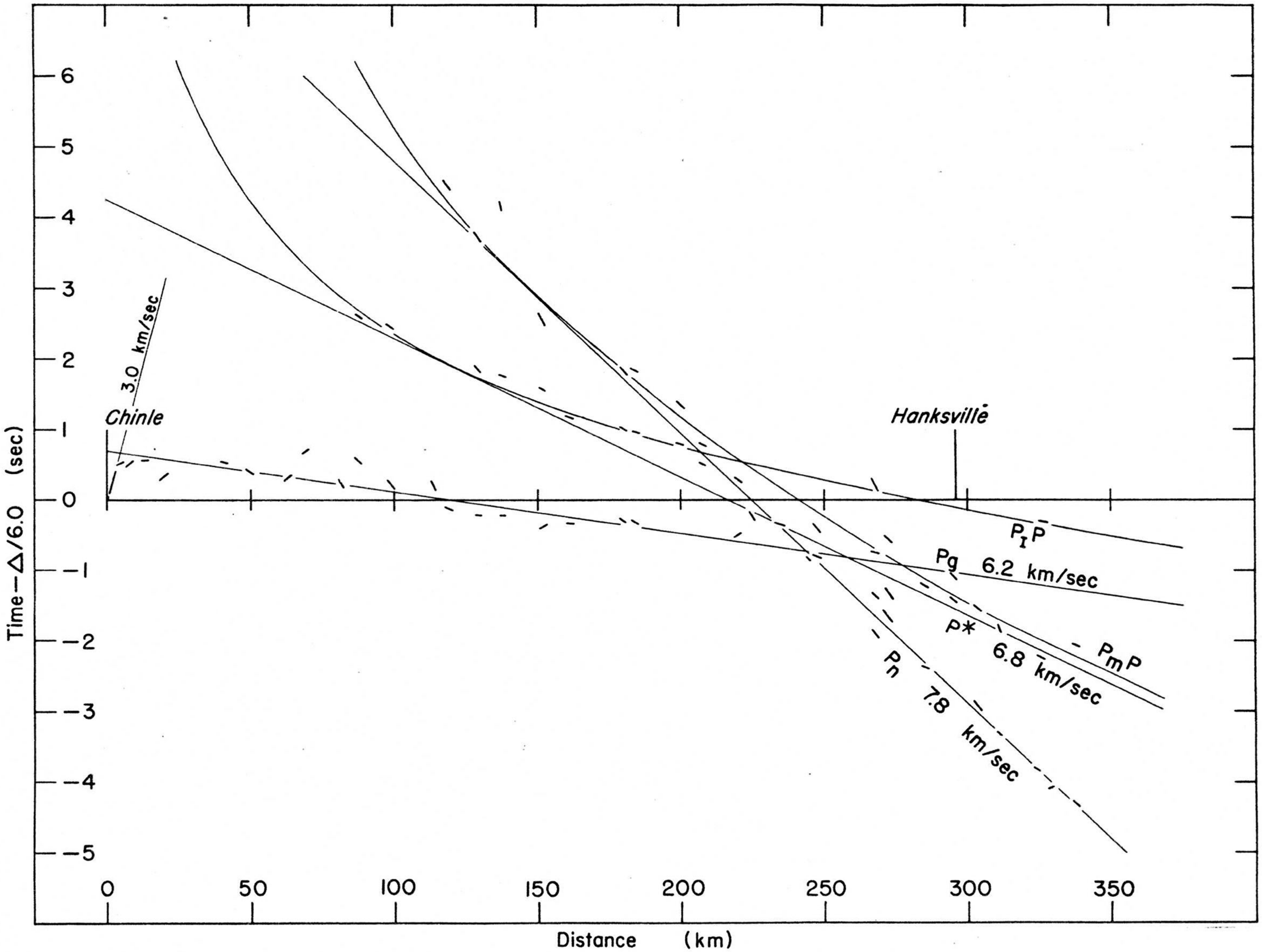

Figure 4.--Reduced time-distance curve from the Chinle shotpoint.

This velocity for P_n is also lower than the 8.1 km/sec found along an unreversed profile recorded in southeastern Arizona by the Carnegie Institution of Washington (Tatel and Tuve, 1955).

