UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 21

SEISMIC-REFRACTION MEASUREMENTS OF CRUSTAL STRUCTURE BETWEEN AMERICAN FALLS RESERVOIR, IDAHO, AND FLAMING GORGE RESERVOIR, UTAH*

by

Ronald Willden**

DENVER, COLORADO

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-21
July 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:

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by

Ronald Willden**

Sincerely,

L. C. Pakiser

L. C. Pakiser, Chief
Branch of Crustal Studies

* Work performed under ARPA Order No. 193-64.

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

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by

Ronald Willden**

Abstract. Interpretation of a reversed seismic-refraction profile recorded between American Falls reservoir and Flaming Gorge reservoir in May 1963 indicates that the depth to the Mohorovicic discontinuity is about 31 km at American Falls and 37 km at Flaming Gorge. The existence of an intermediate crustal layer at a depth of about 19 to 21 km beneath the profile is well supported by refractions and reflections.

The velocity of compressional waves in the mantle just beneath the Mohorovicic discontinuity is about 7.8 km/sec, their velocity in the intermediate layer is about 6.9 km/sec, and their velocity in the upper crust (beneath the near-surface low-velocity material) is about 5.9 km/sec.

A prominent phase with an apparent velocity of 8.4 km/sec was recorded at distances of 210 km to 325 km from shots at American Falls. This phase is believed to be a reflection from a boundary within the mantle.

* Work performed under ARPA Order No. 193-64.

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

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by

Ronald Willden**

Introduction. The U. S. Geological Survey recorded a refraction seismic profile between American Falls reservoir, Idaho, and Flaming Gorge reservoir, Utah, during May 1963 (Fig. 1). Recordings were made at 35 locations between shotpoints in the two reservoirs at the ends of the line (Table 1). Shots of 2,000, 2,000, 4,000, and 6,000 pounds were fired at the end shotpoints and shots of 2,000, 2,000, and 4,000 pounds were fired at an intermediate shotpoint in Bear Lake (Table 2). The American Falls reservoir shotpoint was at latitude 42°50.14' and longitude 112°48.66' at a depth of 62 feet for the first 2 shots and was then relocated at latitude 42°51.40' and longitude 112°47.68' and a depth of 55 feet for the last 2 shots. The Bear Lake shotpoint was at latitude 41°56.35' and longitude 111°17.10' and because the shotpoint was near the steep eastern shore the water depth ranged from 135 to 165 feet. The Flaming Gorge reservoir shotpoint was at latitude 40°56.77' and longitude 109°38.43' at a depth of 23 feet.

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

The seismic-recording units used in this profile have been described by Warrick and others (1961) and the field procedures have been described by Jackson and others (1963).

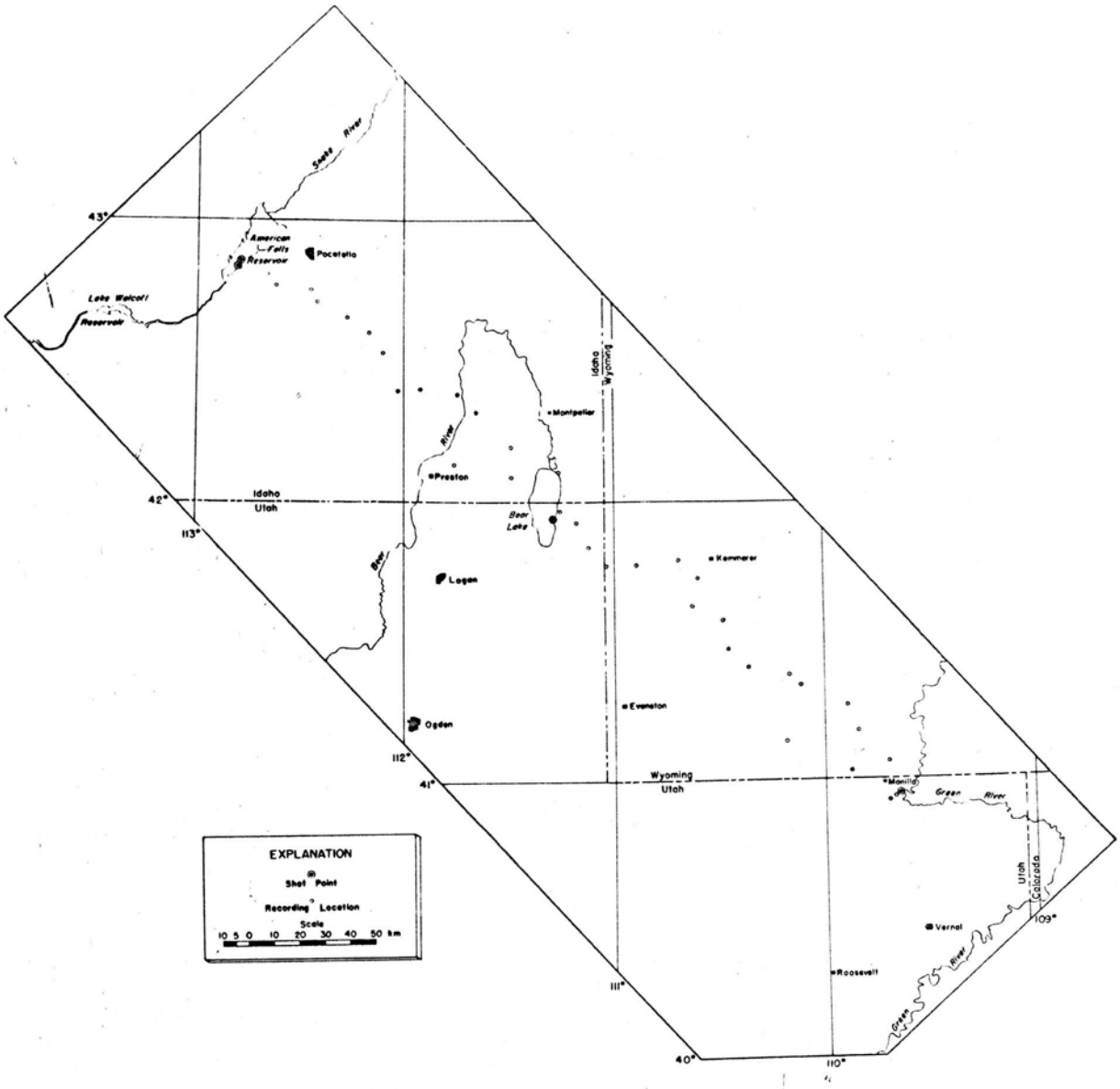

Figure 1.--Location of shot points and recording units on profile American Falls reservoir, Idaho, to Flaming Gorge reservoir, Utah.

Table 1.--Recording Locations

Shot: American Falls 1, Bear Lake 1, Flaming Gorge 1

Recording Unit	Latitude, North	Longitude, West	Altitude (meters)
H	42°39.18'	112°16.29'	1615
I	42°42.48'	112°25.23'	1710
J	42°45.09'	112°27.06'	2010
K	42°35.88'	112°10.02'	1495
L	42°31.74'	112°06.00'	1740
R	42°45.92'	112°37.21'	1400
T	42°48.40'	112°39.95'	1370

Shot: American Falls 2, Bear Lake 2, Flaming Gorge 2

Recording Unit	Latitude, North	Longitude, West	Altitude (meters)
H	42°07.77'	111°45.81'	1555
I	42°18.84'	111°39.36'	1830
J	42°22.74'	111°44.61'	1555
K	42°11.52'	111°29.28'	1980
L	42°05.19'	111°29.22'	2255
P	42°06.21'	111°15.72'	1830
Q	41°58.05'	111°16.2'	1830
R	42°23.81'	111°55.47'	1860
S	41°55.47'	111°10.53'	2105
T	42°23.61'	112°01.74'	1585

Table 1.--Recording Locations (continued)

Shot: American Falls 3, Bear Lake 3, Flaming Gorge 3

Recording Unit	Latitude, North	Longitude, West	Altitude (meters)
H	41°43.26'	110°35.97'	2010
I	41°47.36'	110°41.50'	2105
J	41°46.44'	110°53.73'	2010
K	41°37.38'	110°37.50'	2090
L	41°34.14'	110°28.86'	1980
P	41°28.02'	110°27.36'	2010
Q	41°24.00'	110°21.75'	2060
R	41°46.32'	111°02.07'	1950
S	41°22.26'	110°10.08'	1995
T	41°50.28'	111°07.08'	1920

Shot: American Falls 4, Flaming Gorge 4

Recording Unit	Latitude, North	Longitude, West	Altitude (meters)
H	41°01.65'	109°52.56'	2135
I	42°18.84'	111°39.36'	1830
J[1/]	41°15.75'	109°53.31'	2040

1/ Location questionable.

