UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

TECHNICAL LETTER NUMBER 23

A PRELIMINARY SUMMARY OF A SEISMIC-REFRACTION SURVEY IN THE VICINITY OF THE TONTO FOREST OBSERVATORY, ARIZONA*

by

J. C. Roller,** W. H. Jackson,** D. H. Warren,**
and J. H. Healy**

DENVER, COLORADO

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GEOLOGICAL SURVEY

Technical Letter
Crustal Studies-23
September 20, 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 23

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by

J. C. Roller,** W. H. Jackson,** D. H. Warren,**

and J. H. Healy**

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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ABSTRACT

The U. S. Geological Survey completed a seismic-refraction survey in the vicinity of the Tonto Forest Seismological Observatory (T.F.S.O.) in April and May 1964. More than 1200 km of reversed profiles were surveyed to determine the crustal structure and crustal and upper mantle velocities in this area. The purpose of this work was to provide information on wave-propagation paths of seismic events recorded at T.F.S.O. and to improve the performance of the Observatory in locating and identifying these events.

First arrivals indicate that the Mohorovicic discontinuity dips to the northeast by as much as 6 degrees under T.F.S.O., and may even be displaced vertically by as much as 5 km immediately north of the Observatory near the boundary of the Basin and Range and the Colorado Plateau Provinces.

A preliminary examination of the first arrivals indicates that the crust at T.F.S.O. is at least 30 km thick and is made up of at least two seismic layers. A thin veneer at the surface with a velocity of approximately

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4 km/sec is underlain by a layer with a velocity of approximately 5.9 km/sec to 6.1 km/sec. An intermediate layer with velocity of 6.6 to 7.0 km/sec is probably present in the lower crust, but is not revealed by first arrivals. The velocity of seismic waves in the upper mantle is about 7.9 km/sec.

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INTRODUCTION

This report summarizes the operational procedures and preliminary results of a seismic-refraction program in the vicinity of the Tonto Forest Seismological Observatory (T.F.S.O.), Payson, Arizona, performed from April 15 through May 8, 1964. The purpose of this survey was to determine the crustal structure, crustal seismic-wave velocities, and the upper-mantle seismic-wave velocities at the Observatory and surrounding areas.

The field program was carried out as a joint operation by personnel of the U. S. Geological Survey and United ElectroDynamics, Inc., and coordinated with a simultaneous effort by the Air Force Technical Applications Center and the Geotechnical Corporation.

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

FIELD PROCEDURES

Conventional refraction-seismograph procedures (Jackson and others, 1963) were followed to obtain seismic traveltimes along two profiles intersecting at T.F.S.O. Each profile is approximately 400 km long (Figure 1 and Appendix 1). To obtain detailed crustal information in the immediate vicinity of T.F.S.O., each profile was reoccupied with approximately 3 km spacing, or nearly continuous coverage, within a radius of approximately 75 km of T.F.S.O., and seismic waves were recorded from intermediate shotpoints. Two shorter profiles, each approximately 30 km long were recorded across T.F.S.O., and seismic waves were recorded from shotpoints nearby to obtain detailed information on time delays caused by the near-surface materials. Recordings were made by ten mobile recording units as described by Warrick and others (1961).

Charge sizes ranged from 500 to 10,000 pounds of chemical explosives (Appendix 2). A larger shot of 23,340 pounds was detonated at the "Tonto" location, near T.F.S.O., and was recorded at the end shotpoints as well as other more distant locations. The purpose of this shot was to provide a hypothetical detection problem and to determine the accuracy with which seismic evidence could be used to locate the Tonto shot. These data are not included in this preliminary summary.

A slurry-type explosive, Super Tovex, was used exclusively. Operational statistics of the program are summarized in Table 1 and the organization of personnel is shown in Table 2.

Shot point permits were obtained from the agencies listed in Table 3.