Two secondary events plotted on the Chinle profile are identified as groups of reflections from an intermediate layer in the crust, and as reflections from the Mohorovicic discontinuity. The arrival times and amplitudes of all the prominent phases are listed in Table 2.

DEPTH CALCULATIONS

Two crustal models can be constructed for the Colorado Plateaus: one using only first arrivals and, the other using the reflections which indicate the crust is made up of more than a single layer.

First arrivals from Hanksville can be represented by three straight lines: $T_0 = \Delta/3.0$ sec, $T_1 = 1.12 + \Delta/6.25$ sec, and $T_2 = 8.02 + \Delta/7.85$ sec; and from Chinle first arrivals can be represented by $T_0 = \Delta/3.0$ sec, $T_1 = 0.70 + \Delta/6.2$ sec, and $T_3 = 8.68 + \Delta/7.8$ sec in which Δ is in km. Using these data, a depth to the mantle of 37 km was computed at Hanksville and 41 km at Chinle.

If we assume that the 6.8 km/sec layer indicated by secondary events is a discrete layer, the thickness of the crust is 40 km at Hanksville and 43 km at Chinle. The thickness of the intermediate layer (6.8 km/sec) is 17 km at Chinle and 13 km at Hanksville (Fig. 2). These depths compare closely with the depth of 40 km found by Ryall and Stuart (1963) along an east-trending profile across the Colorado Plateaus Province.

Table 2.--Arrival times and amplitudes of prominent phases

Shot: Hanksville-2; Charge size: 2,000 lbs.

		P_g		P_IP		P_MP		P_n	
Recording Unit	Distance, km	Time, sec	Amplitude, mμ	Time, sec	Amplitude, mμ	Time, sec	Amplitude, mμ	Time, sec	Amplitude, mμ
H	9.38	2.36	80						
I	15.92	3.40	7.0						
J	30.15	5.77	2.8						
K	0.15	0.08	10,000	Note: (First arrival is direct wave through surface material)					
L	9.95	2.81	220						
P	24.50	4.91	(?)	Noisy record					
Q	32.59	6.21	1.8						
R		Not on location							
S	39.80	7.64	2.9						
T	48.84	8.71	1.6						

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

Shot: Hanksville-3; Charge size: 2,000 lbs.

		P_g		P_IP		P_MP		P_n	
Recording Unit	Distance, km	Time, sec	Amplitude, $m\mu$	Time, sec	Amplitude, $m\mu$	Time, sec	Amplitude, $m\mu$	Time, sec	Amplitude, $m\mu$
H	92.34	16.00	0.25						
I	79.65	13.70	0.30						
J	71.14	12.20	1.30						
K	101.27	17.77	VW			21.50	4.0		
L	113.77	19.32	VW	20.91	1.5	23.06	3.5		
P	117.87	20.17	0.30	21.63	5.0	23.70	9.5		
Q		Not on location							
R	63.24	10.69	0.95						
S	141.20	Can't measure				26.45	5.0		
T	48.62	8.94	VW						

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

Shot: Hanksville-4; Charge size: 10,000 lbs.

Recording Unit	Distance, km	P_g Time, sec	P_g Amplitude, mμ	P_IP Time, sec	P_IP Amplitude, mμ	P_MP Time, sec	P_MP Amplitude, mμ	P_n Time, sec	P_n Amplitude, mμ
H	257.05					42.62	3.5	41.42	0.50
I	180.10	30.18	0.7	30.89	11.5	31.62	15.0		
J	169.96	28.35	VW	29.52	10.0	30.02	12.5		
K	197.69	33.08	VW	33.60	4.5	33.94	7.5		
L	276.84					45.21	2.5	44.07	VW
P	293.41					47.68	1.0	46.10	VW
Q		Missed record							
R	161.26	27.14	0.5	28.01	8.0	29.40	11.5		
S	237.64					39.50		38.73	1.0
T	149.32	25.37	1.7	26.33	7.0	27.39	15.0		

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

Shot: Chinle-1; Charge size: 6,000 lbs.