Table 1.--Recording Locations (continued)

Shot: American Falls 4, Flaming Gorge 4 (continued)

Recording Unit	Latitude, North	Longitude, West	Altitude (meters)
K	41°03.54'	109°41.70'	2090
L	40°55.95'	109°40.06'	1845
P	41°20.04'	110°06.51'	2105
Q	41°10.14'	109°50.58'	2150
R	41°08.10'	110°10.71'	2225
S	40°55.14'	109°41.76'	1860
T	41°50.28'	111°07.08'	1920

Location given for west end of each spread.

Table 2.--Shotpoint Locations, Size, and Timing.

Shot	Date	Size (in pounds)	Altitude Meters	Location Lat. North	Location Long. West	Shot time (MST)
American Falls 1	May 22, 1963	2000	1330	42°50.14'	112°48.66'	8:00:00.12
American Falls 2	May 23, 1963	2000	"	"	"	7:49:59.75
American Falls 3	May 24, 1963	4000	"	42°51.40'	112°47.68'	8:59:59.23
American Falls 4	May 25, 1963	6000	"	"	"	7:30:00.21
Bear Lake 1	May 22, 1963	4000	1810	41°56.35'	111°17.10'	8:30:00.37
Bear Lake 2	May 23, 1963	2000	"	"	"	7:19:59.30
Bear Lake 3	May 24, 1963	2000	"	"	"	7:30:00.19
Flaming Gorge 1	May 22, 1963	6000	1730	40°56.77'	109°38.43'	7:00:00.10
Flaming Gorge 2	May 23, 1963	4000	"	"	"	6:59:59.84
Flaming Gorge 3	May 24, 1963	2000	"	"	"	7:09:59.79
Flaming Gorge 4	May 25, 1963	2000	"	"	"	6:59:59.95

GEOLOGY AND PHYSIOGRAPHY

The seismic profile extends from the east edge of the Snake River Plain across the southeastern Idaho - western Wyoming overthrust belt and across the southwestern part of the Green River Basin to the north flank of the Uinta Mountains. The recording locations between American Falls reservoir and Bear Lake were at an average altitude of 1726 meters and those between Bear Lake and Flaming Gorge reservoir were at an average altitude of 2036 meters.

Between American Falls reservoir and Kemmerer, Wyoming, the profile crosses 5 rather prominent north-trending mountain ranges and the intervening valleys. The mountain ranges are characterized by north-trending structural features and owe most of their present relief to post-Pliocene displacement on normal faults that bound the individual mountain blocks (Armstrong and Cressman, 1963, pl. 4, p. J 20). According to Armstrong and Cressman (1963) the pattern of alternating mountains and valleys in southeastern Idaho and adjacent parts of Wyoming and Utah predates the deposition of the Salt Lake formation (Pliocene) and postdates the deposition of the Wasatch formation (Eocene).

Rocks exposed along the profile in the mountain ranges northwest of Bear Lake are mainly Paleozoic carbonate and clastic sediments. In the valleys, the rocks are Tertiary and Quaternary clastic sediments. Southeast of Bear Lake the rocks for the most part are clastic sediments of Mesozoic and Tertiary age. Precambrian Belt series rocks are exposed in the Uinta Mountains just south of the southeast end of the profile and

Precambrian (?) metamorphosed carbonate and clastic rocks are exposed in the Bannock range just north of the profile. The Tertiary and upper Cretaceous clastic sediments -- presumably low-velocity material -- in at least part of the Green River Basin attain a thickness of about 20,000 feet (Jenkins, 1955).

CHARACTERISTICS OF SEISMOGRAMS

All three shotpoints provided relatively efficient conversion of explosive energy to seismic energy, and, except for some locations between American Falls reservoir and Bear Lake, the quality of the seismograms recorded along the profile is good (Fig. 2).

American Falls reservoir. The first arrivals (Table 3 and Fig. 3) on 8 of 9 seismograms out to a distance of about 88 km represent the direct wave and are designated P_g. The first upward (compressive) motion can be identified on most of these seismograms.

The first arrivals on 5 seismograms in the distance range 102 km to 137 km are identified as a refracted wave from an intermediate layer with a velocity of 6.9 km/sec and are designated P*. A strong secondary arrival recorded on the seismograms in the distance range 35 km to 151 km has been identified as a reflected wave from the upper boundary of this intermediate layer and is designated P_IP (Figs. 2 and 4). This arrival is generally the strongest event on the seismograms in the distance range 35 km to 88 km.

Refractions from the Mohorovicic discontinuity (P_n) appear as first arrivals on the seismograms from 151 km to the end of the profile at 336 km.

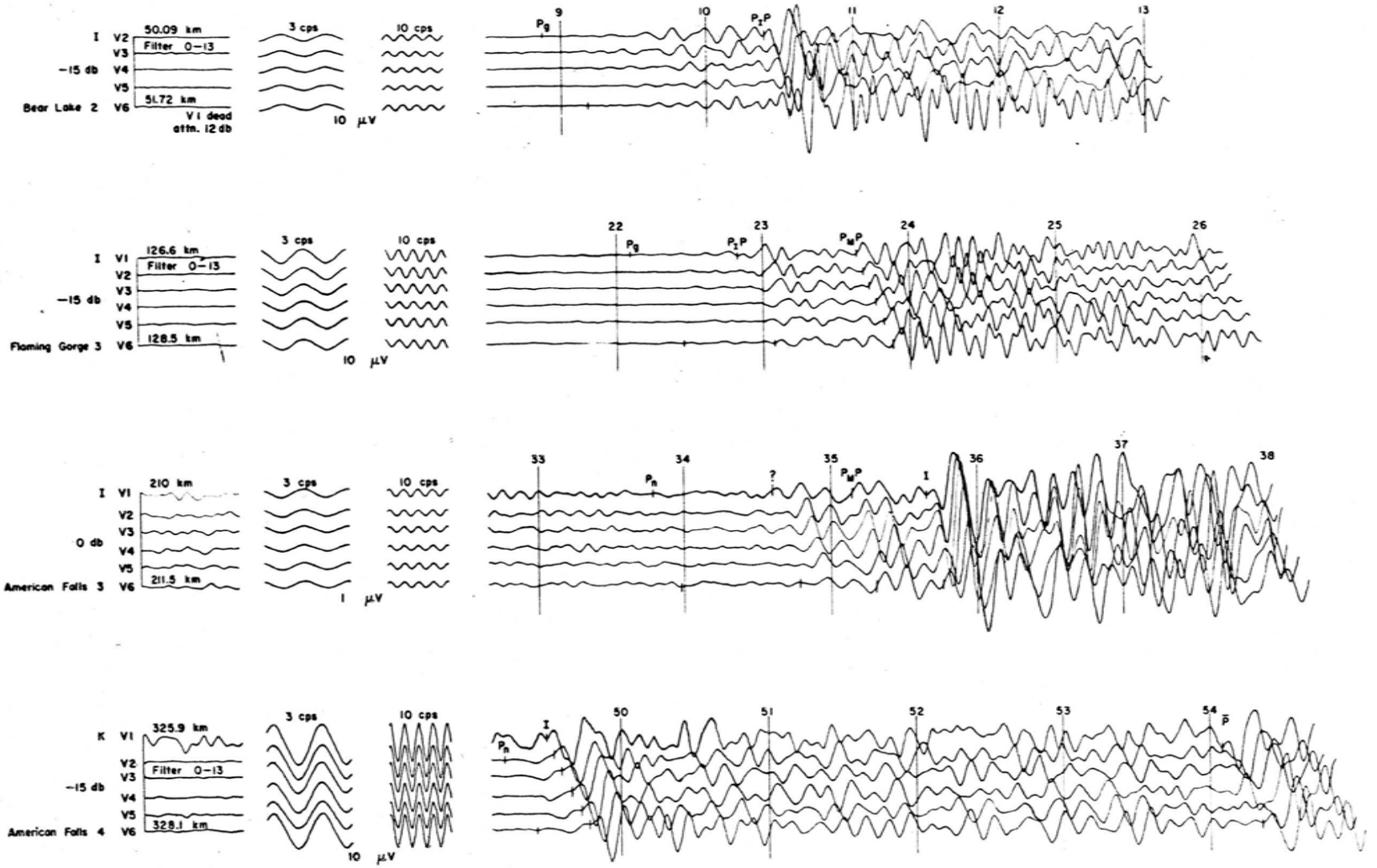

Figure 2.--Representative seismograms from profile American Falls reservoir to Flaming Gorge reservoir. Vertical lines represent seconds after shot time. Calibrations recorded with same instrument adjustments are shown on left.

