UNITED STATES
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TECHNICAL LETTER NUMBER 10

TRAVELTIMES AND AMPLITUDES FROM NUCLEAR EXPLOSIONS: NEVADA TEST SITE TO ORDWAY, COLORADO*

by

Alan Ryall** and David J. Stuart**

DENVER, COLORADO

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UNITED STATES
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GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-10
February 11, 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 10

TRAVELTIMES AND AMPLITUDES FROM

NUCLEAR EXPLOSIONS: NEVADA TEST SITE

TO ORDWAY, COLORADO*

by

Alan Ryall** and David J. Stuart**

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

Sincerely,

David J. Stuart

David J. Stuart, Acting Chief
Branch of Crustal Studies

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

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

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ABSTRACT

This paper treats the results of a study of seismic waves generated by eight nuclear explosions and recorded at 31 locations between the Nevada Test Site and Ordway, Colorado. The line of recording stations crosses the eastern part of the Basin and Range Province, the Colorado Plateaus, the Southern Rocky Mountains, and extends into the Great Plains.

In the eastern Basin and Range Province and the western margin of the Colorado Plateaus ($0 \leq \Delta \leq 385$ km), the time-distance curves for P_g and P_n can be expressed, respectively, as

$$T_1 = 0.8 + \Delta/6.0,$$

$$T_3 = 5.8 + \Delta/7.6.$$

A third phase, tentatively identified as P*, is represented by the equation

$$T_2 = 3.8 + \Delta/6.5.$$

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

Using the crustal structure and P_n velocity (7.9 km/sec) found for the NTS region by other authors, these relations indicate that the thickness of the crust increases from about 25 km at NTS to about 42 km in the western part of the Colorado Plateaus Province. East of this boundary the velocity of P in the upper mantle increases to 8.0 km/sec; depth to the Mohorovičić discontinuity is approximately constant over the range $435 \leq \Delta \leq 645$ km. Beyond 850 km, first arrivals indicate an apparent velocity of about 8.4 km/sec.

Amplitudes of P_n attenuate according to the equation

$$A = A_o \Delta^{-1/2} (\Delta - d)^{-3/2} e^{-0.0022\Delta}$$

over the distance range $150 \leq \Delta \leq 850$ km. This relation yields a value of Q, for P_n, of about 520.

The amplitudes of P_g attenuate extremely rapidly, and beyond about 130 km this phase cannot be identified with certainty. An extension of the P_g traveltime branch at large distances could be associated with waves reflected beyond the critical angle, from the base of the crust. This phase, called $\overline{P}$ after Mohorovičić, appears to attenuate as

$$A = A_o e^{-0.0076\Delta} \Delta^{-1/2}.$$

The value of Q indicated by this equation is about 200.

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INTRODUCTION

During the period from February to October 1962, the U. S. Geological Survey made seismic recordings of nuclear explosions at 31 locations between the Nevada Test Site (NTS) and Ordway, Colorado. The line of recording locations (Fig. 1) crosses the eastern part of the Basin and Range Province, the Colorado Plateaus, the Southern Rocky Mountains, and the western margin of the Great Plains; recordings were made over the range of distances $50 \leq \Delta \leq 1110$ km.

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

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

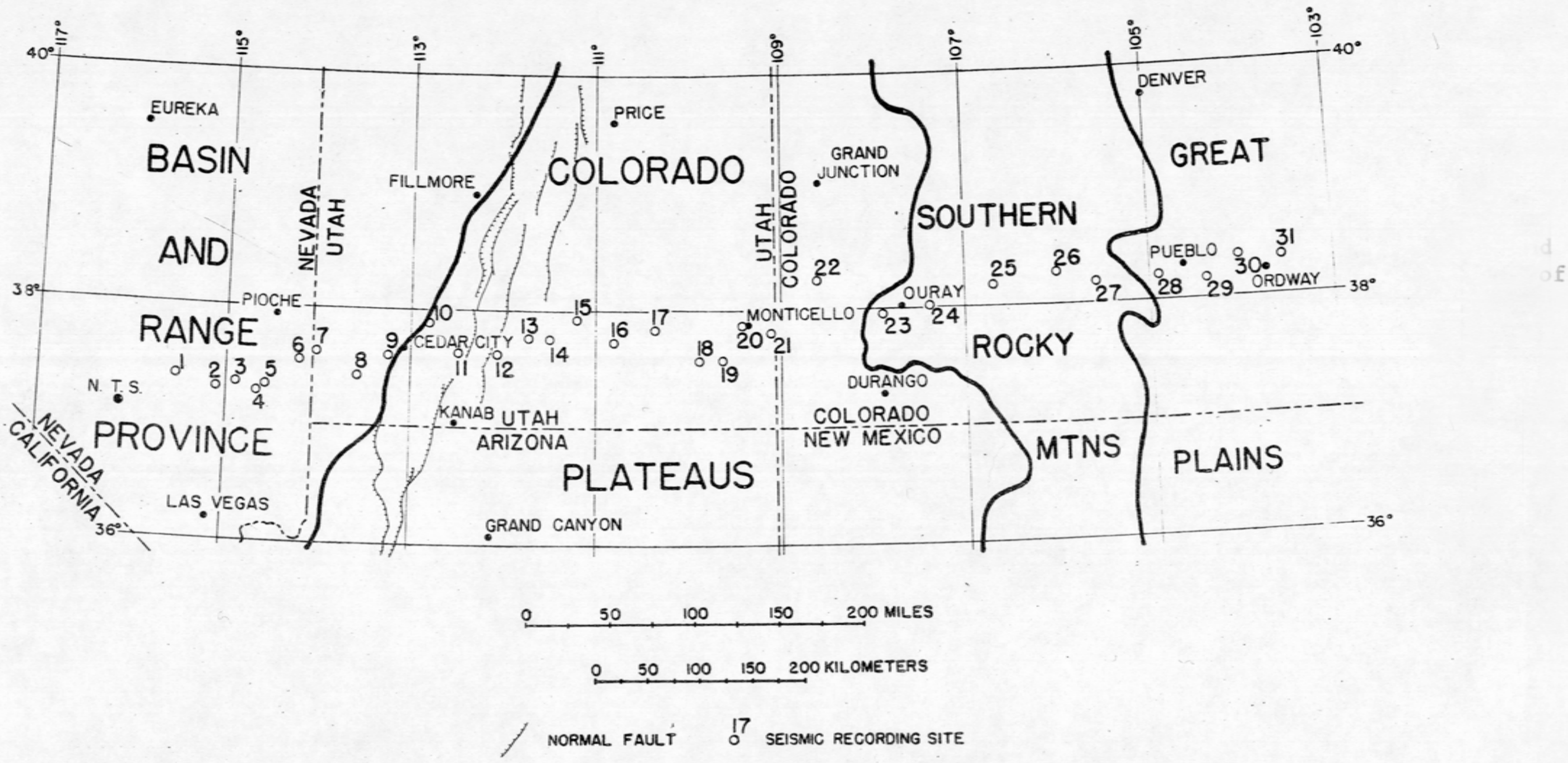

Figure 1.--Location map showing Nevada Test Site (N.T.S.), recording sites, major fault zones, and physiographic boundaries. Physiographic province boundaries from "Physical Divisions of the United States", Nevin M. Fenneman, U. S. Geological Survey, 1946; fault zones generalized from "Tectonic Map of the United States", U. S. Geological Survey and American Association of Petroleum Geologists, 1961.

Of the eight explosions used in this study, five have been declassified by the Atomic Energy Commission, and pertinent information on these five explosions is presented in the following table:

Table 1.--Nuclear Test Data

No.	Name	Date, 1962	Origin Time, GCT h	m	s	Yield, KT	Medium
I.	HARDHAT	February 15	18	00	00.10	5	Granite
II.	CHINCHILLA	February 19	16	30	00.132	1.8	Alluvium
III.	CIMARRON	February 23	18	00	00.160	11	Alluvium
IV.	BRAZOS	March 8	18	00	00.206	7.8	Alluvium
VI.	HOOSIC	March 28	18	00	00.163	3	Tuff

Sections of the NTS-Ordway profile which were recorded during five of the nuclear explosions are overlapping, in the sense that at least one recording location is common to successive shots.

Thirty of the seismic recordings used in this study were made with the U. S. Geological Survey's seismic-refraction system (Warrick and others, 1961). In this system, the signals from six vertical seismometers and two horizontal seismometers are amplified and filtered, and are then recorded at two levels (0 db and -15 db), together with chronometer and WWV signals, on a photographic recording oscillograph; in addition, chronometer marks and signals from the six vertical seismometers are recorded at two levels (0 db and -30 db) on magnetic tape. As a rule, the six vertical seismometers are placed at equal intervals along a 2-1/2-km spread, with the radial and transverse detectors buried alongside one of the vertical seismometers nearest the center of the spread. Amplitudes of recorded events can be calculated by reference to calibrated oscillator signals which are recorded on the tape and oscillogram. For signals with frequency, f, equal to two cps or greater, the system magnification is given by Eaton (1963):

$$M = \frac{10^6 \ C \ f}{5.2 \ V} ,$$

where C is the peak-to-peak amplitude, in millimeters, of the calibration signal, V is the metered calibration voltage of the same signal, in microvolts, and f is the frequency of the seismic event.

A single recording near the eastern end of the profile was made with a vertical-component seismograph of the Benioff type.