Recording Unit	Distance, km	P_g Time, sec	P_g Amplitude, mμ	P_IP Time, sec	P_IP Amplitude, mμ	P_MP Time, sec	P_MP Amplitude, mμ	P_n Time, sec	P_n Amplitude, mμ
H	302.15							47.77	0.3
I	310.51							48.45	0.5
J	323.22							50.08	VW
K	293.78							Can't measure	
L	283.87							44.96	2.0
P	270.65							43.55	2.5
Q	266.29							42.56	1.0
R	328.33							50.63	0.8
T	336.64							51.84	0.5

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

Shot: Chinle-2; Charge size: 4,000 lbs.

Recording Unit	Distance, km	P_g Time, sec	P_g Amplitude, mμ	P_IP Time, sec	P_IP Amplitude, mμ	P_MP Time, sec	P_MP Amplitude, mμ	P_n Time, sec	P_n Amplitude mμ
H	206.55	Can't measure		34.95		35.26		Identification of P_IP and P_MP not positive	
I	219.13	36.00	0.5			36.64	8.0		
J	224.14								
K	198.53	Can't measure		33.90	25	34.46	30		
L	182.57	30.14	0.2	31.40	25	32.29	35		
P	178.80	29.54	0.5	30.82	30	31.69	35		
Q		Not on location							
R	233.67							38.62 (Identification Questionable)	3.0
S	160.15	26.36	1.5	27.87	10				
T	246.26							40.25	

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

Shot: Chinle-3; Charge size: 2,000 lbs.

Recording Unit	Distance, km	P_g Time, sec	P_g Amplitude, mμ	P_IP Time, sec	P_IP Amplitude, mμ	P_MP Time, sec	P_MP Amplitude, mμ	P_n Time, sec	P_n Amplitude, mμ
H	39.37	7.12	735						
I	117.33	19.48	0.6			24.08	1.1		
J	128.33	21.28	0.5	23.29	3.0	25.20	7.0		
K	97.57	16.54	2.5	18.75	3.0				
L	18.51	3.45	(Off Scale)						
P	.65	.17	(Off Scale)						
Q	80.42	13.70	12.4						
R	136.93	22.60	0.5	24.50	3.0				
S	61.65	10.54	12.5						
T	150.55	24.69	0.4	26.68	7.5	27.73	6.0		

Table 2.--Arrival times and amplitudes of prominent phases (concluded)

Shot: Chinle-4; Charge size: 2,000 lbs.

Recording Unit	Distance, km	P_g		P_IP		P_MP		P_n	
		Time, sec	Amplitude, mμ	Time, sec	Amplitude, mμ	Time, sec	Amplitude, mμ	Time, sec	Amplitude, mμ
H	6.73	1.58	3,000						
I	113.18	19.13	3.0						
J		No Timing							
K	86.36	14.99	3.0						
L	0.46	.23	(Direct arrival through surface material)						
P	3.22	1.04	8,000						
Q	183.04	Very weak signal - Can't measure first arrivals							
R	12.14	2.58	1,650						
S	68.07	11.97	4.5						
T	48.35	8.48	15.0						

Note: VW - Very Weak.

AMPLITUDES

The maximum peak-to-peak amplitudes of P_g, P_IP, P_MP, and P_n were measured on all of the seismograms on which they could be identified. These measurements are tabulated in Table 2 and are plotted versus distance in Figures 5 and 6. An average frequency of 5 cps was used to reduce the measured values to equivalent ground motion. The values shown in Figures 5 and 6 have been normalized to a 2,000 lb shot by assuming a linear relationship between charge size and amplitude.

The amplitude of P_g from both the Hanksville and Chinle shotpoints is attenuated approximately as the inverse square of the distance between the source and receiver. These data show why it is generally impossible to identify P_g as a secondary arrival beyond the P_g-P_n crossover. The amplitude of P_g from the Chinle shotpoint is approximately an order of magnitude greater than from the Hanksville shotpoint.