Table 3.--Arrival Times of Prominent Phases

Shot: American Falls 1 - 2000 lbs.

		P_g		P_IP		P_MP		P*		P_n		$\bar{P}$		I		Other(x)	
Unit	Dist (km)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)
T	12.30	3.29	150														
R	17.46	3.86	140														
J	30.90	5.97	13.1														
I	34.97	6.63	18.2	9.46	33.8											8.09	27.1
H	48.61	8.90	15.8	11.59	35.7											10.26	39.7
K	58.99			13.07	2.1	14.45	3.0									11.87	3.3
L	67.50	12.46		13.77													

Shot: American Falls 2 - 2000 lbs.

T	81.13	14.54	2.8	15.36	29.1												
R	87.56	15.42	1.3	15.98	10.9												
J	101.48			18.66	13.5	19.76	22.6	18.51	1.5							19.06	
I	111.13			20.24	9.5	20.94	6.8	19.79	3.8							22.04	8.7
H	116.50			21.05	10.1	21.50	14.1	20.80	2.5								
K	130.48					23.73	12.9	22.81	2.1							23.21	4.5
L	137.27			23.98	1.7	24.62	6.3	23.59	.83								
P	151.14			26.70	3.6					26.01	1.7					26.90	2.7
Q	158.54									27.09						28.61	
																29.48	5.0
S	168.48									28.45	5.4					30.32	5.3

Table 3.--Arrival Times of Prominent Phases (continued)

Shot: American Falls 3 - 4000 lbs.

		P_g		P_IP		P_MP		P*		P_n		$\bar{P}$		I		Other(s)	
Unit	Dist(km)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)
T	178.58					30.23	6.1			29.56	1.2					31.23	7.6
R	188.61					32.11											
I	210.02					35.17	.48			33.79	.28			35.68	4.5	34.63 36.48	.91 2.2
H	220.66					36.64	2.4			35.48	.97			37.23	7.5		
K	225.50					37.26	1.3			36.29	.40			37.70	7.2		
L	238.66					38.52	2.2							39.16	3.6	38.19	.75
P	247.34					39.89	2.3			39.61	.46			41.20	3.3		
Q	258.11									40.31	.57	43.53	2.8	41.56	2.1	41.13 42.33	.34 2.8
S	272.80					43.77	1.04			42.40	.25			43.25	1.3		
Shot: American Falls 4 - 6000 lbs.																	
P	279.26					43.44	1.7			43.02	0.1			44.00	1.7	44.94	1.7
R	289.06					46.21	3.6			44.32	0.07			45.22	1.2	44.85 45.92 50.20	0.29 0.74 4.5
J	298.69			(Recording unit not accurately located)						44.99	0.13				.89		
Q	308.08					49.29				47.02		51.65		47.51		48.25	
H	315.99									47.90	0.15			48.24	.41	48.72 49.10	.19 .68
K	325.86									49.19	0.07	54.08	2.6	49.49	1.8	49.83 50.39 51.27	0.62 0.69 1.01
S	335.34									49.66							
L	336.17									49.68							

Table 3.--Arrival Times of Prominent Phases (continued)

Shot: Bear Lake 1 - 4000 lbs

		P_g		P_IP		P_MP		P*		P_n		$\overline{P}$		I		Other(s)	
Unit	Dist(km)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)
T	149.07			26.09												26.50	
R	142.02			24.95	3.0			24.36	1.9								
J	129.68			22.90	4.5			22.59	0.77								
I	124.66			22.31	14.5			21.89	4.9								
H	111.99			20.21	53.7			20.21	53.7	(Can not separate P_IP and P* on seismogram)							
K	101.29	18.21	2.8	18.96	21.5												
L	92.27	16.79															

Shot: Bear Lake 2 - 2000 lbs.

T	77.62	14.26	2.8														
R	71.54	12.9	1.7	13.32	10.6												
I	50.09	8.87	1.6	10.39	26												
H	42.81	8.12	31.7	9.56	167												
K	31.41	5.80	9.7														
L	22.49	4.52															
P	16.18	3.66	1172														

Table 3.--Arrival Times of Prominent Phases (continued)

Shot: Bear Lake 2 - 2000 lbs (recording towards Flaming Gorge shot point)

		P_g		P_IP		P_MP		P^*		P_n		$\bar{P}$			I	Other(s)	
Unit	Dist(km)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)
S	9.23	2.17	1518														
Shot:	**Bear Lake 3 - 2000 lbs**																
T	17.84	3.63	35														
R	27.88	5.28	103														
J	36.35	7.12	129														
I	52.00	9.71	9.6	11.25	52.8												
H	61.89	11.63	7.7	12.67	10.9												
K	65.15	12.25	9.0														
L	78.50	13.56	0.88	14.86	5.5												
P	86.67	15.59	0.57	15.73	6.5												
Q	97.41	17.24		17.24	25.5												
S	112.43			19.65	1.8	20.31	2.4	19.38	0.95								
Shot:	**Flaming Gorge 1 - 6000 lbs**																
T	325.22															49.49	
R	317.60											52.77	1.6			47.50	0.44
I	300.71											49.91	2.6			48.28	
H	287.67									43.70	1.04						
K	277.11															42.49 44.82	
L	268.23									40.94		45.18				41.54	

Table 3.--Arrival Times of Prominent Phases (continued)

Shot: Flaming Gorge 2 - 4000 lbs

		P_g		P_IP		P_MP		P*		P_n		$\bar{P}$		I		Other(s)	
Unit	Dist(km)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)
T	253.81									39.44		42.19	1.8				
R	247.56									38.97	0.25	41.18	0.63				
J	234.72									37.64	0.45	39.24	2.1				
I	224.64									36.25	0.18	37.32	0.44			36.73	.46
H	218.40															36.29	2.2
K	207.10									33.31							
L	198.29									32.37	1.9						
P	184.62					31.03	8.3			30.71	2.4						
S	166.29					28.52	8.8	27.89	4.0								
Shot: Flaming Gorge 3 - 2000 lbs																	
T	156.62					27.26	10.1	26.40	2.5								
R	146.05					26.02	8.4	25.28	5.5								
J	139.57			24.81	11.8			24.02	0.74								
I	126.65	22.10	0.32	22.83	3.3	23.64	4.3										
H	115.69	20.34	4.5	21.13	8.4	22.32	14.5										
K	109.36	19.11	1.1	19.82	11.8												
L	98.39	17.58		18.41		20.36										19.46	
P	87.12	16.01	6.0	16.62	5.7	18.92	8.9										
Q	76.33	14.14		14.89		17.79											
S	62.37	11.91		12.81													

Table 3.--Arrival Times of Prominent Phases (continued)

Shot: Flaming Gorge 4 - 2000 lbs

		P_g		P_IP		P_MP		P*		P_n		$\bar{P}$		I		Other(s)	
Unit	Dist(km)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)	t(sec)	A(mμ)
P	55.96	11.12	19.6	11.95	15.5												
R	47.77	9.41	15.6	10.48	17.7												
J	39.04	8.80	7.9	10.06	45.5	(Recording unit not accurately located)											
Q	28.25	6.32															
H	19.78	4.54	117														
K	10.98	2.73	120														
S	3.30	Direct wave in surface material 0.81 sec, 4520 amp															
L	0.39	Direct wave in surface material 0.18 sec, 5650 amp															