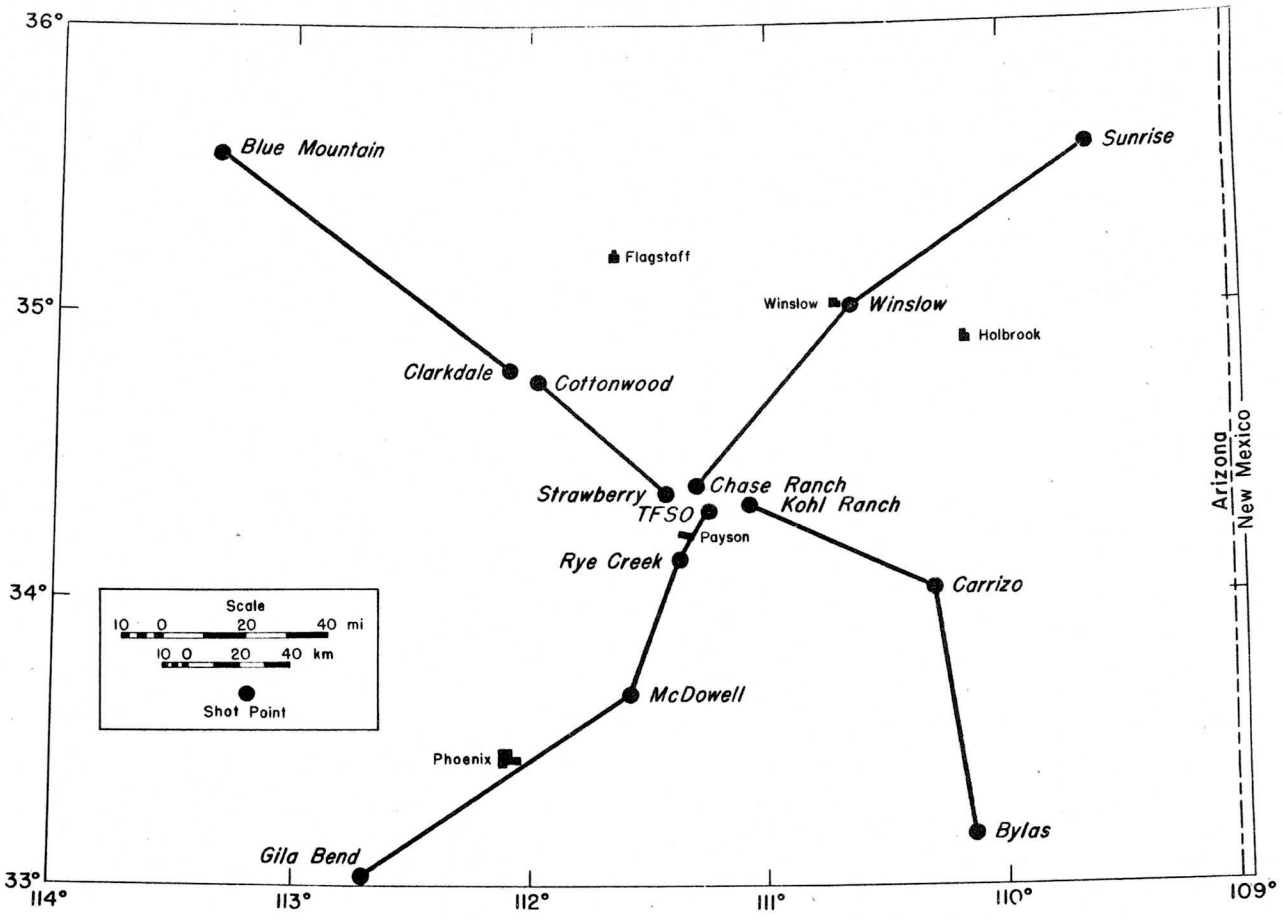

Figure 1.--General index map showing the location of the seismic profiles.

Table 1.--Operational Statistics

Number of drilled-hole shot points	14
Number of production days	20
Number of shots	44
Number of seismograms recorded	477
Kilometers of reversed profile coverage	1,210
Total footage drilled	15,098
Number of holes drilled	75
Number of rock bits used	99
Pounds of drilling mud used	2,200
Pounds of super Tovex-Gel (slurry) explosives used	207,960
Number of HDP-1 primers used	311
Number of detonators used	206
Feet of Primacord used	37,000