All of the recording locations used in this study were plotted on topographic maps. In the course of preliminary analysis, coordinates of the No. 1 (nearest the shotpoint) and No. 6 (farthest from the shotpoint) seismometer locations were read to the nearest 0.01 minute, and shot-receiver distances and azimuths were computed using a program written for a CDC-1604 digital computer. For distances less than 500 km, calculations were made using the method described by Richter (1958) for calculation of short distances; for stations located farther than 500 km from the shotpoint, calculations were made using spherical trigonometry and geocentric coordinates.

This research was supported by the Advanced Research Projects Agency, Department of Defense, as part of project VELA UNIFORM, under ARPA Order No. 193-62.

TRAVELTIMES AND CRUSTAL STRUCTURE

In preliminary analysis of the seismograms, prominent events were timed to 0.01 sec on the original oscillographic recordings or on playbacks made from the magnetic tape with different filter and gain settings from those of the original recording. All seismograms were read independently by each of the authors, and the two sets of readings were checked for consistency. Final times, usually for the No. 1 and No. 6 vertical traces, were plotted as a function of distance from the shotpoint (Figs. 2, 3, and 4), and time-distance curves were drawn through sets of points which, on the basis of a number of criteria (apparent velocity across the spread, amplitude relationships, frequency of the waves, similar appearance at adjacent spreads), were judged to belong to distinct phases. Traveltimes and distances to the No. 1 seismometer are presented for selected phases in Table 2.

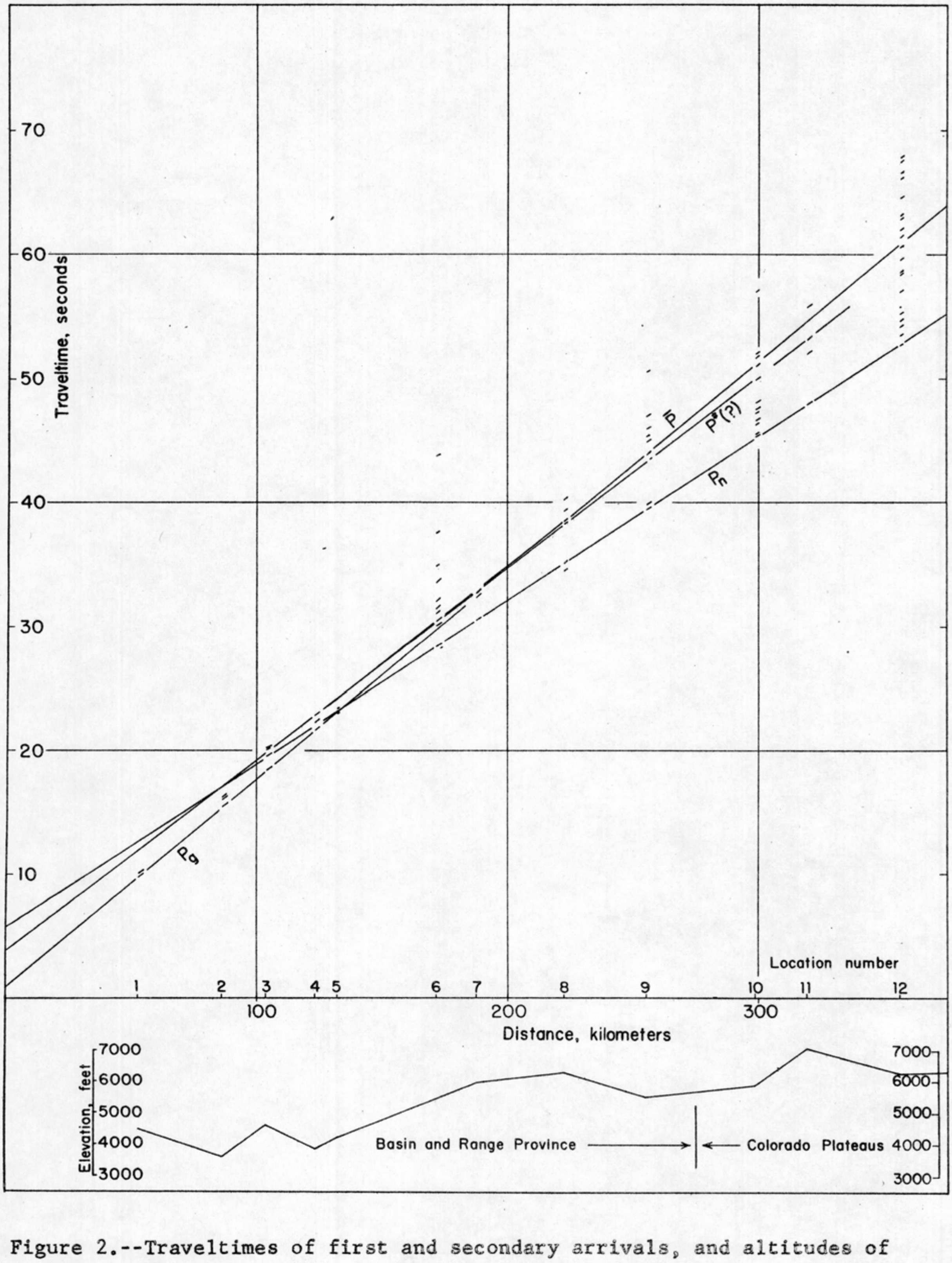

Figure 2.--Traveltimes of first and secondary arrivals, and altitudes of recording sites, from Nevada Test Site to 375 km.

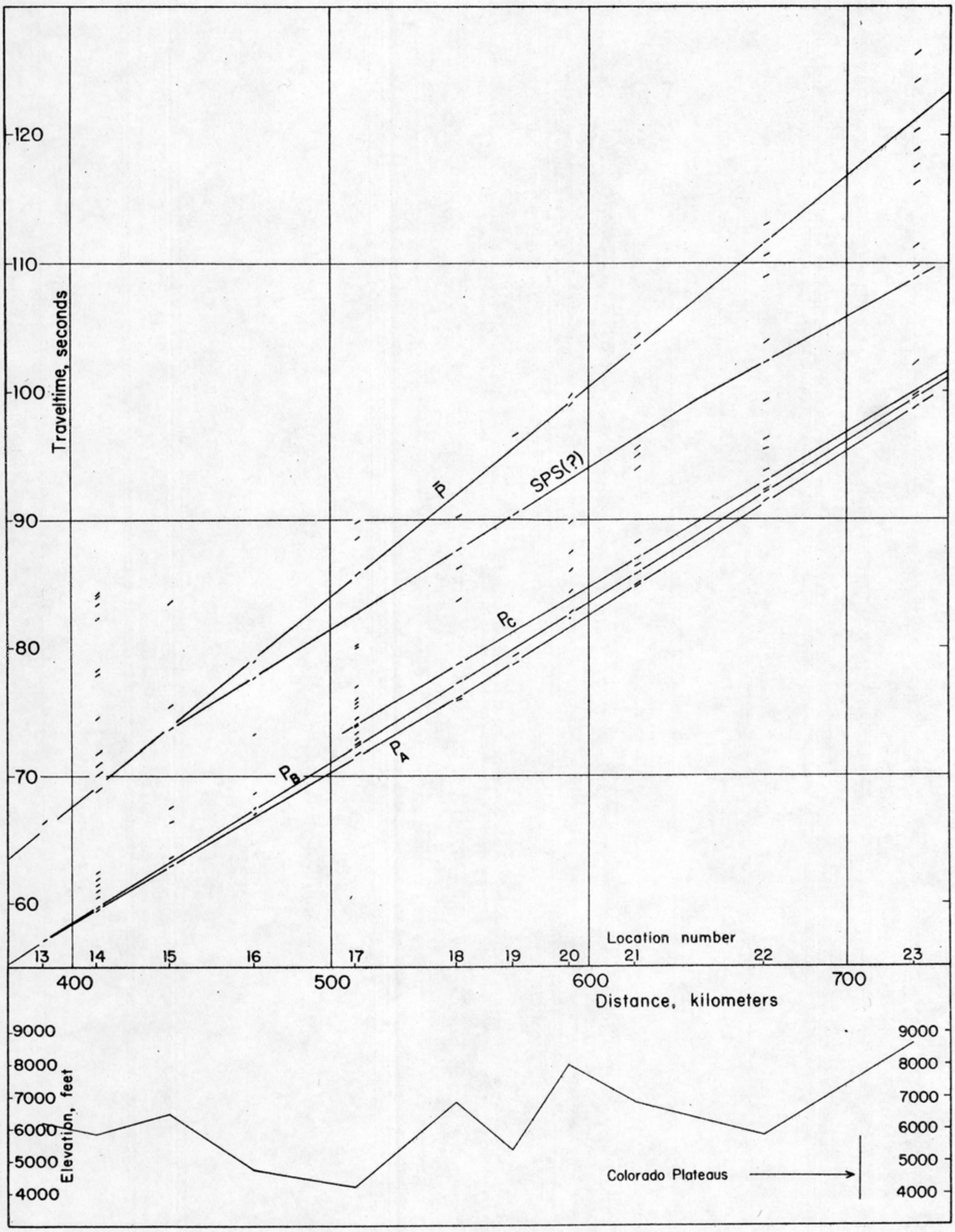

Figure 3.--Traveltimes of first and secondary arrivals, and altitudes of recording sites, in the distance range 375 to 740 km from Nevada Test Site.