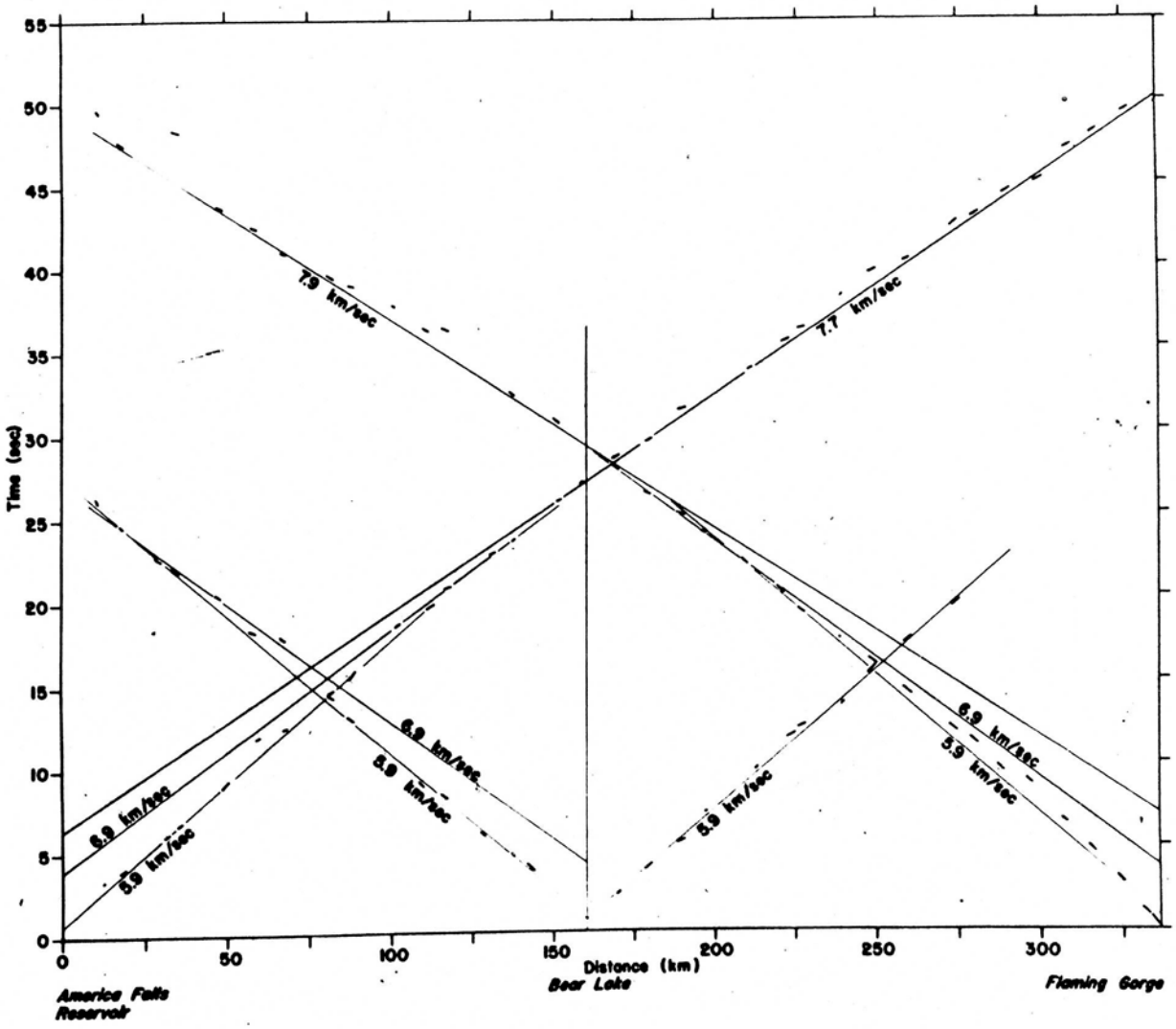

Figure 3.--Travel-time curve of first arrivals between American Falls reservoir and Flaming Gorge reservoir.

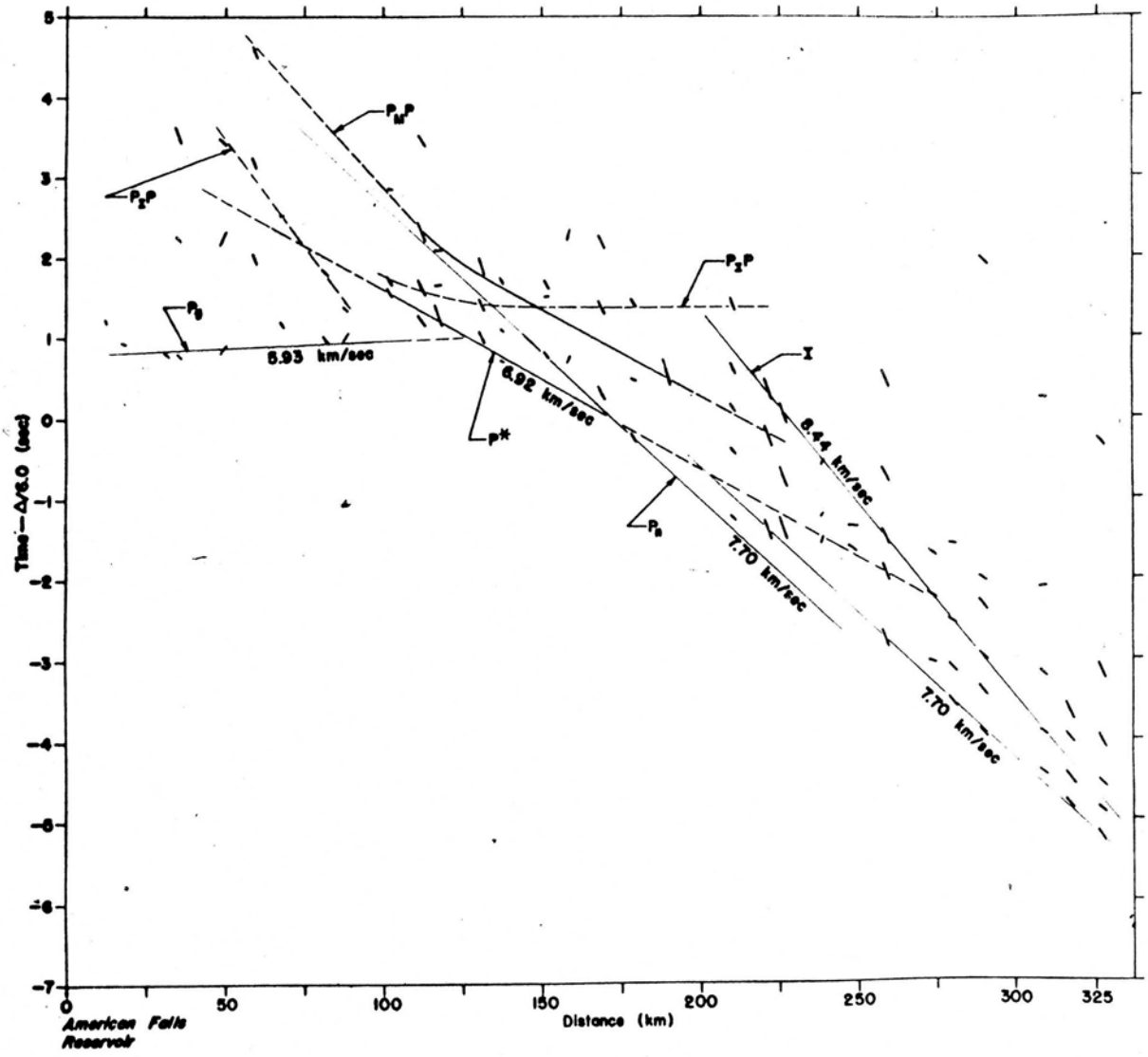

Figure 4.--Reduced travel-time graph: American Falls to Flaming Gorge.

Their identification is somewhat questionable on some of the seismograms at distances greater than 280 km. Reflections from the Mohorovicic discontinuity (P_MP) can be identified on assorted seismograms from 59 km to 308 km (Fig. 4). This event is the strongest arrival on the records in the distance range 101 km to 137 km.

A very strong event appears on the records at a distance of about 210 km (Fig. 2) and persists to the end of the profile. It is the strongest event on the records to a distance of 280 km. This phase has the properties of a reflection from a boundary within the mantle and is herein designated I (Fig. 4). The apparent velocity of this phase is 8.4 km/sec.

On three of the records near the Flaming Gorge end of the profile a strong event with an apparent velocity of about 6.0 km/sec appears. This phase is designated $\overline{P}$.

Many other events on the seismograms cannot be correlated from one recording location to the next.

Bear Lake. Seismograms recorded from explosions in Bear Lake are similar to those recorded out to distances of about 150 km from shots in both American Falls reservoir and Flaming Gorge reservoir.

The first arrivals (Table 3 and Fig. 3) on nine seismograms recorded at distances of 16 km to 101 km towards American Falls reservoir are designated P_g. A phase identified as P_IP first appears at 43 km and persists to the last recording location at a distance of 149 km from the shotpoint (Fig. 5). This phase is the strongest event on the records. The first arrivals on the seismograms from 112 km to 142 km have an apparent velocity appropriate for a refracted wave from an intermediate layer and are designated P*.