Table 2.--Organization Chart

Chief, Branch of Crustal Studies	L. C. Pakiser	
Field Supervisor	W. H. Jackson	
Interpretation Staff	J. H. Healy (Chief) J. C. Roller D. H. Warren B. D. Marcellus	
U.E.D. Coordinator	C. B. Forbes (U.E.D.)	
Permitting	B. L. Tibbetts	
Surveyor	W. Neiberger (U.E.D.)	
Shot Point Management	W. Neiberger (U.E.D.) D. Hennon (U.E.D.)	
Seismic Laboratory	R. E. Warrick	
Maintenance	J. C. Clark	
Observers	B. Tibbetts	HOTEL
	D. Stuart	INDIA
	R. Senterfit	JULIET
	J. Gibbs	KILO
	A. Pitt	LIMA
	C. Tippens	PAPA
	K. Hansen (U.E.D.)	QUEBEC
	J. Ewing (U.E.D.)	ROMEO
	J. Van Schaack	SIERRA
	R. Munson	TANGO
Communications	G. Mangan	ALFA
	J. Clark	MIKE
	D. Murrey	ZULU

Table 3.--Permits

Shot Point	Agency Contacted
Blue Mountain	Hualapai Indian Tribal Council Bureau of Indian Affairs U. S. Department of the Interior Peach Springs, Arizona
Clarkdale	Phoenix Cement Company Clarkdale, Arizona
Strawberry Kohl Ranch Rye Creek Chase Ranch	Tonto National Forest U. S. Forest Service U. S. Department of Agriculture Payson, Arizona
Cottonwood	Coconino National Forest U. S. Forest Service U. S. Department of Agriculture Sedona, Arizona
Carrizo	Fort Apache Indian Reservation U. S. Bureau of Indian Affairs U. S. Department of Interior Whiteriver, Arizona
Bylas	San Carlos Apache Indian Reservation U. S. Bureau of Indian Affairs U. S. Department of the Interior San Carlos, Arizona
Gila Bend	Mr. Ben Harrelson, owner Gila Bend, Arizona
Winslow	Arizona State Land Commission Phoenix, Arizona
Sunrise	Navajo Tribal Council Window Rock, Arizona
Fort McDowell	Tonto National Forest U. S. Forest Service U. S. Department of the Interior Mesa, Arizona

PRELIMINARY RESULTS

The time-distance data are presented as three time-distance curves for each of the seismic lines. The quality of the data, and times of arrival of seismic waves will be discussed separately for each reversed section of the profiles. Each line consists of three reversed profiles: (1) a short profile to study the details of the near-surface material, (2) a profile of medium length to study the nature of P_g, and (3) a long-range profile to study the crustal structure and mantle velocities. The time-distance curves shown in this preliminary report are based on the first arrivals. The seismograms contain many correlatable secondary events which had not been evaluated at the time of completion of this report (August, 1964). The grading system used in this report is the same as that described in Healy and others (1962).

Short profiles.--Charges were fired at four shot points spaced at distances of approximately 15 km from the center of the T.F.S.O. seismometer array (Figure 2). Seismic waves generated by these explosions were recorded across the array to determine the time delay caused by the near-surface rocks. The quality of the seismograms from all of these shots was good.

First arrivals from the Strawberry and Kohl Ranch shotpoint are plotted in Figure 3 and the first arrivals from the Rye Creek and Chase Ranch shotpoints are plotted in Figure 4. The near-surface velocities (V_0) range from 3.12 km/sec at Strawberry to 5.34 km/sec at Kohl Ranch and average 4.13 km/sec (Table 4). The velocity of P_g averages 5.92 km/sec from all four shotpoints. The thickness of the near-surface layer (H_0) is 0.31 km at Strawberry, 1.53 km at Kohl Ranch, 0.31 km at Chase Ranch, and 0.18 km at Rye Creek.