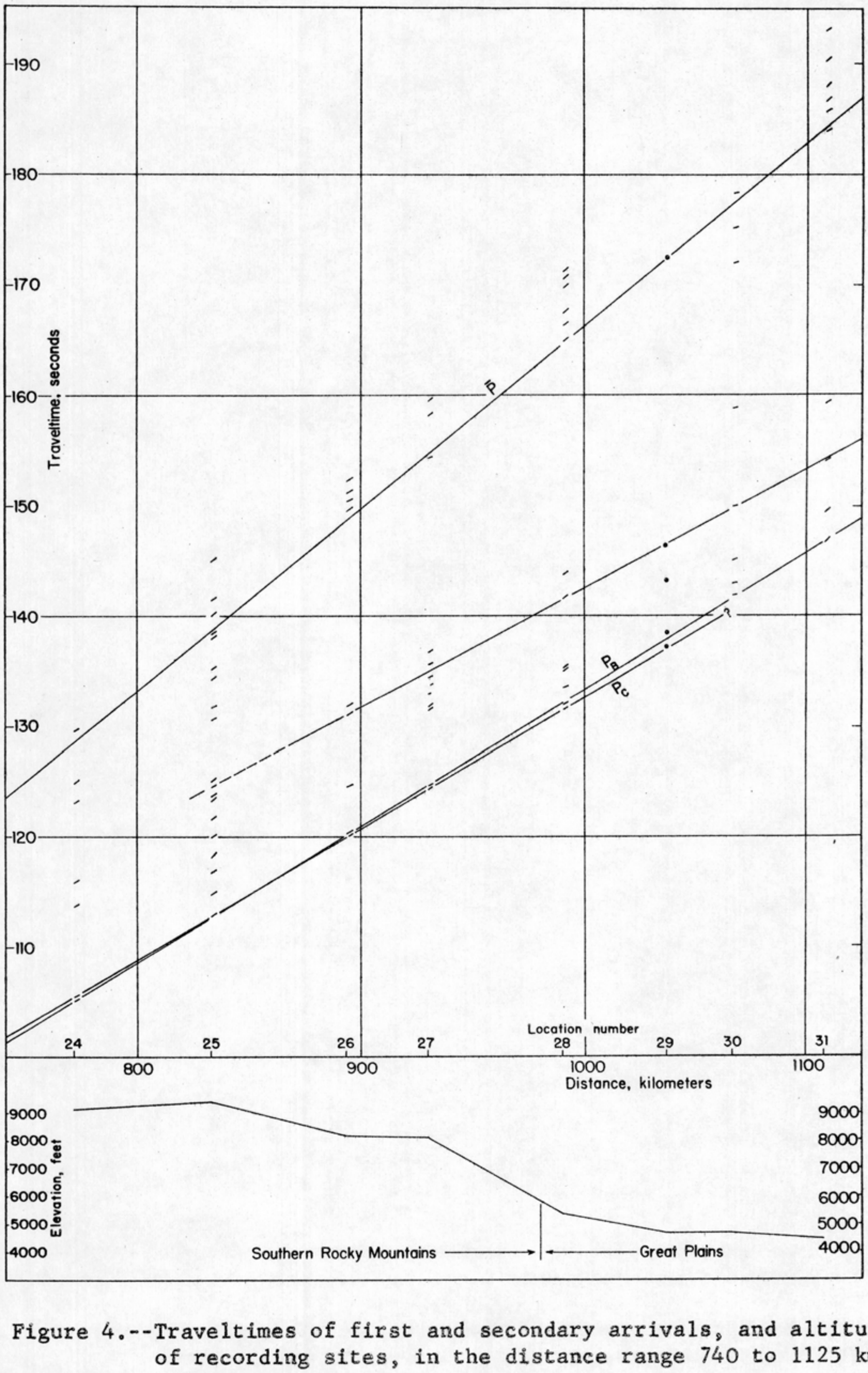

Figure 4.--Traveltimes of first and secondary arrivals, and altitudes of recording sites, in the distance range 740 to 1125 km from Nevada Test Site.

Table 2.--Distances and traveltimes for selected phases observed along a profile from the Nevada Test Site to Ordway, Colorado. Times within parentheses represent questionable or weak arrivals.

Recording site number	Shot or shots recorded	Distance in km to nearest seismometer	Traveltime in seconds						
			P_g	P*(?)	P_n/P_B	$\overline{P}$	P_A	P_C	SPS(?)
1	VI	52.6	9.74						
2	V	86.0	15.49						
3	VI	103.6	18.42		(19.53)	(20.04)			
4	VI	123.1	21.60	(22.80)		(22.80)			
5	VI	132.1	22.97						
6	V	171.5	(30.01)	(30.42)	28.34	(30.42)			
7	VI	187.5	(32.30)	(32.67)	30.47	(32.67)			
8	V	222.6		38.26	35.06	38.26			
9	III,IV,V	254.9		43.25	39.36	43.85			
10	IV	298.8		49.95	45.37	50.97			
11	VI	319.4		53.15	47.90				
12	IV	356.3			52.77	60.53			
13	VI	388.3			57.07	66.22			
14	IV	409.1			59.59	(70.00)	(59.36)		
15	VII	437.0			63.56	(75.27)	62.90		73.52

Table 2.--Distances and traveltimes for selected phases observed along a profile from the Nevada Test Site to Ordway, Colorado. Times within parentheses represent questionable or weak arrivals. (Continued)

Recording site number	Shot or shots recorded	Distance in km to nearest seismometer	Traveltime in seconds						
			P_g	P*(?)	P_n/P_B	$\overline{P}$	P_A	P_C	SPS(?)
16	VII	470.1			67.39	(78.80)	66.93		77.55
17	IV	509.2			72.13	85.62	71.52	(73.86)	
18	VII	548.4			77.17		75.81	(78.62)	87.51
19	VII	570.2				(96.48)	78.67		90.33
20	II	592.0			82.64	99.40			
21	I,II,III	617.7			85.66	103.22	84.66	86.84	(95.38)
22	I	667.6			92.02	(111.57)	(91.32)	92.83	102.14
23	I	726.2			99.35		98.54		108.63
24	I	771.5			105.01	(129.51)		105.42	
25	I	832.9			(112.79)	(138.36)		(112.79)	
26	I	893.6			120.25	(149.45)		119.95	
27	I	930.0			124.61	(154.31)		124.21	
28	I	990.6			(131.88)	(164.81)		131.40	
29	VIII	1037.1			(138.50)	172.41		(137.20)	
30	VIII	1066.7			141.91	(178.23)			
31	VIII	1108.4			146.79	(183.91)			

Traveltimes in the eastern Basin and Range Province. From four first arrivals in the distance range $53 \leq \Delta \leq 123$ km, the velocity and intercept time for the phase P_g are found to be 6.0 km/sec and 0.8 sec, respectively. From 172 to 388 km, times of eight first arrivals fit a time-distance curve for P_n with an intercept time of 5.8 sec and an apparent velocity of 7.6 km/sec. Another phase, which is probably related to an intermediate boundary in the crust, is represented by questionable secondary arrivals in a relatively complicated region of the traveltime curve ($123 \leq \Delta \leq 319$ km). This phase, labeled P*(?) in Table 2, has an apparent velocity of 6.5 km/sec and an intercept time of 3.8 sec. An additional phase (Fig. 2), characterized by large amplitudes and relatively low frequencies (2-3 cps) in comparison with those (about 4 cps) of P_g, is asymptotic to the P*(?) curve at short distances and at larger distances is a continuation of the P_g branch. This phase, called $\overline{P}$ after Mohorovičić (1910), can be identified over the entire NTS-Ordway profile; in a later section the amplitudes of P_g and $\overline{P}$ will be compared and the nature of the $\overline{P}$ phase will be discussed.

The apparent velocity for P_n of 7.6 km/sec is practically identical to a velocity (7.59 km/sec) found in the eastern Basin and Range Province by Berg and others (1960), using quarry blasts in the Salt Lake region; it is also in good agreement with the velocity of P_n (about 7.5 km/sec) found by Ryall (1962) for the same region. The apparent velocity of 6.5 km/sec for P*(?) is close to an intermediate velocity (6.6 km/sec) found by Eaton (1963) for the northern Basin and Range Province. If the velocity of P waves in the near-surface low-velocity zone in the vicinity of NTS is assumed to be 3.0 km/sec, and if the crust in the eastern Basin and Range Province is assumed to consist of horizontal, constant-velocity layers, then the observed velocities and intercept times along the NTS-Ordway profile lead to a crustal model with a thickness of about 26 km (Table 3, Model I). This figure is slightly higher than that (25 km) found by Berg, et al., and is less than the thickness (28 km) obtained by Diment, Stewart, and Roller (1961) from observations to the southeast of NTS.

Table 3.--Calculated crustal models for the eastern Basin and Range Province.

I -- Horizontal, constant-velocity layers: v_o = 3.0 km/sec, v_1 = 6.0 km/sec, I_1 = 0.8 sec, v_2 = 6.5 km/sec, I_2 = 3.8 sec, v_3 = 7.6 km/sec, I_3 = 5.8 sec.

II -- Two-layer crust: v_o = 3.0 km/sec, v_1 = 6.0 km/sec, I_1 = 0.8 sec, v_2 = 7.9 km/sec, $\overline{v}_2$ = 7.6 km/sec, I_2 = 5.8 sec.