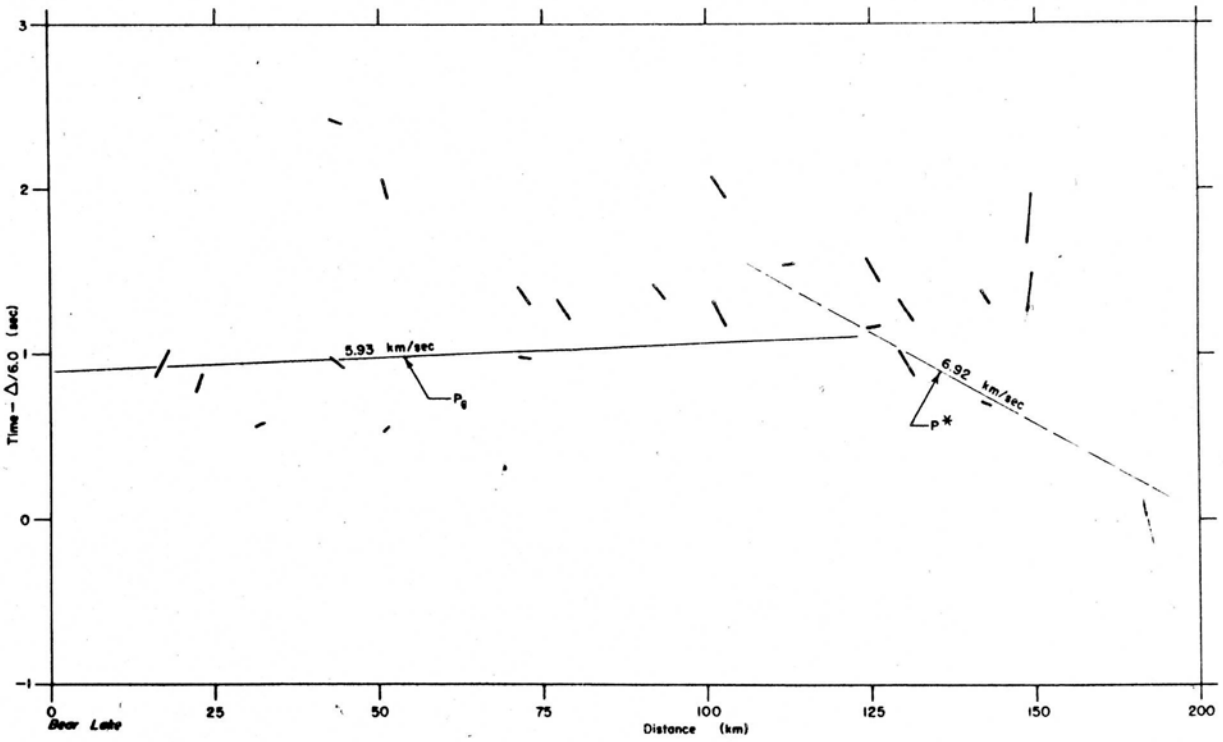

Figure 5.--Reduced travel-time graph: Bear Lake to American Falls.

Recording from Bear Lake towards Flaming Gorge reservoir the seismograms are much the same except the profile covers a shorter distance and P* was identified as a first arrival only on the last record at a distance of 112 km. On this last seismogram the strongest event, which is later than the phase identified as P_IP, has been tentatively identified as a reflection from the Mohorovicic discontinuity (Fig. 6). Such a phase could not be positively identified on the records obtained on the line extending toward American Falls.

Flaming Gorge reservoir. The Flaming Gorge reservoir shotpoint was somewhat more efficient than the American Falls shotpoint, and the records obtained from shots at Flaming Gorge are generally somewhat better out to a distance of about 200 km. Beyond 200 km the background noise at some recording locations was high enough to obscure first motion on the seismograms and some records were so noisy that only some of the strong late events could be identified.

Two recording units were laid out essentially end to end and as near the shotpoint as practicable. The closest of these units recorded a direct wave with an apparent velocity of 4.05 km/sec. The two units together indicate a velocity of 4.75 km/sec for the near surface material.

The first arrivals (Table 3, Fig. 3) on thirteen seismograms from 11 km to 127 km are the direct wave (P_g). The first upward motion can generally be identified on these records.

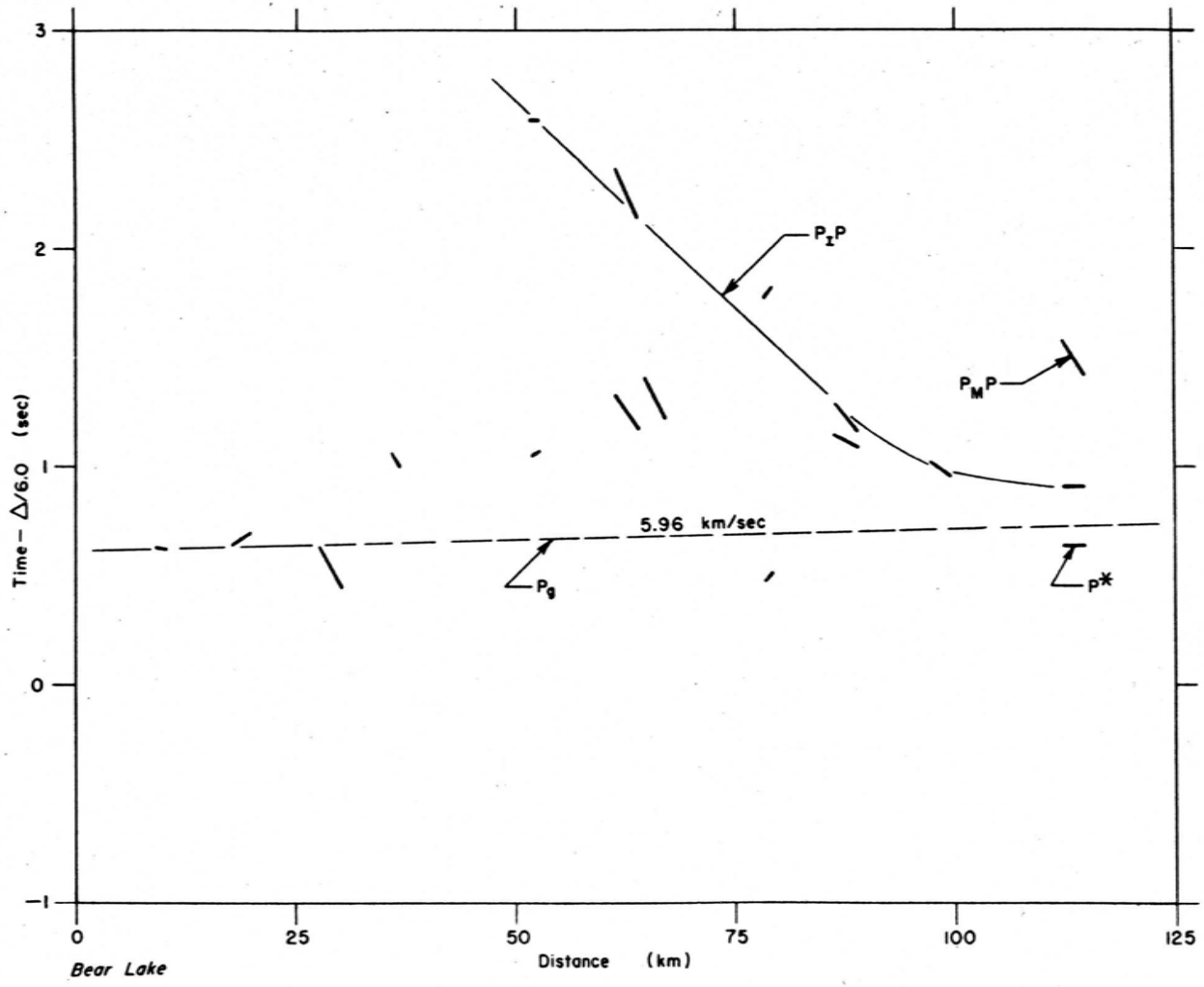

Figure 6.--Reduced travel-time graph: Bear Lake towards Flaming Gorge.

The first arrivals on four seismograms from 140 km to 166 km are identified as a refracted wave from an intermediate layer (P*). The reflected wave from the upper surface of this layer (P_IP) appears as a strong secondary event on the records from 39 km to 139 km and in the distance range 39 km to 76 km is the strongest event on the records (Fig. 7).

The refracted wave from the Mohorovicic discontinuity (P_n) appears as a first arrival at 184 km and generally persists to the end of the profile, although on most of the records something later than the first motion has been picked. The reflected wave from this discontinuity (P_MP) is first identified at 76 km and it persists to 184 km and is generally the strongest event on the records in this distance range (Fig. 7). A large-amplitude low-frequency wave with a velocity of about 6.0 km/sec that has been identified as $\bar{P}$ appears on six records in the distance range 225 km to 318 km. This phase is generally the strongest event on the records on which it can be identified. The arrival times of this phase are earlier than traveltimes of the extension of P_g.