The amplitude of P_n could be measured accurately on only a few seismograms because of distortion of the waves caused by background noise; however, extension of the P_g amplitude curve indicates that the amplitude of P_n is slightly greater than the amplitude of P_g. Beyond the critical distance the highest amplitude events on the seismograms are the waves identified as P_MP, which are only slightly higher than the amplitudes of P_IP. The amplitude of both of these reflected events is more than an order of magnitude higher than that of P_g or P_n. This agrees well with the theoretical amplitudes computed by McCamy and others (1962).

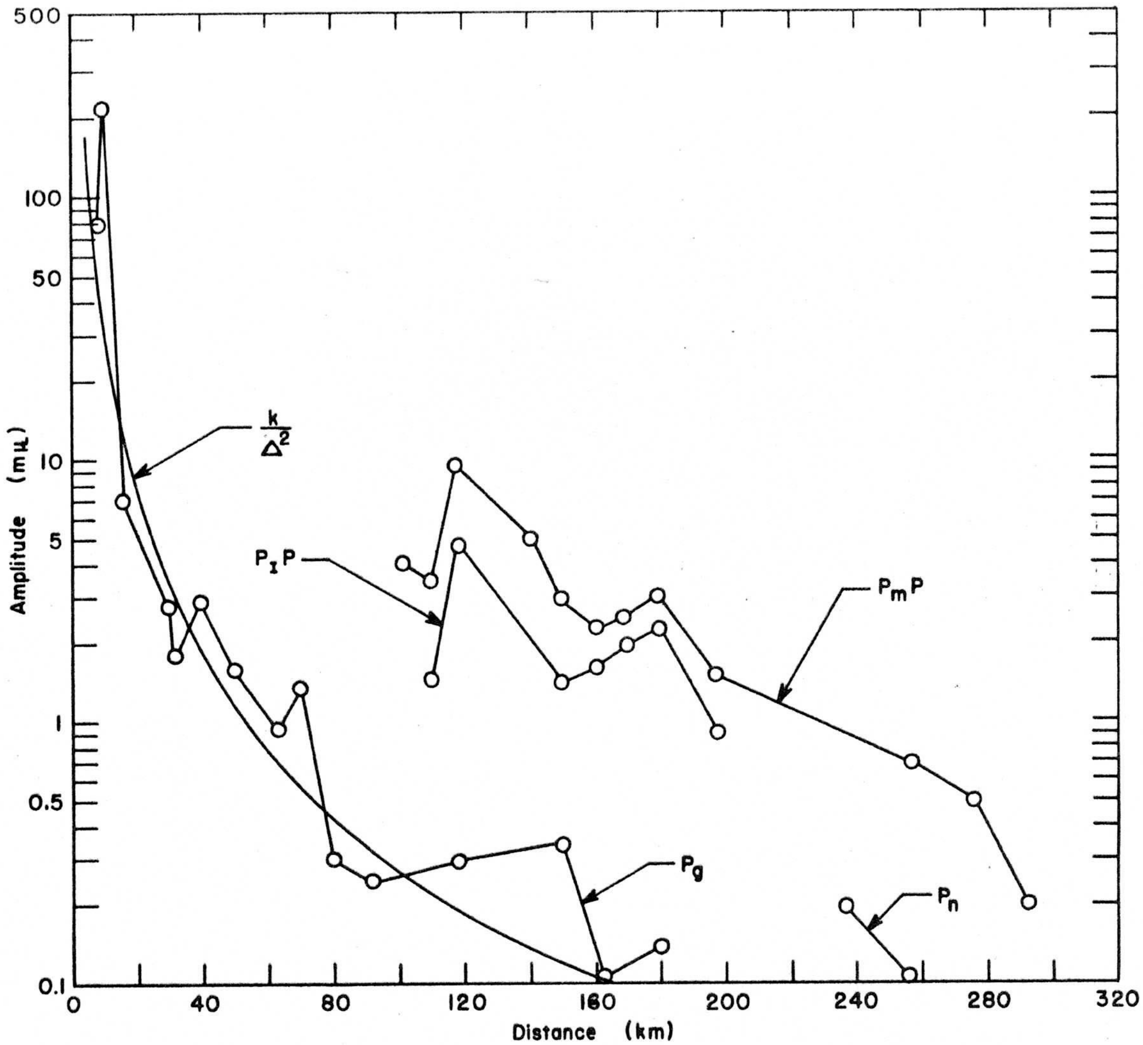

Figure 5.--Amplitudes of prominent phases from the Hanksville shotpoint.