III -- Three-layer crust: v_o = 3.0 km/sec, v_1 = 6.0 km/sec, I_1 = 0.8 sec, v_2 = 6.7 km/sec, $\overline{v}$ = 6.5 km/sec, I_2 = 3.8 sec, v_3 = 7.9 km/sec, $\overline{v}_3$ = 7.6 km/sec, I_3 = 5.8 sec.

Intercepts and apparent velocities are those obtained for the NTS-Ordway profile.

Model	Velocity of P waves in the layer, km/sec	Vertical thickness of layer at NTS, km	Dip of layer toward east	Total crustal thickness, km
I	3.0	1.4	0°00'	
	6.0	22.9	0°00'	
	6.5	1.6	0°00'	
	7.6			25.9
II	3.0	1.4	0°00'	
	6.0	22.9	2°35'	
	7.9			24.3

Table 3.--Calculated crustal models for the eastern Basin and Range Province. (Continued)

Model	Velocity of P waves in the layer, km/sec	Vertical thickness of layer at NTS, km	Dip of layer toward east	Total crustal thickness, km
III	3.0	1.4	0°00'	
	6.0	20.3	3°48'	
	6.7	3.8	2°20'	
	7.9			25.5

A different crustal model is obtained using apparent velocities observed during detailed explosion-seismic studies by the U. S. Geological Survey along profiles within the Basin and Range Province. Some of these studies are presented in some detail in the present symposium (Eaton, 1963; Roller and Healy, 1963; Pakiser and Hill, 1963), and a summary of additional, preliminary results is given in the introductory paper by Pakiser (1963). For two reversed profiles in the region south and southeast of NTS (NTS to Kingman, Arizona, and NTS to Ludlow, California) the average velocity of P_n is about 7.7 km/sec; for two profiles in the western part of the Province (Lake Mead, Nevada, to Mono Lake, California, and Lake Mead to Santa Monica Bay, California) the average P_n velocity is 7.8 km/sec. This last value also agrees with the velocity found by Eaton (1963) from observations in the west-central Basin and Range Province (Fallon, Nevada, to Eureka, Nevada). Pakiser and Hill (1963) find a velocity of 7.84 km/sec for waves traveling north from NTS. Finally, preliminary results for a reversed profile in the eastern part of the Province (Lake Mead to Eureka) indicate a P_n velocity of about 7.9 km/sec.

The velocities of P_n found in all of these studies suggest a consistent pattern: from 7.8 km/sec in the western Basin and Range Province, the velocity of P_n decreases slightly, to 7.7 km/sec, toward the southeast, and increases to about 7.9 km/sec in the eastern part of the Province. If, for the NTS-Ordway profile, a P_n velocity of 7.9 km/sec is assumed, and if the evidence for an intermediate layer is neglected, then the total thickness of the crust in the NTS region is calculated to be 24.3 km, and this thickness increases to about 42 km in the western part of the Colorado Plateaus Province (Table 3, Model II). If a three-layer crust is assumed for the eastern Basin and Range Province, with the velocity of P_n equal to 7.9 km/sec and that of P* equal to 6.7 km/sec, then the depth to the base of the crust near NTS is 25.5 km, increasing to 42 km at Δ = 400 km (Table 3, Model III). The principal difference between the last two models is the presence in Model III of a poorly-defined intermediate layer; both have about the same thickness in the NTS region, and both increase to about 42 km in the Plateaus region. Either of these models would be preferable to Model I, since they are consistent with detailed observations of P_n velocity in the Basin and Range Province, and also because they indicate a crust-mantle boundary which is continuous across the eastern Basin and Range Province into the Colorado Plateaus. The continuity of this boundary will be further supported, in a later section, by a consideration of the decrease of amplitudes of P_n along the NTS-Ordway profile.

The depth of 24-26 km to the Mohorovičić discontinuity in the NTS region agrees with that (25 km) found by Berg and others (1960), but is less than the depth of 28 km found for the same region by Diment, Stewart, and Roller (1961) and by Pakiser and Hill (1963). These differences in crustal thickness could be accounted for by the small differences in P_g velocity and intercept time found by the various authors, or they could result from some uneven configuration of the crust-mantle interface; the data in the present paper would be consistent, under assumptions differing slightly from those given above, with crustal thicknesses ranging from 24 to 30 km. The depth of 42 km to the Mohorovičić discontinuity in the western Colorado Plateaus region agrees with the crustal thickness obtained in the following section for that region, based on differences in arrival time of the phase P_n and a phase tentatively identified as SPS.

Traveltimes in the Colorado Plateaus Province. From distances of about 275 to 710 km, the NTS-Ordway profile crosses the Colorado Plateaus Province: differences in crustal structure from that of the eastern Basin and Range Province are indicated by changes in the traveltime curve, beginning at about Δ = 385 km and extending to about 775 km. Along this portion of the profile, five events on the seismograms can be traced, with varying degrees of reliability, from one recording location to the next.

Examples of these five arrivals are shown in Figures 5 and 6 on records made at the same recording location (number 21, near Monticello, Utah) during the explosions HARDHAT and CHINCHILLA. The differences in frequency content between these two recordings, especially in the initial part of the seismogram, are striking. The frequency characteristics of P_n at considerable distance appear to be primarily source-dependent; frequencies vary on records made at the same location during different explosions, but remain fairly constant from one location to another during a single shot. Because the seismograms in the distance range $385 \leq \Delta \leq 775$ km were obtained from six different explosions, correlation of the various phases from one record to another could not be based on similarity of appearance or frequency content of the waves, and analysis of the records was more difficult for the Colorado Plateaus region than for the eastern Basin and Range Province.

The phase which appears as a first arrival at most locations in the Colorado Plateaus is enigmatic. This event, labeled P_A in Figure 3 and Table 2, is characterized by small amplitudes: at location number 20 it can not be identified on the seismogram, and on some of the other recordings it is a questionable arrival. In the distance range from about 390 to 550 km P_A has an apparent velocity of 8.4 km/sec, and from 550 to 730 km it travels with an apparent velocity of about 7.9 km/sec (Fig. 3). Beyond a point at about the eastern boundary of the Colorado Plateaus region, this phase can no longer be picked on the seismograms.

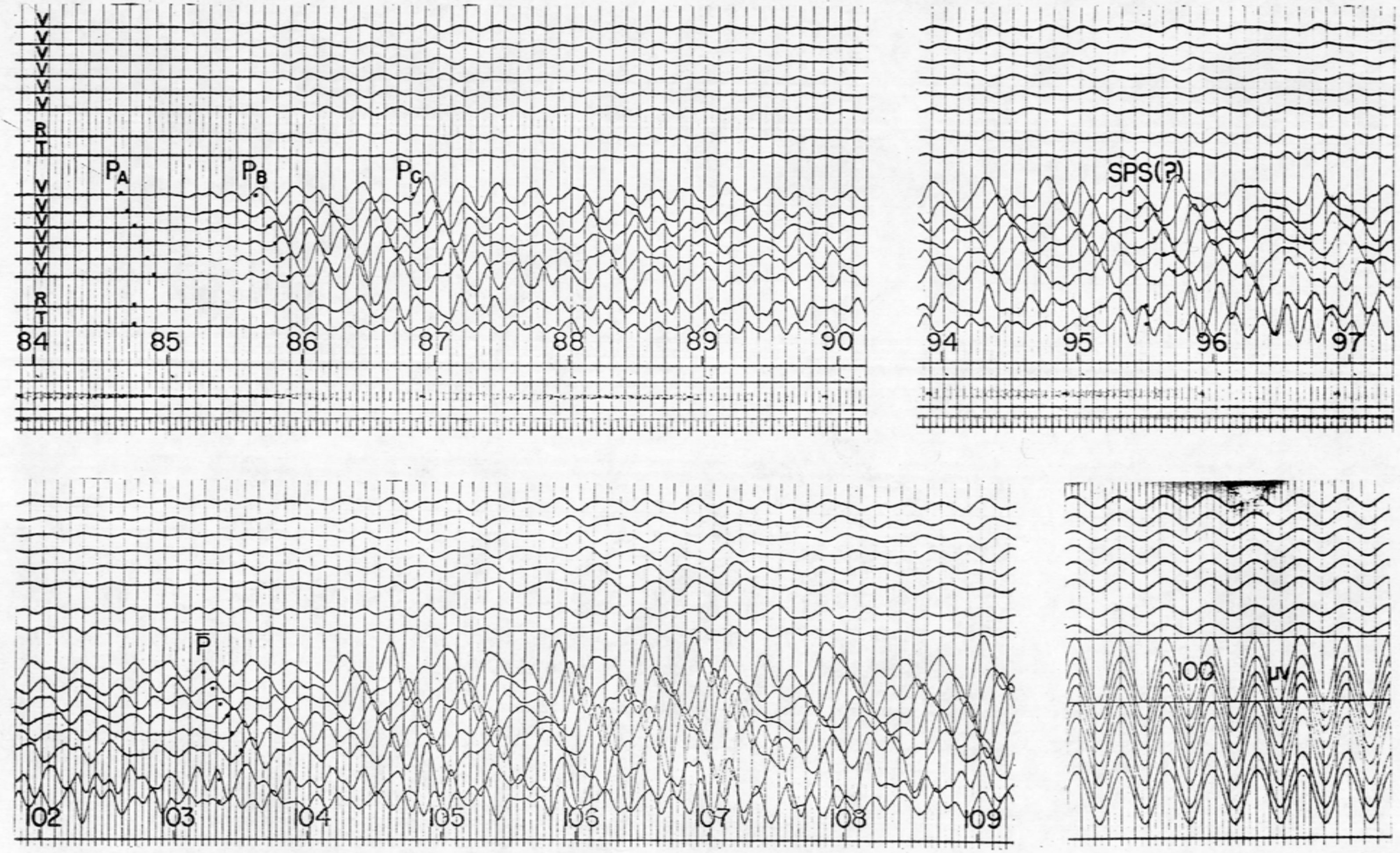

Figure 5.--Seismogram from the HARDHAT nuclear explosion of February 15, 1962, recorded 617.7 - 620.0 km from the source, showing the phases P_A, P_B, P_C, SPS(?), and $\overline{P}$, and the 100-μv calibration signal. Traveltime, in seconds, is plotted along the lower edge of the seismogram. The seismogram was made at two levels of amplification separated by 15 db. At each level of amplification the uppermost six traces are vertical components, and the seventh and eighth traces are radial and transverse horizontal components, respectively. Horizontal seismometers were placed alongside the No. 3 vertical seismometer.