No phase comparable to the high-amplitude event identified as I on the seismograms recorded from American Falls was recognized on the seismograms recorded from Flaming Gorge.

Amplitudes. The amplitudes of prominent phases were measured and tabulated with arrival times (Table 3). Because the first upward motion could be identified with certainty on only a few of the records, the

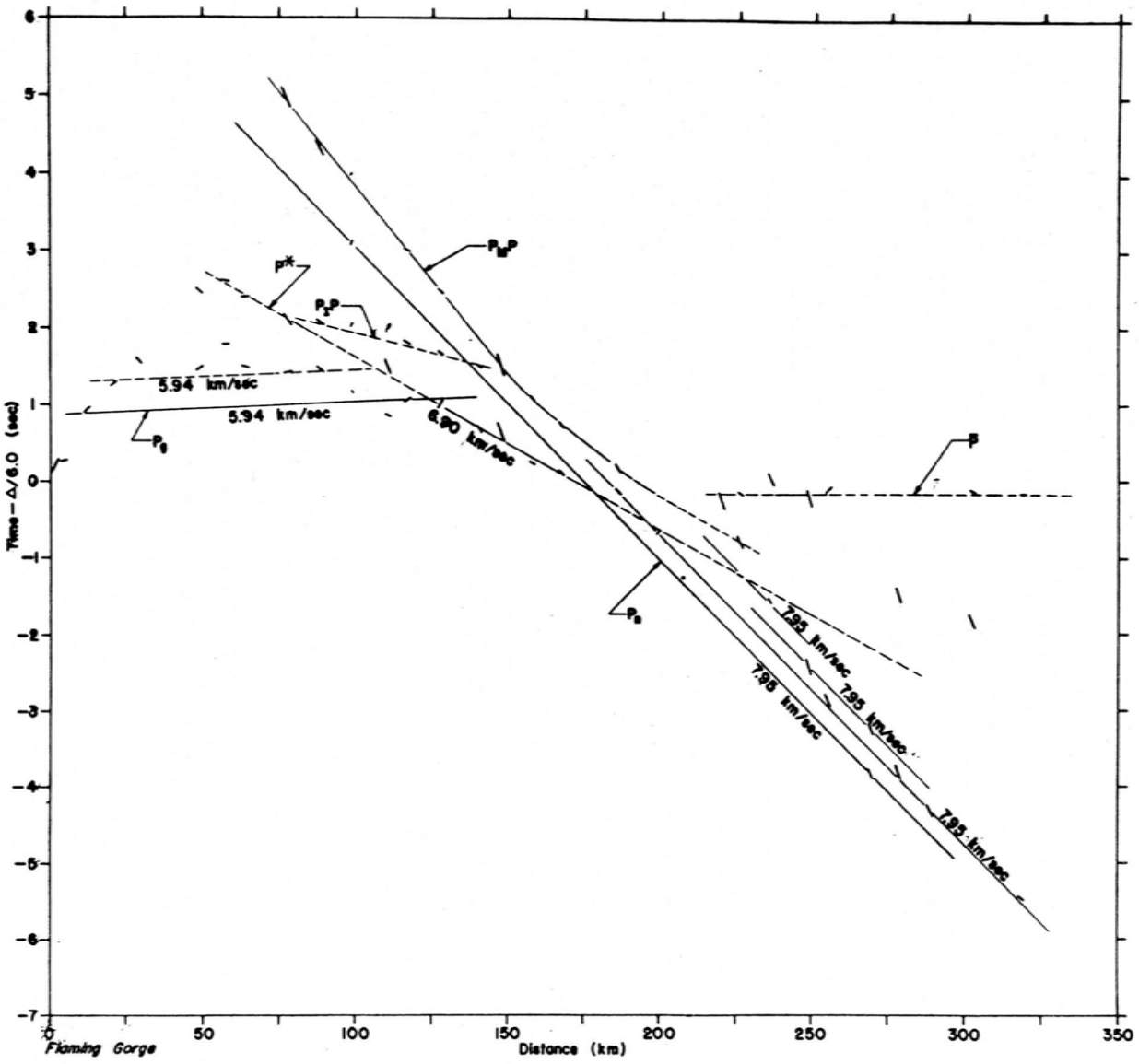

Figure 7.--Reduced travel-time graph: Flaming Gorge to American Falls.

amplitude was measured as the maximum peak to trough displacement in the first few half-cycles of the arrival of each phase. These measurements were converted to ground motion in the manner described by Eaton (1963, p. 5791-5792), and assuming linear scaling to convert to a uniform shot size of 2000 lbs. These amplitudes are plotted for each individual profile: American Falls to Flaming Gorge in Figure 8; Flaming Gorge to American Falls in Figure 9; and Bear Lake to American Falls and Bear Lake towards Flaming Gorge in Figure 10.

Amplitudes of the refracted waves P_n and P* and the direct wave, P_g, generally attenuate rapidly with distance, but there is considerable scatter about any line that would represent a regular decrease in amplitude with distance. P_g is difficult to pick above the noise level at distances near those at which P* appears as the first arrival. P_n could be picked to the Flaming Gorge end of the profile because of the generally quiet recording locations. In the reverse direction the first motion of P_n generally was not identified due to the higher noise level.

The reflected events P_IP, P_MP, and I generally have the largest amplitudes on the seismograms over the first 50 to 100 km that they appear. The phase $\overline{P}$ is the strongest event on the records on which it can be identified.

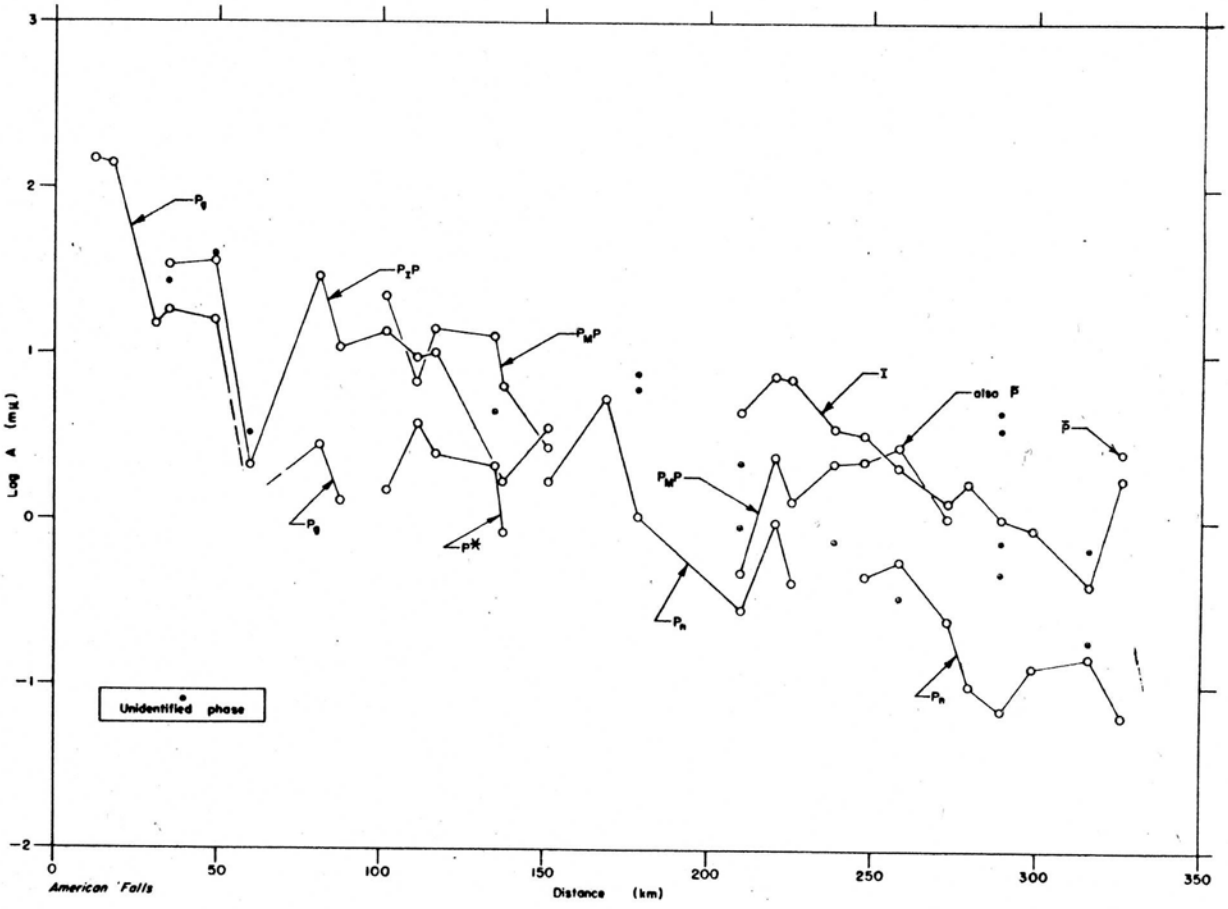

Figure 8.--Amplitude versus distance of prominent phases recorded from shots in American Falls reservoir.