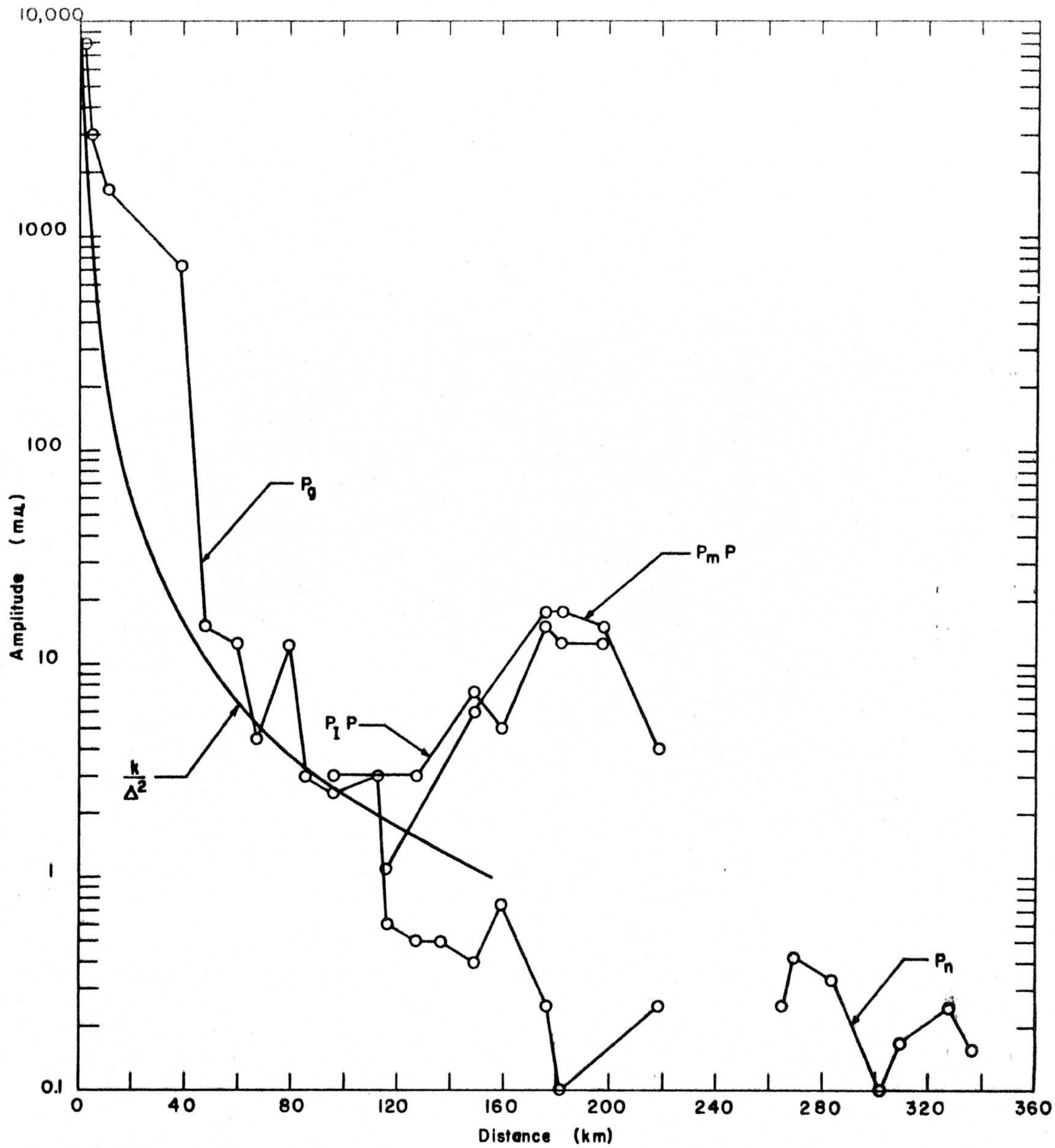

Figure 6.-- Amplitudes of prominent phases from the Chinle shotpoint.