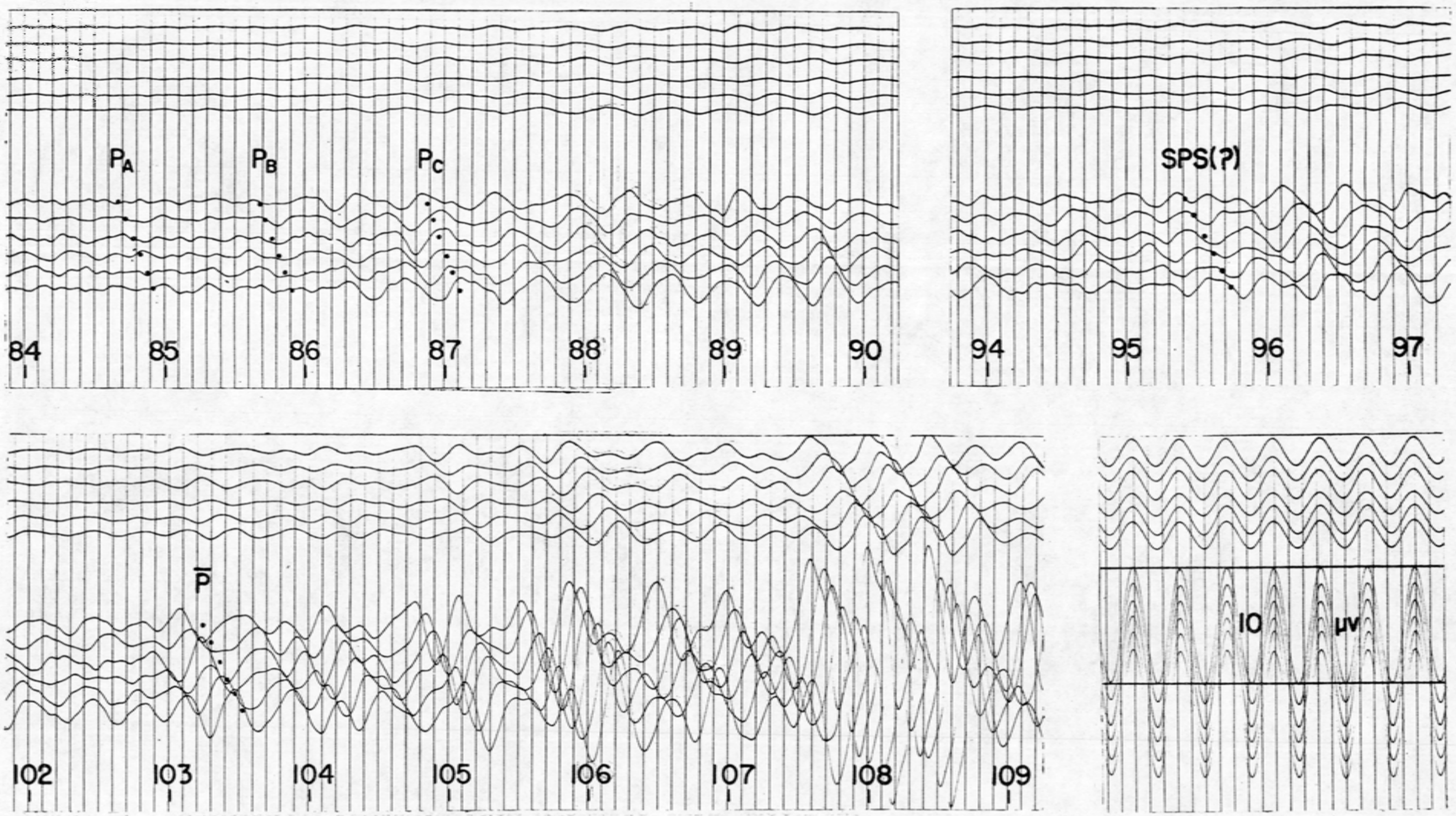

Figure 6.--Seismogram (playback from magnetic tape recording) from the CHINCHILLA nuclear explosion of February 19, 1962, recorded 618.2 - 620.4 km from the source, showing where P_A, P_B, P_C, SPS(?), and $\overline{P}$ would be expected on the basis of the traveltime curve, Figure 3. Traveltime, in seconds, is plotted along the lower edge of the seismogram. The record was made at two levels of amplification separated by 15 db; all traces represent vertical motion.

P_A can be separated from the phase P_B which follows it, by differences in frequency, amplitude, and particle motion of the two phases. On most of the seismograms obtained in the Colorado Plateaus, the beginning of P_B is marked by an abrupt change in slope or increase in amplitude; on at least two seismograms the frequency of P_B is somewhat lower than that of P_A, but since the frequency content of both phases varied from one shot to another, it was not possible to study in detail the frequency relation between the two events. On the seismogram shown in Figure 5, there appears to be a gradual increase in amplitude and period of the waves throughout the first 1.7 seconds of recording, and on this record the phase P_B could be taken for a continuation of P_A. However, when the particle motion in the r-z plane is plotted for the first two seconds of this recording (Fig. 7), the motion is seen to change, from progressive-elliptical in P_A to a more complicated, more linear motion in P_B.

Neither of the phases, P_A nor P_B, is observed as a secondary arrival in the Basin and Range Province, and it is not possible to trace the 7.6 km/sec branch of the traveltime curve from that region into the Colorado Plateaus. It therefore seems probable that either P_A or P_B must represent P_n in the Colorado Plateaus region, and that the differences in apparent velocity between the two provinces are due either to structure or to a lateral change in upper-mantle velocity.

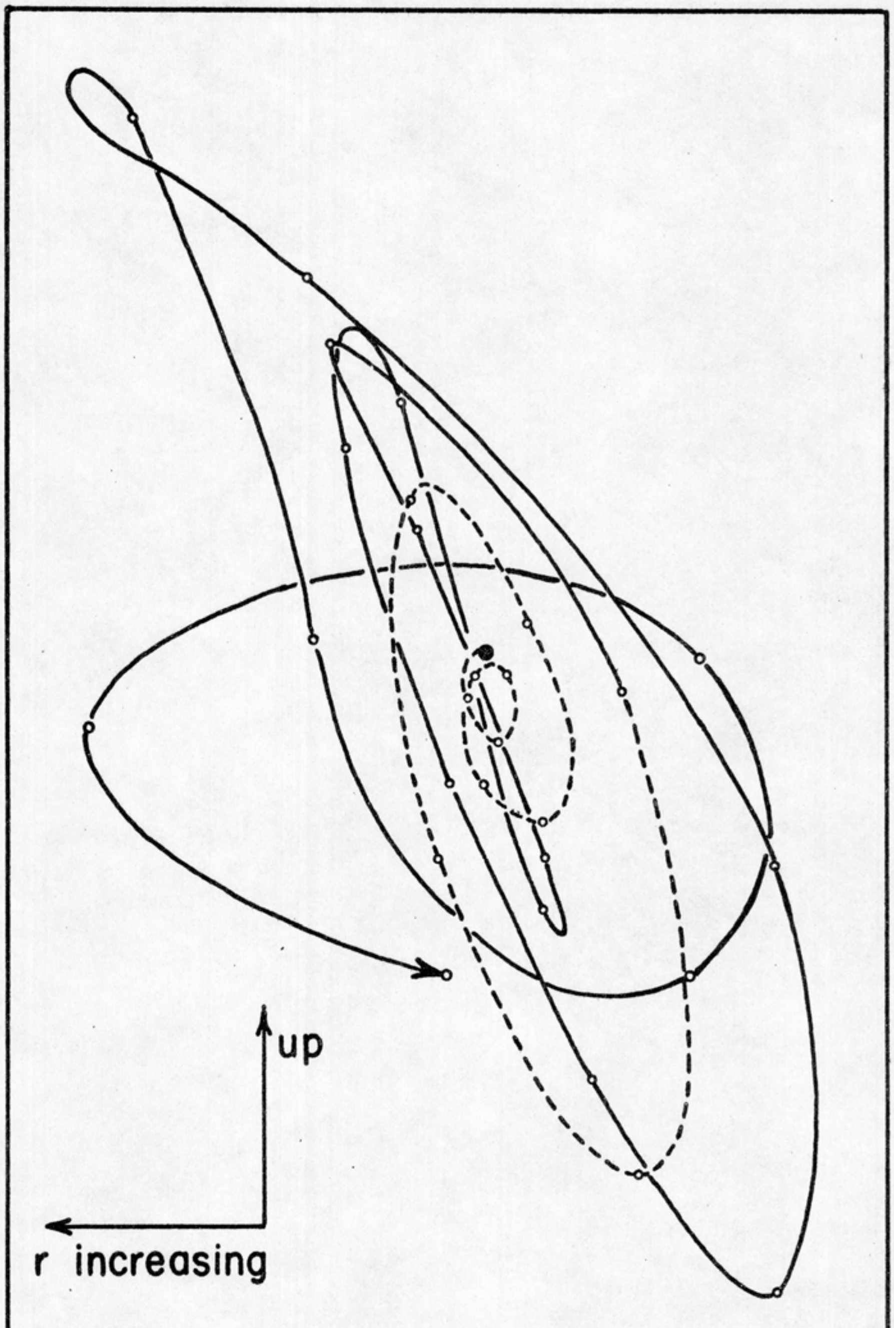

Figure 7.--Particle motion diagram of the phases P_A (dashed line) and P_g (solid line), for the HARDHAT nuclear explosion, recorded at 618.7 km from the source. Points are separated in time by 0.05 sec.