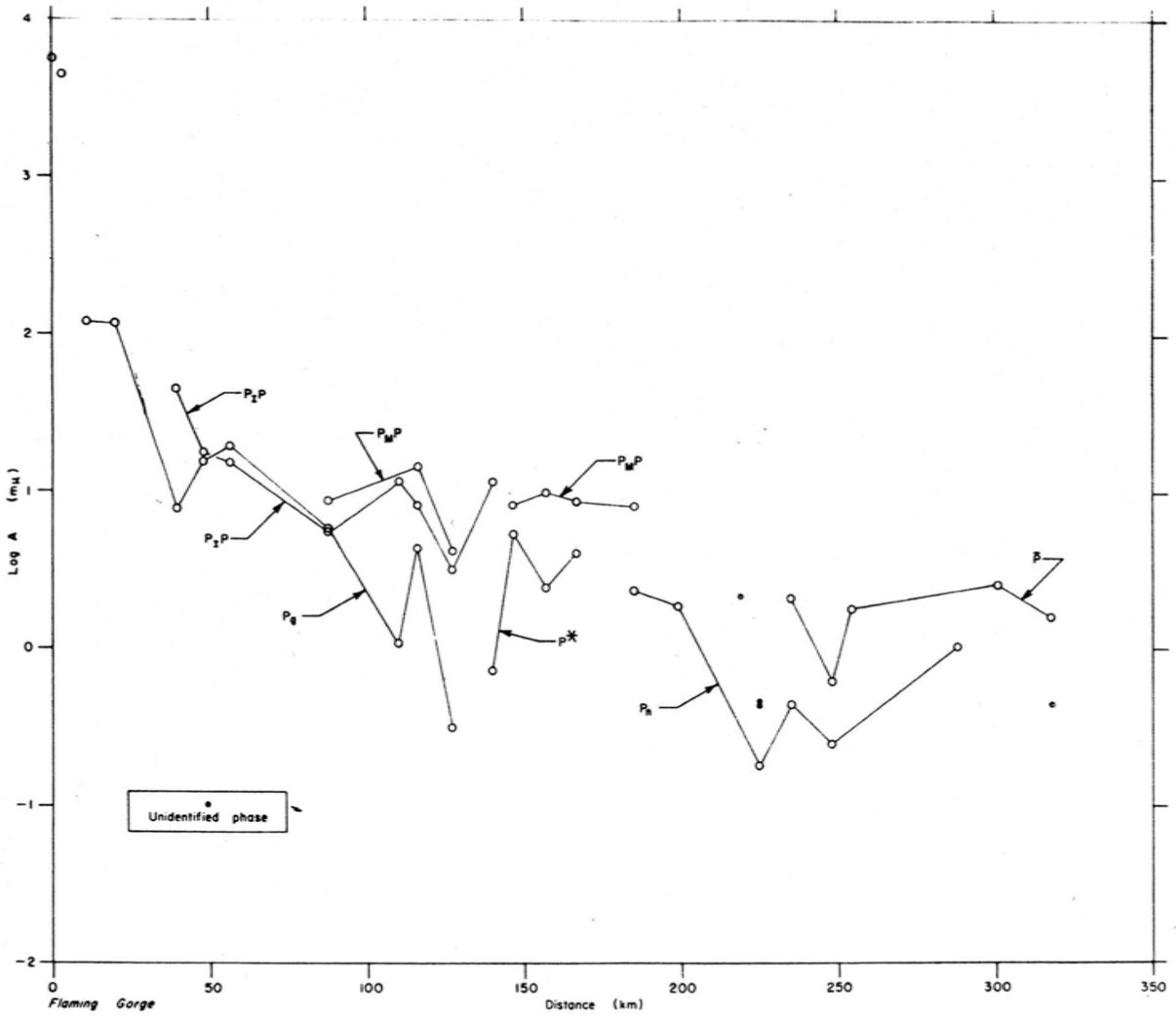

Figure 9.--Amplitude versus distance of prominent phases recorded from shots in Flaming Gorge reservoir.

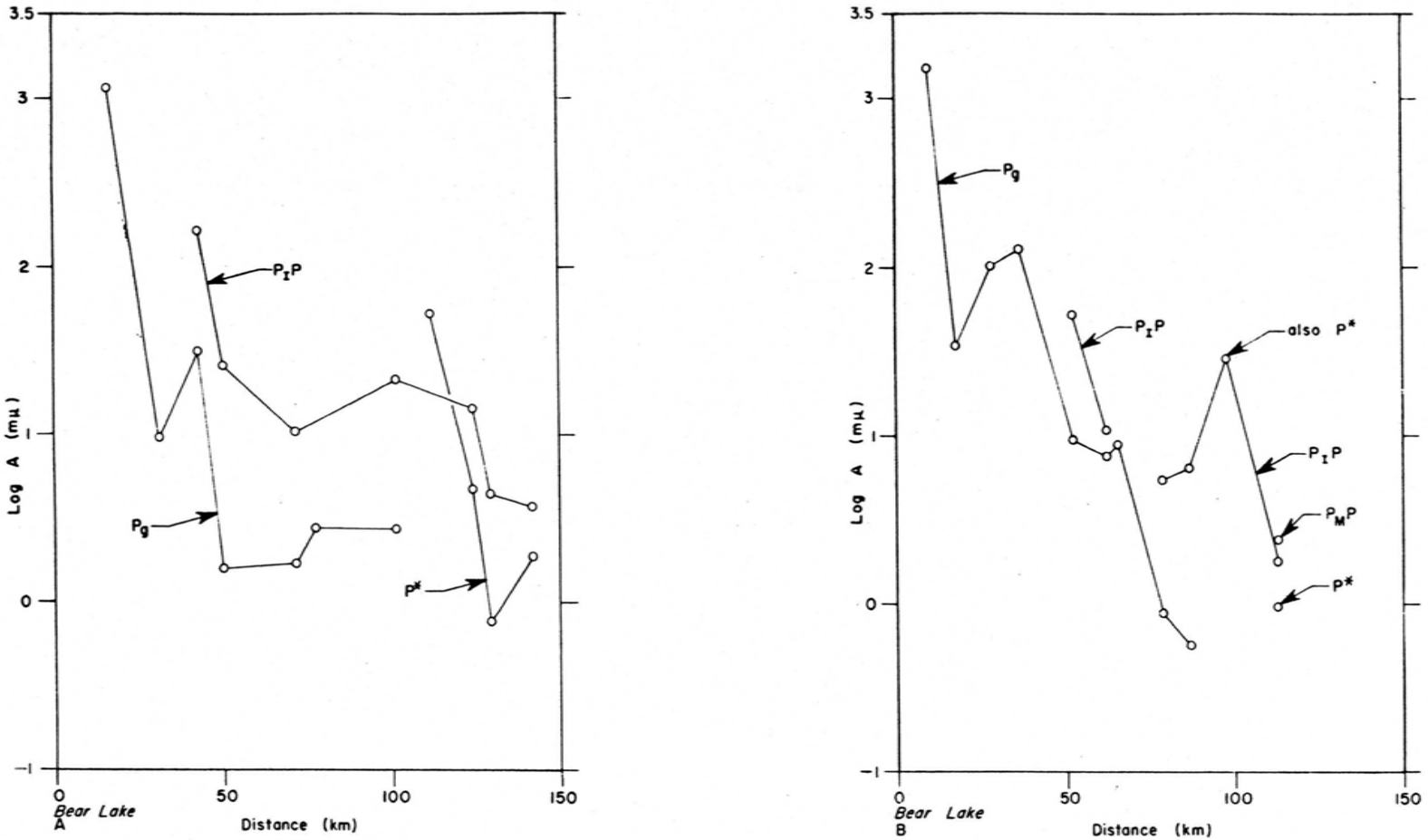

Figure 10.--Amplitude versus distance of prominent phases recorded from shots in Bear Lake. A: Bear Lake to American Falls. B: Bear Lake towards Flaming Gorge.

TRAVELTIMES AND CRUSTAL STRUCTURE

First arrivals. The equations of the lines chosen as the best fit to the observed time of first arrivals are given in Table 4. The observed deviation from these lines (Fig. 3) is large only for recording locations in the Green River Basin and for the noisy locations near the American Falls end of the line that were recorded from shots in Flaming Gorge reservoir.