Theoretical amplitudes computed from a model that approximates the crustal model found in the Colorado Plateaus Province are shown in Figure 7. This graph shows the same general trends that are shown by the observed data. The P_g curve attenuates rapidly with distance, the reflection curves show the highest amplitudes beyond the critical-reflection distance, and the amplitude of P_n is slightly higher than P_g beyond the P_g-P_n crossover distance. The theoretical amplitude curves were computed by S. W. Stewart.

CONCLUSIONS

The thickness of the crust in the Colorado Plateaus Province is approximately 40 km. This is from 5 to 10 km greater than that observed in the Basin and Range Province (see, e.g., Roller and Healy, 1963; Eaton, 1963); and approximately 10 km less than that observed on the High Plains of eastern Colorado (Jackson, Stewart, and Pakiser, 1963).

A velocity of 6.2 km/sec in the crust and a velocity of 7.8 km/sec in the upper mantle found in the Colorado Plateaus are the same as reported in the Basin and Range, but the upper-mantle velocity is less than reported on the High Plains.

A group of strong arrivals that seem to be reflections from an intermediate layer are observed in the Colorado Plateaus. The same events can be found on seismograms from the Basin and Range Province.

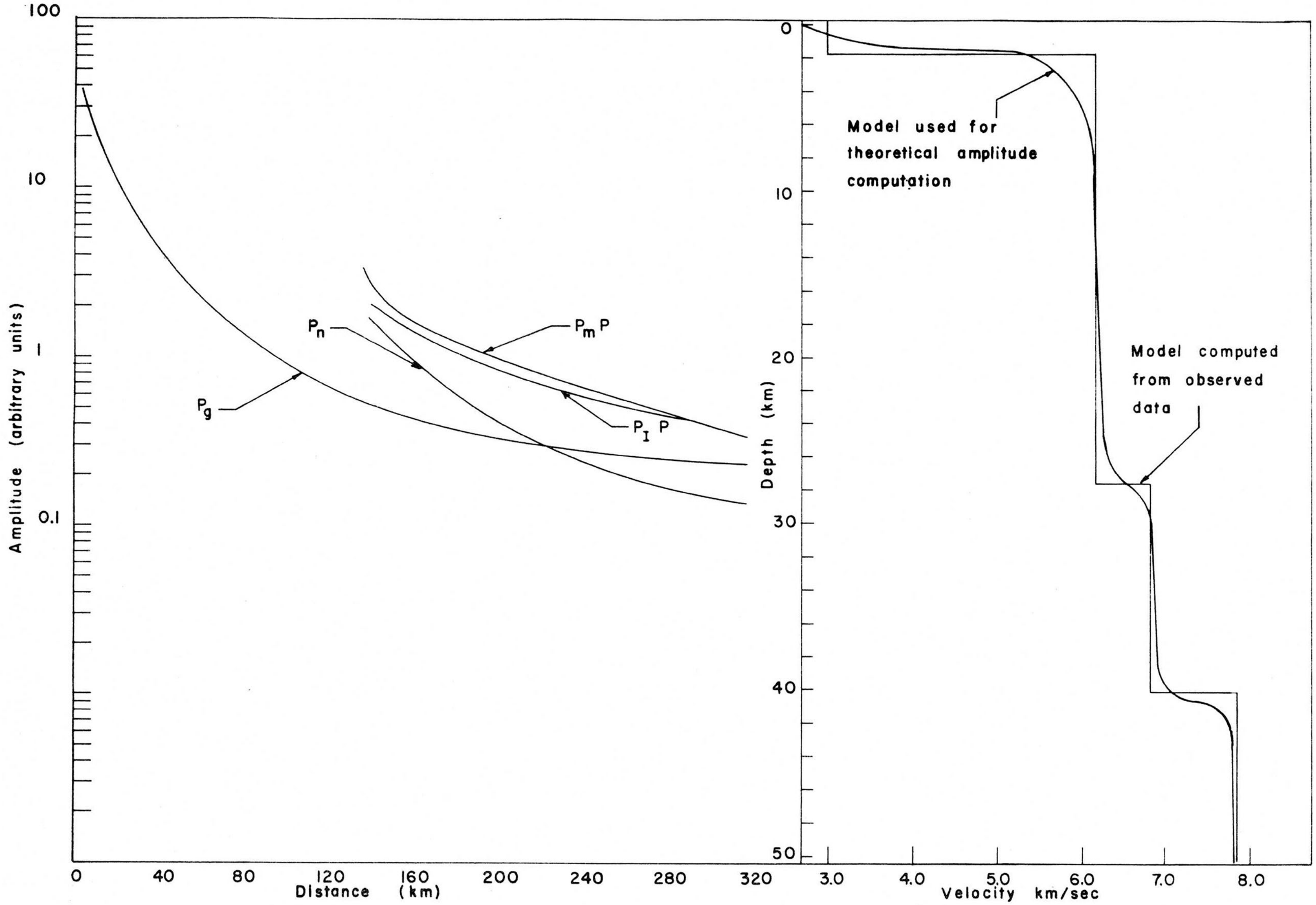

Figure 7.--Theoretical amplitudes of prominent phases from a typical crustal model of the Colorado Plateaus Province.

Crustal structure and seismic properties of the crust and upper mantle in the Colorado Plateaus are very similar to those in the Basin and Range Province, and are significantly different from those in the High Plains east of the Rocky Mountains. These data strengthen the concept that low P_n velocities are associated with areas that have been tectonically active in the later part of the earth's history (Pakiser, 1963).

REFERENCES

Eardley, A. J., 1962, Structural geology of North America: New York, Harper and Row, 2d ed. 743 p.