The ambiguity regarding the relation of these two events to P_n can be resolved by a consideration of amplitudes. Amplitudes of P_n in the Basin and Range Province and P_B in the Colorado Plateaus have been plotted together as a function of distance (Fig. 8), and the points fit a distance-amplitude curve which is reasonable for P_n, over the distance range $150 \leq \Delta \leq 850$ km. It is therefore concluded that P_B is the P_n phase in the Colorado Plateaus. Without additional data, it is not possible to speculate further on the nature of P_A, or on its relationship to the structure of the crust and upper mantle.

An estimate of the crustal structure in the Colorado Plateaus is provided by a consideration of a phase tentatively identified as SPS. This phase, illustrated in Figure 5, is characteristically a weak but identifiable arrival on both the horizontal and vertical traces. The potential usefulness of SPS in determining crustal structure on an unreversed profile, as well as the ambiguities connected with identification of the phase, are discussed by Pakiser and Hill (1963). SPS(?) is identified on records of the NTS-Ordway profile, in the distance range $435 \leq \Delta \leq 730$ km (Fig. 3). From 435 to about 640 km this phase has an apparent velocity of 8.0 km/sec, and follows P_B (P_n) by 10.3 sec; between 640 and 730 km the apparent velocity of SPS(?), based on two spreads, is about 9 km/sec.

Since both SPS(?) and P_n in the Colorado Plateaus region have an apparent velocity of 8.0 km/sec, it can be inferred, following Pakiser and Hill, that the crust in this region is of constant thickness.

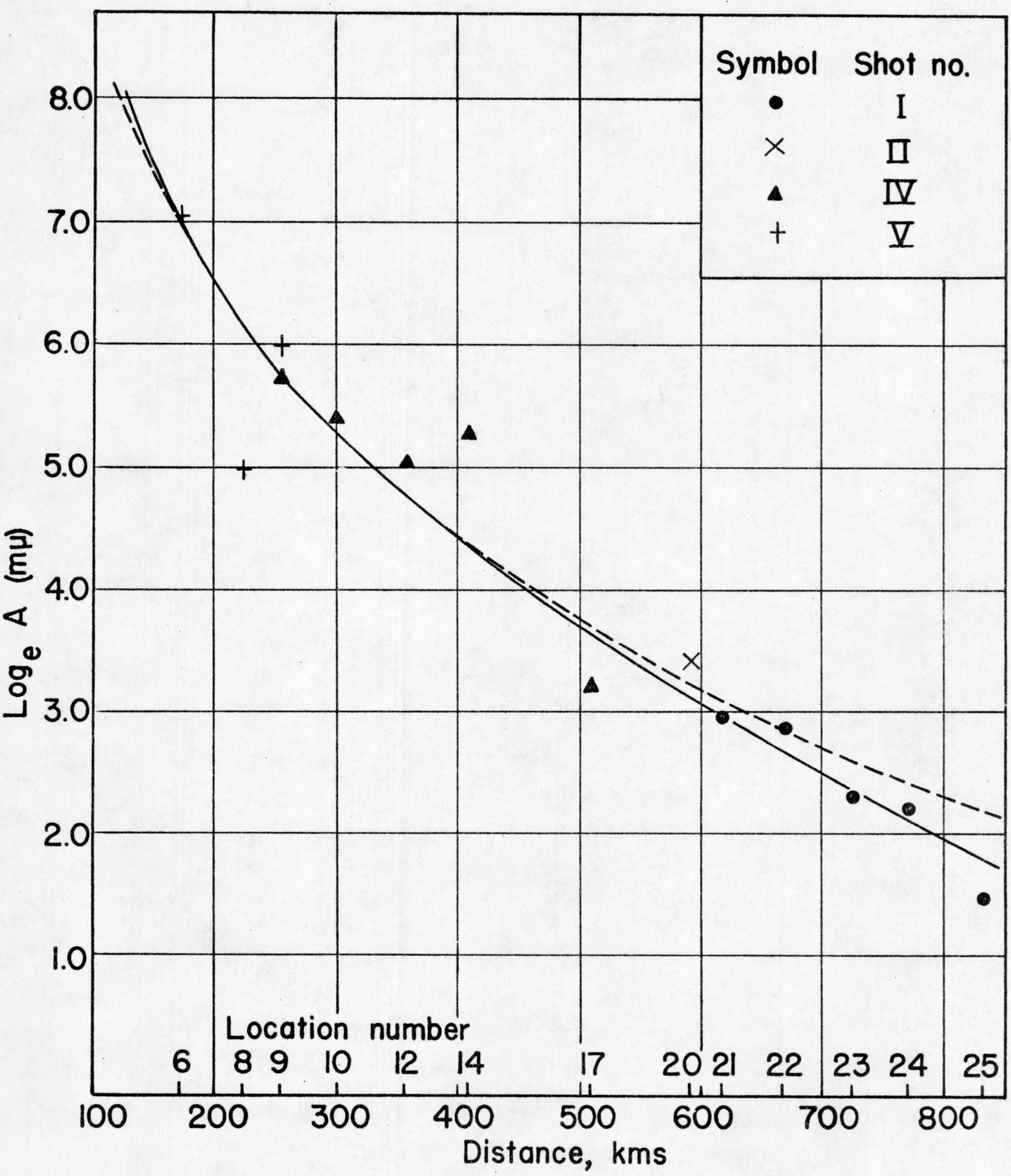

Figure 8.--Measured amplitudes of P_n, in millimicrons. Dashed line: $A = A_o \Delta^{-3}$; solid line: $A = A_o \Delta^{-1/2} (\Delta - d)^{-3/2} e^{-k\Delta}$.

Further, if values of 6.1 and 3.5 km/sec are assumed to represent the average velocities in the Colorado Plateaus crust for P and S waves, respectively, and if Model II in Table 3 is taken to represent the crustal structure in the vicinity of the shotpoint, then from a simple geometric consideration of the refraction paths for SPS(?) and P_n, the thickness of the crust in the Colorado Plateaus region can be found as a function of the time interval SPS(?)-P_n. For SPS(?)-P_n = 10.3 sec, the value obtained for the crustal thickness in the Colorado Plateaus is about 43 km. This is in good agreement with the value for crustal thickness (42 km) found in a previous section for the easternmost part of the Basin and Range Province; however, the identification of SPS on the NTS-Ordway profile must be regarded as provisional, and the agreement in crustal thicknesses may be fortuitous. If, for example, the phase is regarded as PPPPS, a phase which involves multiple crustal paths and reflection from the surface and which would follow P_n by 10.36 sec, the crustal thickness obtained in the Colorado Plateaus would be about 30 km.

It should be noted in passing that the traveltime branch obtained for SPS(?) would not be consistent with a P_n branch represented by the curve for P_A. The velocity pattern for P_A from about 409 to 730 km would imply either a pronounced change in upper-mantle velocity or a change in dip of the Mohorovičić discontinuity at a distance of about 575 km. The constant velocity for SPS(?) from 435 to 640 km would rule out a change in P_n velocity in that region, and the increasing time interval between P_A and SPS(?) from 435 to 550 km would not agree with the crust becoming progressively thinner.

Two additional phases were identified on seismograms made in the Colorado Plateaus Province. The first of these, labeled P_C in Figures 3 and 5, is a questionable secondary event which because of its higher velocity appears as a first arrival beyond about 850 km (Fig. 4). The phase $\overline{P}$ is also a prominent event on seismograms obtained in this region, although the onset of the phase is usually somewhat emergent and mixed with other waves, so that the points for $\overline{P}$ are more scattered than for the other phases on the traveltime curve. The apparent velocity of $\overline{P}$, both in the Colorado Plateaus and in the Southern Rocky Mountains-Great Plains part of the traveltime curve, is about 6.1 km/sec. The traveltime branch for this phase in Figures 3 and 4 is about 0.5 sec early with respect to the $\overline{P}$ branch in the eastern Basin and Range Province.