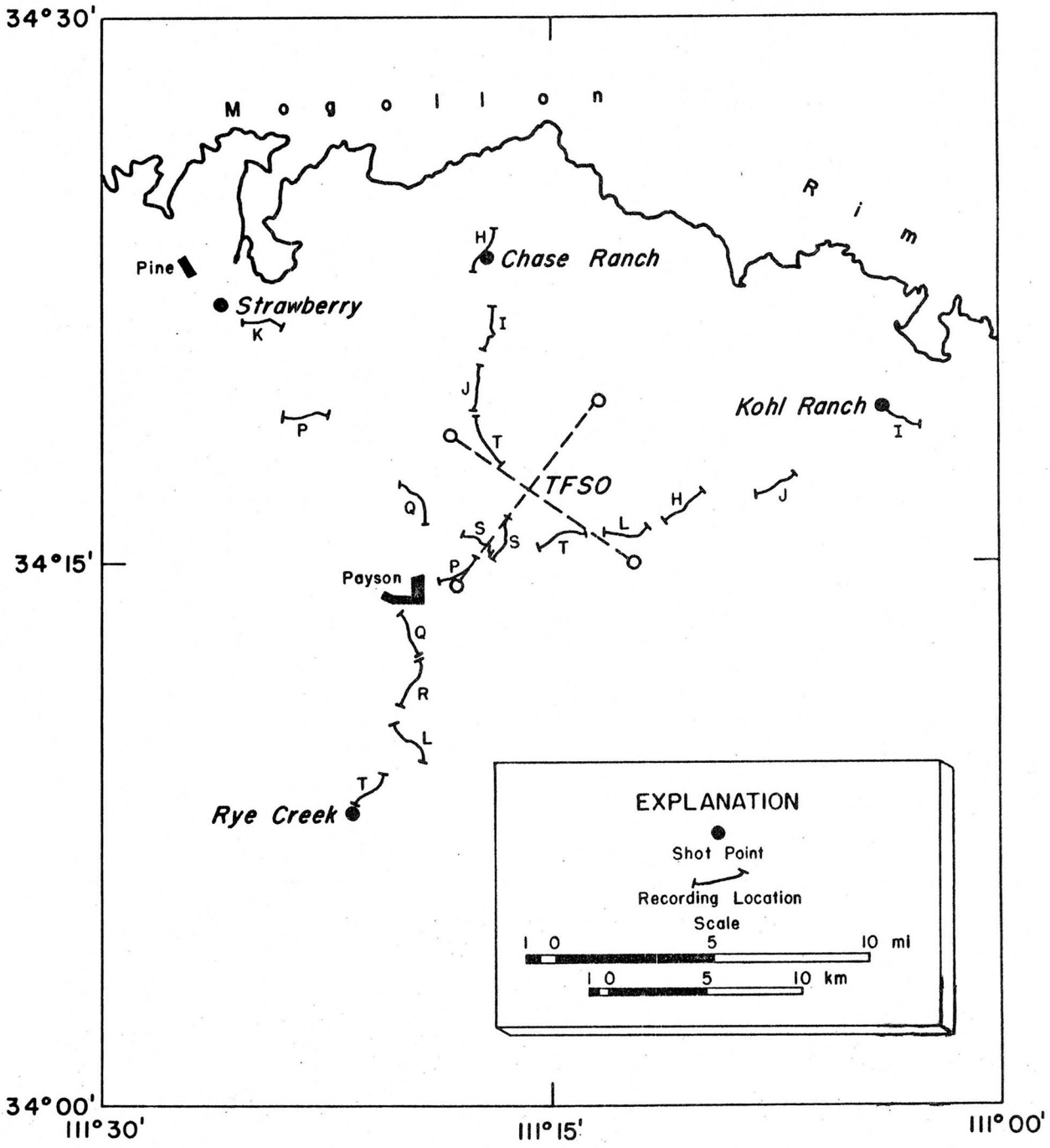

Figure 2.--Index map of short profiles.