Eaton, Jerry P., 1963, Crustal structure from San Francisco, California, to Eureka, Nevada, from seismic-refraction measurements: Jour. Geophys. Research, v. 68, no. 20, p. 5789-5806.

Gilluly, James, 1929, Geology and oil and gas prospects of part of the San Rafael Swell, Utah: U. S. Geol. Survey Bull. 806-C.

Gilluly, James, 1963, The tectonic evolution of the western United States: Geol. Soc. London Quart. Jour., v. 119, p. 133-174.

Hunt, C. B., 1953, Geology and geography of the Henry Mountain Region, Utah: U. S. Geol. Survey Prof. Paper 228.

Jackson, W. H., S. W. Stewart, and L. C. Pakiser, 1963, Crustal structure in eastern Colorado from seismic-refraction measurements: Jour. Geophys. Research, v. 68, no. 20, p. 5767-5776.

King, P. B., 1959, The evolution of North America: Princeton, Princeton Univ. Press, 189 p.

McCamy, Keith, R. P. Meyer, and T. J. Smith, 1962, General applicable solutions of Zoeppritz amplitude equations: Seis. Soc. of America Bull., v. 52, no. 4, p. 923-955.

O'Sullivan, R. B., and H. M. Beikman, 1963, Geology, structure, and uranium deposits of the Shiprock Quadrangle, New Mexico and Arizona: Misc. Geol. Inv. Map I-345, U. S. Geol. Survey.

REFERENCES (continued)

Pakiser, L. C., 1963, Structure of the crust and upper mantle in the western United States: Jour. Geophys. Research, v. 68, no. 20, p. 5747-5756.

Roller, John C., and J. H. Healy, 1963, Seismic-refraction measurements of crustal structure between Santa Monica Bay and Lake Mead: Jour. Geophys. Research, v. 68, no. 20, p. 5837-5849.

Ryall, Alan, and David J. Stuart, 1963, Travel-times and amplitudes from nuclear explosions, Nevada Test Site to Ordway, Colorado: Jour. Geophys. Research, v. 68, no. 20, p. 5821-5835.

Tatel, H. E., and M. A. Tuve, 1955, Seismic exploration of the continental crust _in_ Crust of the Earth, Geol. Soc. America Spec. Paper 62.

Warrick, R. E., D. B. Hoover, W. H. Jackson, L. C. Pakiser, and J. C. Roller, 1961, The specification and testing of a seismic-refraction system for crustal studies: Geophysics, v. 26, no. 6, p. 820-824.