Traveltimes in the Southern Rocky Mountains and in eastern Colorado. Beyond the Colorado Plateaus Province, the NTS-Ordway traveltime curve is complicated and admits of only cursory analysis. The phase P_C which appears as a first arrival from 850 to 1040 km travels with an apparent velocity of 8.4 km/sec, and can be traced as a questionable second arrival back to a distance of about 509 km. In the Southern Rocky Mountains, the onset of P_C is characteristically a weak compression followed by a large, clear dilatation (Fig. 9). P_C is recorded as a clear arrival on the single-component Benioff system at location 29, at a distance of 1037 km, but at locations 30 and 31 it can not be identified on the seismograms.

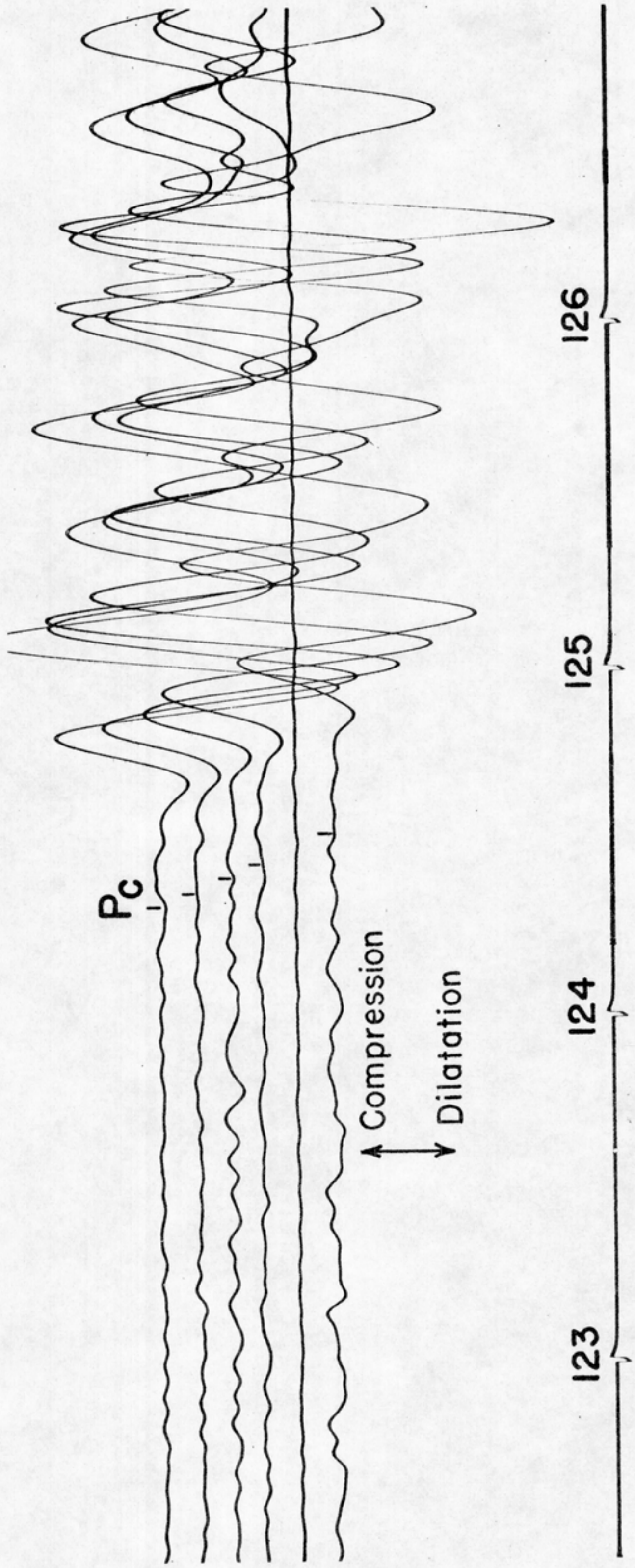

Figure 9.--Seismogram (playback from magnetic tape recording) from the HARDHAT nuclear explosion of February 15, 1962, recorded 930.0 - 932.1 km from the source, showing the onset of the phase P_C. Traveltime, in seconds, is plotted along the lower edge of the seismogram.

Because of its high velocity and the relationship of its travel-time branch to that of P_B, the phase P_C is thought to represent a wave which is refracted from a boundary below the Mohorovičić discontinuity. The possibility is not ruled out, however, that P_C may represent P_n in the Southern Rocky Mountains and that the lineup of secondary arrivals from 509 to 833 km along an extension of the P_C branch of the travel-time curve is merely fortuitous.

In the Southern Rocky Mountains, no prominent arrival is observed, on both the vertical and horizontal traces, which would correspond to SPS(?) of the Colorado Plateaus region. At locations 26 and 28, a phase is observed which is clearly recorded on the horizontals, and a line connecting the picks at these two locations also passes through events which were timed on the vertical traces at locations 25, 29, 30, and 31. The apparent velocity of this wave, 9.3 km/sec, rules out the possibility that the phase is SPS: such a high velocity for SPS would imply that the crust thins rapidly from the Rocky Mountains into eastern Colorado, where crustal thicknesses of 48-50 km have been obtained by several workers (Ewing and Press, 1959; Stewart and Pakiser, 1963; Jackson, Stewart, and Pakiser, 1963).

The phase $\overline{P}$ is also strongly recorded in the Southern Rocky Mountains-eastern Colorado region, but the picks for this phase are scattered on the traveltime curve (Fig. 4). The arrivals at locations 25-31 suggest a 6.1 km/sec traveltime branch for $\overline{P}$. This branch is a continuation of the line plotted in Figure 3 for $\overline{P}$ arrivals in the Colorado Plateaus region.

An extension of the P_B curve, from the eastern part of the Colorado Plateaus Province to the end of the profile, passes through a first arrival at location 24 and through secondary arrivals at locations 26, 27, 28, 30, and 31. This alignment of points suggests that P_n is continuous throughout the regions shown in Figures 3 and 4, but alternative explanations are not ruled out.

Discussion. Two additional points should be mentioned in regard to the analysis of traveltimes. First, it is possible to delineate seismic "provinces", on the basis of variations in upper-mantle velocity and crustal thickness, which correlate roughly with the provinces defined by physiography. Such a correlation was noted earlier by Ryall (1962) in his study of P waves generated by the Hebgen Lake earthquake. In the case of the Basin and Range Province and the Colorado Plateaus, however, there is an apparent discrepancy between the physiographic boundary as defined by Fenneman (Fig. 1), and that obtained in the analysis of seismic waves. The former lies at a distance of 275 km to the east of NTS, while the boundary indicated by changes in the traveltime curve (Figs. 2 and 3) is at a distance of about 385 km, and correlates with the eastern limit of a north-trending fault zone that traverses the region. The area traversed by this fault zone is known as the High Plateaus, and has usually been considered a subprovince of the Colorado Plateaus. There is geologic evidence, however, that would support the assignment of the north-trending fault zone of the High Plateaus to the Basin and Range Province rather than with the Colorado Plateaus (Kelley, 1955). The seismic data suggest that the influence of Basin and Range tectonics extends across the High Plateaus region.

Secondly, no definite relationship was observed, on the NTS-Ordway profile, between elevation of the recording location and delays or early arrivals on the traveltime curve (Figs. 2, 3, and 4). Arrivals of the phase $\overline{P}$ are somewhat delayed in the high Rocky Mountains region, in comparison with the arrivals at lower elevations in the western part of the Great Plains, but the phase P_C is not delayed in the same region. In spite of considerable differences in elevation in the eastern Basin and Range-western Colorado Plateaus region (Fig. 2), most of the picks in that area fall within 0.1 sec of branches of the traveltime curve.

AMPLITUDES AND FREQUENCIES

For three of the phases discussed in the previous section---P_g, P_n, and $\overline{P}$---peak-to-peak amplitudes were measured on the seismograms and reduced to ground displacement in millimicrons (mμ), using system calibration curves derived by Eaton (1963). By comparing measured amplitudes of prominent arrivals on seismograms obtained at the same location during different explosions, it was possible to calculate "shot factors" that could be used to inter-relate amplitudes of the various sections of the profile, without taking into account the yield or medium of the shot. During three of the explosions (VI, VII, and VIII), previous recording locations were not reoccupied and it was not possible to relate amplitudes of these explosions to those of the other five.

Predominant frequencies of measured amplitudes were estimated by eye. For the phase P_n these frequencies fell into a fairly narrow band, 2.2 to 4.0 cps. Some correlation was observed between individual shots and frequencies in P_n (Table 4), and this correlation is presumed to be primarily a function of the source medium. The frequency content was not observed to behave regularly as a function of distance from NTS (Table 5). In calculating the value of the constant, Q, for P_n, an average value of 3.0 cps was assumed.

Table 4.--Mean estimated frequencies for P_n.

Shot	Mean Frequency, cps	No. of Points	Yield, KT	Medium
I	3.3 ± 0.4	5	5	Granite
II	2.0 ± 0.0	2	1.8	Alluvium
IV	3.1 ± 0.6	5	7.8	Alluvium
V	2.4 ± 0.1	3		

In general, the frequency content of the $\overline{P}$ wave on the NTS-Ordway profile is constant - about 3 cps - for the first two seconds of recording. At larger distances the later part of the phase contains lower frequencies, down to about 1-1/2 cps. The frequency of $\overline{P}$ does not change noticeably from one shot to another. The predominant frequency of P_g, based on four recordings of a single explosion, is about 4 cps out to a distance of 150 km.