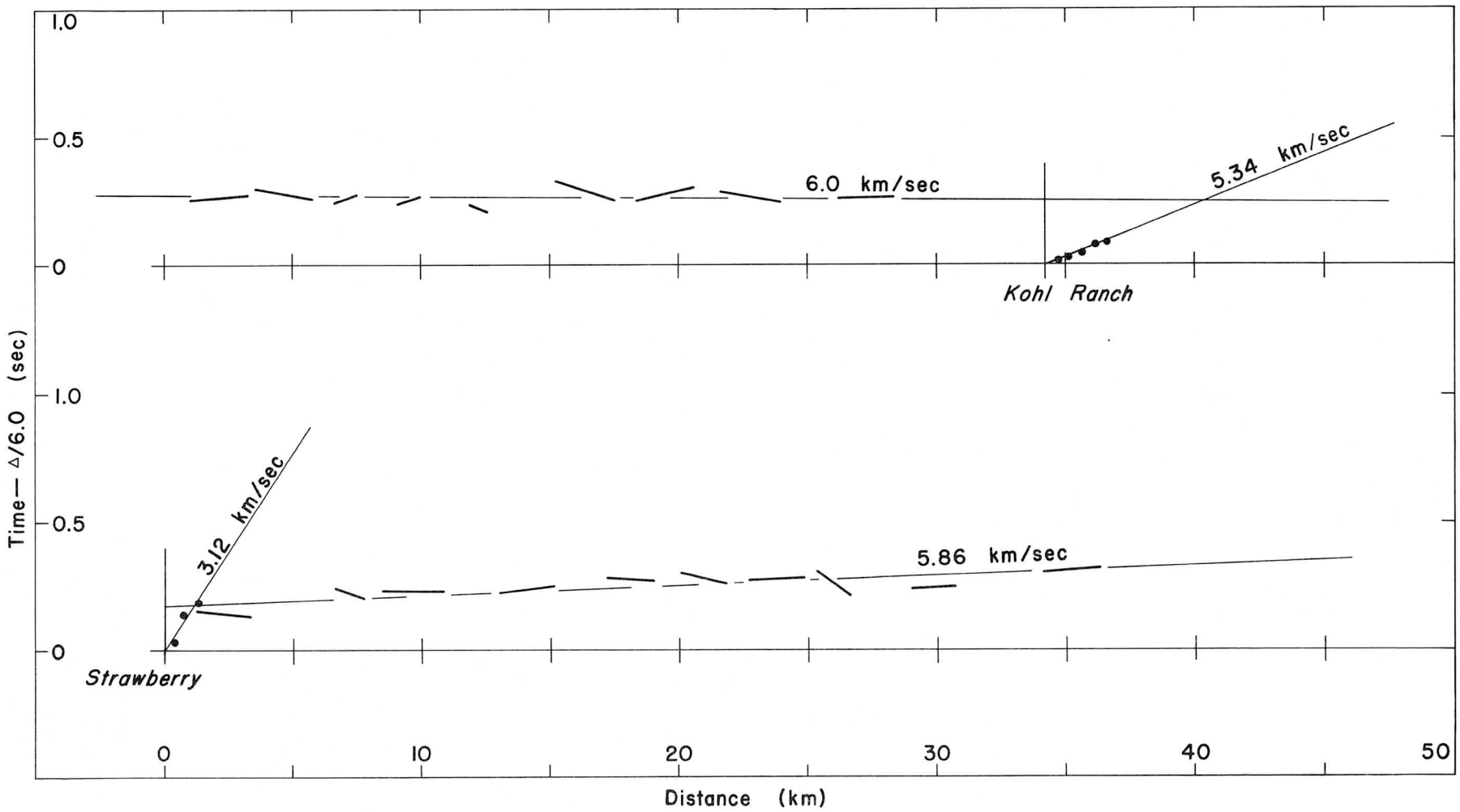

Figure 3.--Time-distance curves from Strawberry - Kohl Ranch profile.