Depth calculations. The depths to the top of the intermediate layer and the Mohorovicic discontinuity have been calculated using first arrivals and velocities from the travel time curves. The average of the two velocities for the layer immediately beneath the Mohorovicic discontinuity was used to calculate its depth. The computed crustal models are given in Table 5 and a cross section along the profile constructed from these figures is shown in Figure 11. The difference in intercept times and apparent velocities of P_n from American Falls and Flaming Gorge can be accounted for by a dip of about 1° on the mantle down from American Falls toward Flaming Gorge.

An approximation of the depth to the reflecting horizon represented by the strong phase I was made by assuming that a travel-time curve for a refracted wave from the same horizon would be tangent to and essentially parallel with the segment of the travel-time curve shown on the reduced travel-time graph of Figure 4. An intercept time obtained by projecting this line to the zero distance line and the apparent velocity shown for the phase on Figure 4 permit calculating a total depth to the horizon of about 69 km.

Table 4.--Traveltime Equations

Profile	Phase	Traveltimes in seconds
American Falls to Flaming Gorge	P_g	$0.67 + \Delta/5.93$
	P*	$3.88 + \Delta/6.92$
	P_n	$6.34 + \Delta/7.70$
Bear Lake to American Falls	P_g	$0.66 + \Delta/5.93$
	P*	$4.10 + \Delta/6.92$
Bear Lake to Flaming Gorge	P_g	$0.65 + \Delta/5.96$
Flaming Gorge to American Falls	P_g	$0.70 + \Delta/5.96$
	P*	$3.76 + \Delta/6.90$
	P_n	$6.97 + \Delta/7.95$

TABLE 5.--Computed Crustal Model

Layer	From American Falls Reservoir		From Bear Lake towards American Falls		From Bear Lake towards Flaming Gorge Reservoir		From Flaming Gorge Reservoir	
	Velocity (km/sec)	Thickness (km)	Velocity (km/sec)	Thickness (km)	Velocity (km/sec)	Thickness (km)	Velocity (km/sec)	Thickness (km)
1	3.6[1/]	1.5	3.6 (assumed)	1.5	4.0 (assumed)	1.75	4.05[2/]	1.9
2	5.93	18.1	5.93	19.4			5.96	17.6
3	6.92	11.2					6.91	17.3
4	7.82[3/]						7.82	
	Total depth to M-discontinuity 30.8 km				Total depth to M-discontinuity 36.8 km			

1/ Average value derived from near-in recordings made from the two American Falls shotpoints.

2/ Value derived from a recording unit covering the distance range of 0.39 to 2.75 km from the shotpoint.

3/ Average value of P_n from reduced travel-time graphs of Figures 4 and 7.

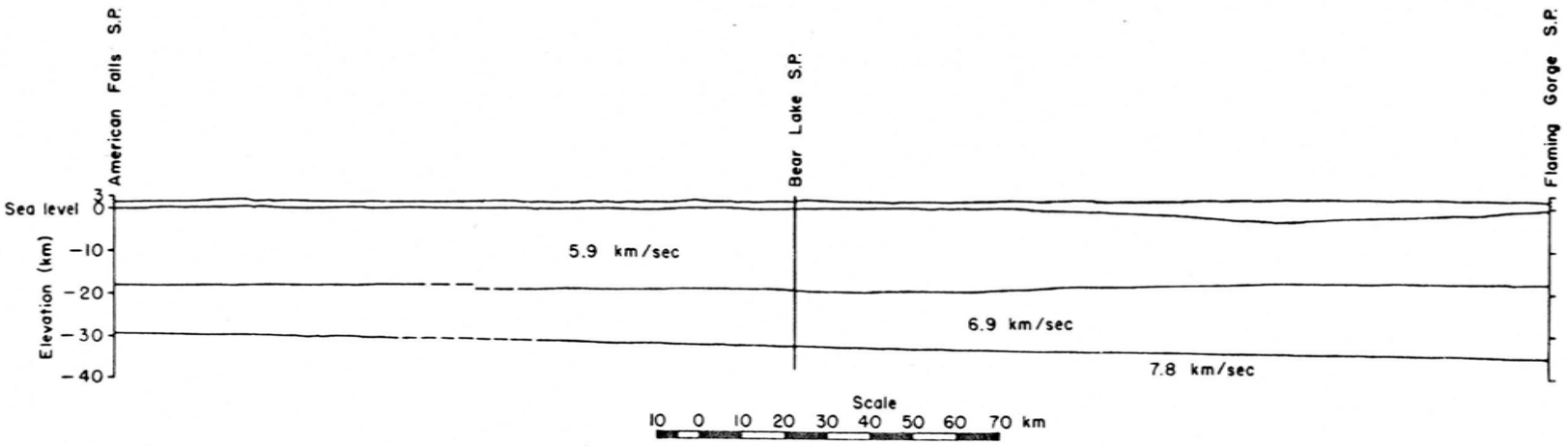

Figure 11.--Cross section from American Falls reservoir to Flaming Gorge reservoir. Horizontal and vertical scale the same. Surface altitude is that of recording units projected to line of section. Average altitude southeast of Bear Lake is 2036 meters and that northwest of Bear Lake is 1726 meters.

Discussion of results. The existence of an intermediate layer with a velocity of 6.9 km/sec is well established on this profile by two-way refraction coverage and by reflections at both ends of the profile. The depth to the top of the intermediate layer is appreciably greater near Bear Lake than it is near either American Falls or Flaming Gorge. This greater depth near Bear Lake probably accounts for the phase P*, although it is the first event on the records, arriving later than the projection of the P_g travel time curve.

The fairly shallow depth to the intermediate layer probably accounts for the refracted wave, P*, from the intermediate layer appearing as first arrivals on this line. This phase is rarely observed as a first arrival in the nearby Basin and Range province. The strong phase labeled I in this study that has an apparent velocity of 8.4 km/sec in the distance range 210 km to 325 km has the properties of a reflection from a layer within the mantle. Extending this profile to the southeast with another shotpoint might provide a reversal of this phase, particularly if it emerges as a first arrival, and permit calculations of its true velocity and the true depth of the reflecting layer. Ryall and Stuart (1963) identified phases with apparent velocities of about 8.4 km/sec recorded at large distances from the Nevada Test Site toward Ordway, Colorado. They attributed some of these to a change in velocity of P_n going under the Colorado Plateau but considered one phase with this velocity, which they designated P_c, to be a reflection from a deep-mantle layer. The greater distance at which P_c first appeared on their records suggests that it comes from considerably greater depth than does the phase I on the American Falls - Flaming Gorge profile.

An increase in velocity downward in the upper crustal layer (beneath the low-velocity material) seems to be required to account for the phase $\overline{P}$ arriving appreciably earlier than the projection of the P_g travel-time curve. The apparent velocity of 6.0 km/sec for the phase $\overline{P}$ as contrasted to the velocity of 5.9 km/sec determined for P_g indicates that such a velocity gradient does indeed exist.

Near-surface geology affects the traveltimes recorded along this profile at several places. The most striking effect is the large delay of both P_g and P_n at all recording locations across the Green River Basin. The early arrival of P_n at the two recording locations closest to Flaming Gorge is probably due to the Paleozoic section being appreciably thinner there than it is elsewhere along the line. Other effects that may be attributable in some way to near-surface geology include the delay of P_g at the first two recording locations southeast of American Falls reservoir. The offset of about 1/2 second between adjacent recording locations of the traveltime curve for the phase P_IP shown on Figure 4 is better explained by a sudden increase in the total thickness of the 5.9 km/sec velocity layer. Such an increase could be accomplished by a fault at depth in the area north of Preston, Idaho, that would elevate the crustal block to the west of it somewhat more than 1 km.

CONCLUSIONS

Two-way refraction coverage along this profile indicates a thickening of the crust from about 31 km at American Falls reservoir to about 37 km at Flaming Gorge reservoir. The intermediate layer thickens from about 11 km at American Falls to about 17 km at Flaming Gorge.

The velocity of compressional waves in the crust beneath the near-surface low-velocity material is about 5.9 km/sec along this profile. Compressional waves in the intermediate layer travel with a velocity of 6.9 km/sec, and those in the mantle immediately below the Mohorovicic discontinuity travel with a velocity of 7.8 km/sec. A deeper layer within the mantle with an apparent velocity of 8.4 km/sec is indicated by strong secondary events recorded from shots at American Falls.

The crust along this profile is more nearly like that in the Basin and Range province than it is in other provinces covered by U. S. Geological Survey refraction profiles (Pakiser, 1963).

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