Table 5.--Estimated frequencies (f, cps) and measured amplitudes (A, mμ). Amplitudes for shots I to V were scaled to the HARDHAT explosion using shot factors; amplitudes for shot VI were shifted by an arbitrary amount to approximately scale to HARDHAT.

Location Number	Shot	P_g		P_n		$\bar{P}$	
		f	A	f	A	f	A
1	VI	4.0	8,100				
2	V					4.3	20,900
3	VI	4.5	434			2.2	60,700
4	VI	4.0	160				
5	VI	4.0	57.8				
6	V			2.2	1,140	2.4	3,210
8	V			2.5	147	3.0	6,440
9	III			4.0	241		
	IV			3.0	300	2.5	2,530
	V			2.5	414	3.0	3,520
10	IV			3.0	222	3.0	3,890
11	VI					2.2	1,274
12	IV			3.8	153	3.0	637
13	VI					2.2	1,075
14	IV			3.6	194	3.3	765
17	IV			2.2	25.1	3.0	538

Table 5.--Estimated frequencies (f, cps) and measured amplitudes (A, mμ). Amplitudes for shots I to V were scaled to the HARDHAT explosion using shot factors; amplitudes for shot VI were shifted by an arbitrary amount to approximately scale to HARDHAT. (Continued)

Location Number	Shot	P_g f	P_g A	P_n f	P_n A	$\overline{P}$ f	$\overline{P}$ A
20	II			2.0	30.8		
21	I			4.0	19.5	3.0	81.0
	II			2.0	19.5	2.0	79.7
22	I			3.0	17.7	3.0	96.2
23	I			3.0	10.1	3.0	84.4
24	I			3.0	9.20	3.0	20.4
25	I			3.6	4.49	3.0	24.9
26	I					3.0	9.56
27	I					3.0	12.0
28	I					3.0	4.08

Amplitudes of P_n. P_n amplitudes were measured using arrival times indicated by the traveltime branches P_n and P_B. Following the time on the seismogram corresponding to the time indicated by the P_n or P_B line in Figures 2 and 3, measurements were made, on at least two traces, of the peak-to-peak amplitudes of the first dilatation and the compression following this dilatation. An estimate was made of the predominant frequency in this part of the recording, and, using the 3-cps calibration signals, the mean of the amplitude measurements was reduced to ground displacement. By means of shot factors, all amplitudes were then scaled to the HARDHAT explosion. The final values are listed, together with estimated frequencies, in Table 5, and are plotted as a function of distance in Figure 8.

Two curves have been drawn through the points in Figure 8. The first of these, $A = A_o \Delta^{-3}$, corresponds to the inverse-cube amplitude-distance relation found by Romney (1959) in a study of underground nuclear explosions. The second curve was drawn with the requirement that the amplitudes die off as $\Delta^{-1/2} (\Delta - d)^{-3/2} e^{-k\Delta}$, where d = 60 km is the distance to the point of emergence of the first critically refracted P_n ray. The attenuation factor $\Delta^{-1/2} (\Delta - d)^{-3/2}$ corresponds to a geometrical spreading factor for head waves, derived by Heelan (1953); the term $e^{-k\Delta}$ represents the effect of scattering and absorption in the medium in which the wave propagates. The line which provided a best fit to the data points has a value of k equal to 0.0022/km.

Using this value for k (the absorption coefficient), Q, can be calculated (Knopoff, 1956; Gutenberg, 1959):

$$Q = \pi f / kv,$$

where f and v are the frequency and velocity, respectively, for P_n waves. For an average velocity of 7.95 km/sec for the P_n waves observed in the distance range $100 \leq \Delta \leq 850$ km, and an average frequency for these waves of 2.9 ± 0.5 cps obtained from the values in Table 4, the dimensionless constant, Q, is equal to 520. For the range of frequencies just given, Q can have values in the range 430-610. The value of 520 for Q of P_n waves is higher than that found by Werth, Herbst, and Springer (1962) and Wright, Carpenter, and Savill (1962) in studies of amplitudes from nuclear explosions; it is lower than values found by Gutenberg (1959) for body waves with periods of 2-4 sec.

Amplitudes of $\overline{P}$. The maximum amplitudes of $\overline{P}$, within the first two seconds of recording of the phase, were measured and are shown in Figure 10. The points represented by square symbols in this figure were obtained from recordings of shot VI. Since it was not possible to obtain a shot factor for this explosion, these points were shifted by an arbitrary amount, such that the $\overline{P}$ amplitudes for shot VI fall within the zone of measurements of $\overline{P}$ from other explosions. By this means, it was possible to illustrate the rapid decrease of amplitudes of the phase P_g (measured only for shot VI) in comparison with those of $\overline{P}$.

Several lines were drawn through the points in Figure 10 corresponding to amplitude-decrease formulas involving geometrical spreading factors Δ^{-3}, Δ^{-2}, Δ^{-1}, and $\Delta^{-1/2}$. At distances beyond about 150 km, the best fit

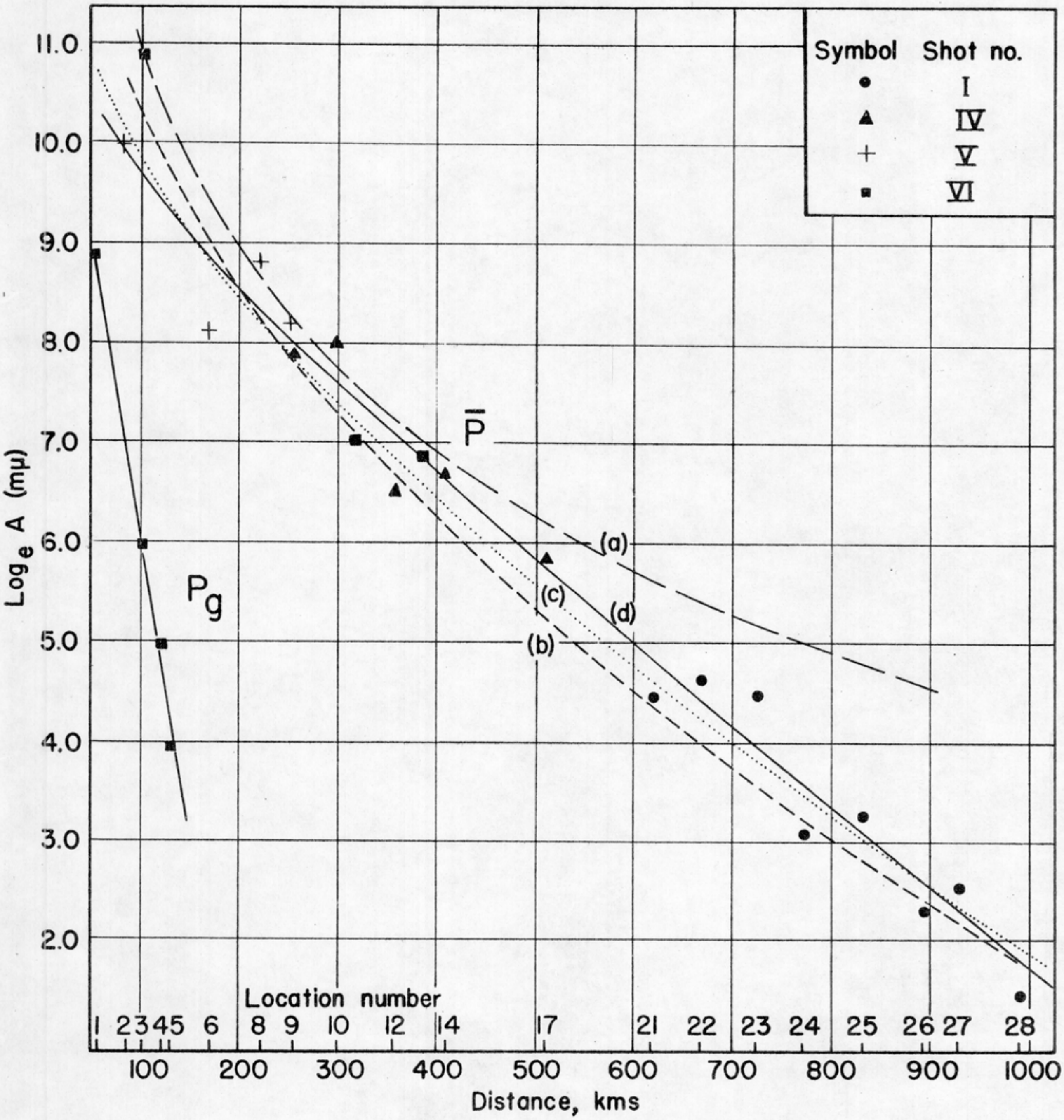

Figure 10.-- Measured amplitudes of P_g and $\overline{P}$, in millimicrons. Equations of curves: (a) $A = A_o \Delta^{-3}$; (b) $A = A_o \Delta^{-2} e^{-0.0046 \Delta}$; (c) $A = A_o \Delta^{-1} e^{-0.0056 \Delta}$; (d) $A = A_o \Delta^{-1/2} e^{-0.0076 \Delta}$.

seems to be obtained with the equation $A = A_o \Delta^{-1/2} e^{-0.0076\Delta}$. This equation would imply that the $\overline{P}$ wave is propagating essentially in two dimensions, and is probably, therefore, trapped in the upper part of the crust. Such a phase might correspond to waves reflected at the intermediate boundary beyond the critical angle. The value of Q for this phase is about 200.

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