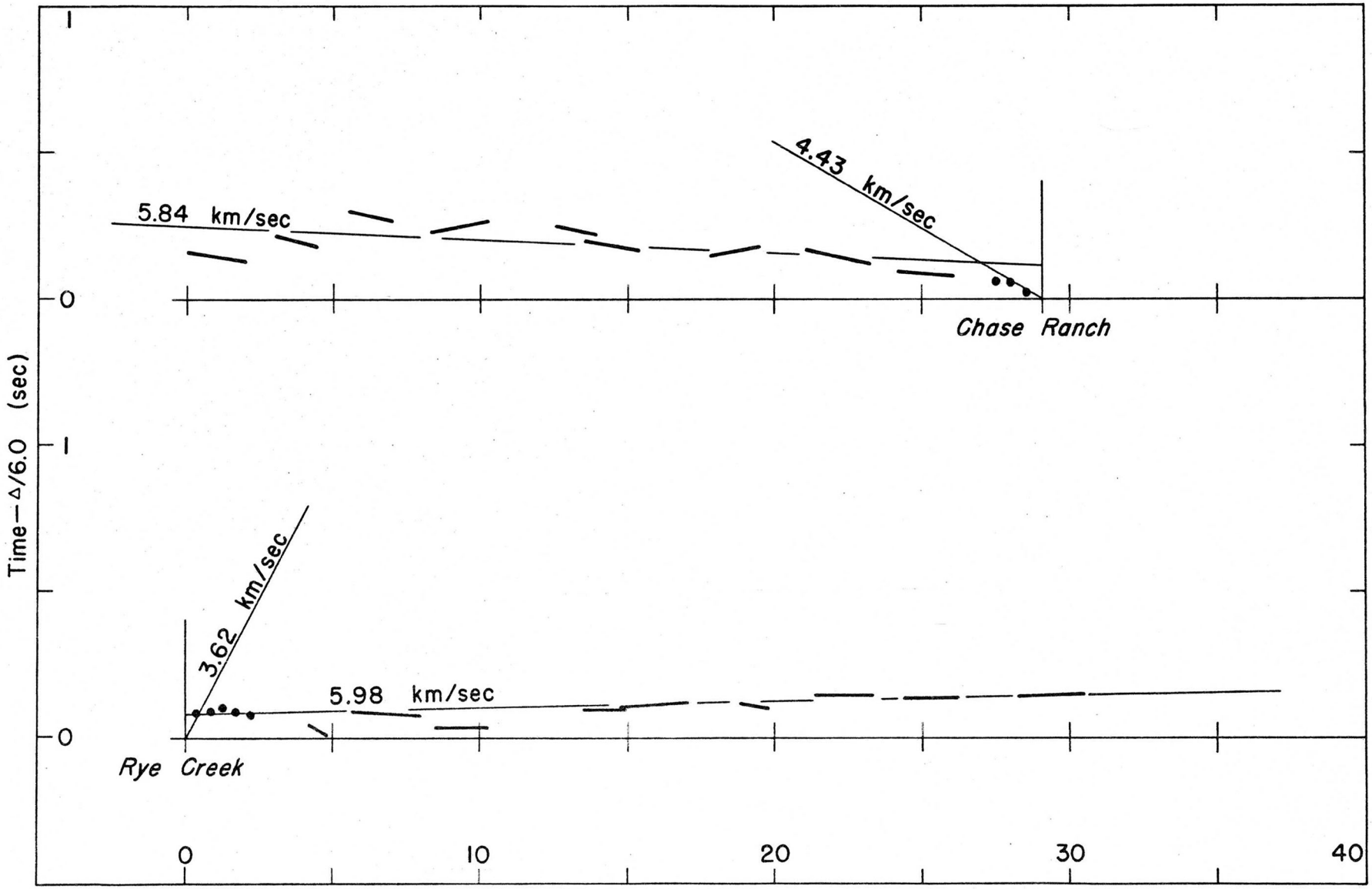

Figure 4.--Time-distance curves from Rye Creek - Chase Ranch profile.

Table 4.--Velocities and depths from short profiles.

Shot point	V_0 (km/sec)	P_g (km/sec)	H_0 (km)
Strawberry	3.12	5.86	0.31
Kohl Ranch	5.34	6.00	1.53
Rye Creek	3.62	5.98	0.18
Chase Ranch	4.43	5.84	0.31
Average	4.13	5.92	0.58

Profiles of medium length.--Charges were fired at four shotpoints, each approximately 75 km from T.F.S.O., to study the nature of P_g and determine delay times for P_n (Figure 5). Coverage between these shotpoints was made nearly continuous in an attempt to use reflections to map crustal structure and to give detailed information on P_g. The efficiency of the Clarkdale shotpoint was very poor and this shotpoint was moved to Cottonwood (Figure 5). Seismograms from these two shotpoints were combined to form one profile, which will be referred to as the Cottonwood profile in this report.

The first arrivals from the Cottonwood shotpoint can be represented by two straight-line segments (Figure 6). From near the shotpoint to a distance of 50 km four arrivals define an apparent velocity of 5.9 km/sec. Beyond 50 km an apparent velocity of 6.1 km/sec is defined by 32 first arrivals. All arrivals fall within less than 0.20 second of these lines.

The first arrivals from the Carrizo shotpoint can also be represented by two straight-line segments (Figure 6). Four arrivals define an apparent velocity of 5.9 km/sec for a distance of 60 km. Beyond 60 km, 33 first arrivals define an apparent velocity of 6.1 km/sec. All points fall within less than 0.20 second of these lines. The record quality on these two profiles ranges from fair to good.

First arrival times along the northeast-trending profile, from Winslow to Fort McDowell, are scattered due to topography, especially at the Mogollon Rim, which is the boundary between the Colorado Plateau Province and the Basin and Range Province. The first arrivals from Fort McDowell can

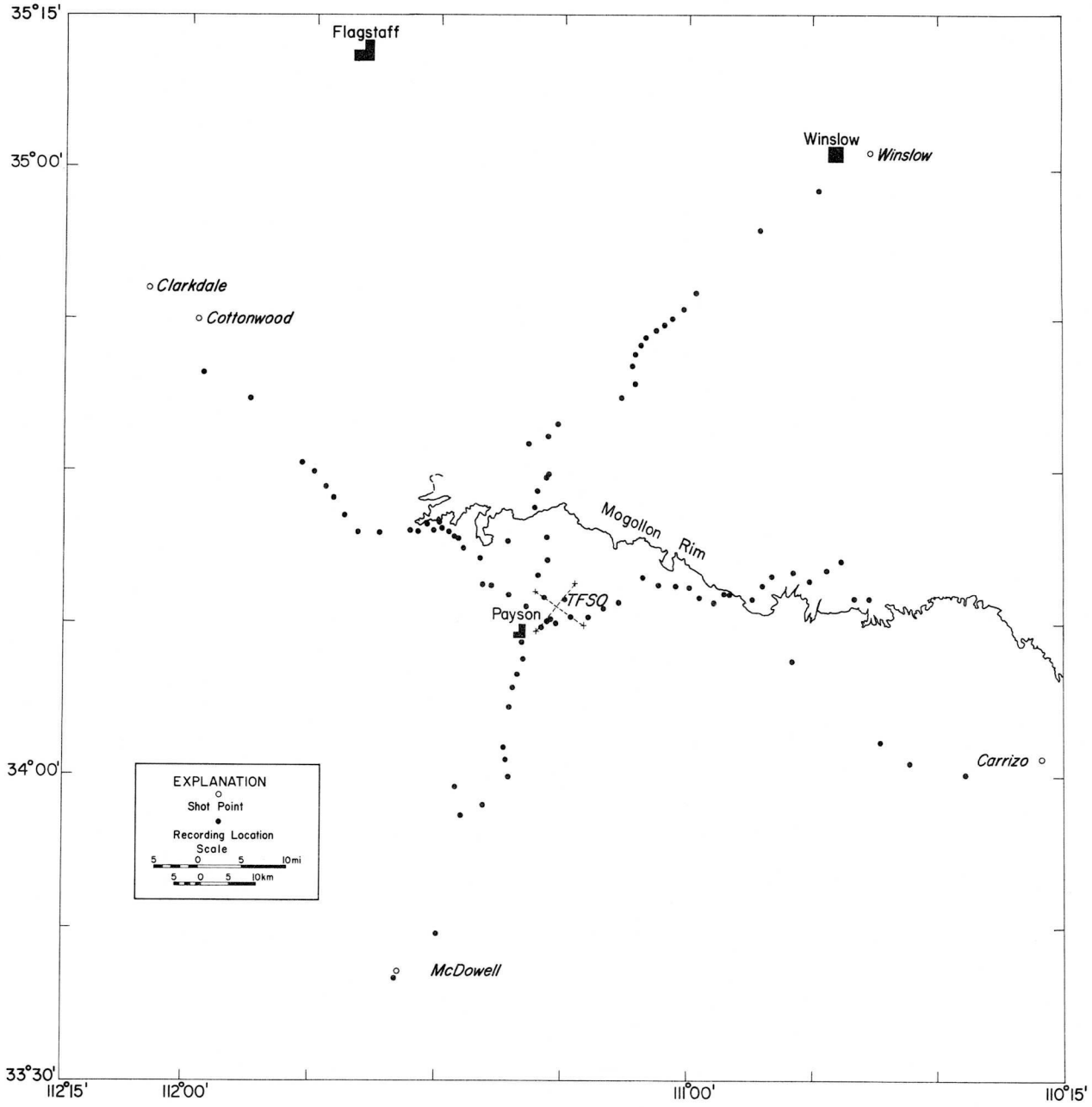

Figure 5.--Index map of profiles of intermediate length.

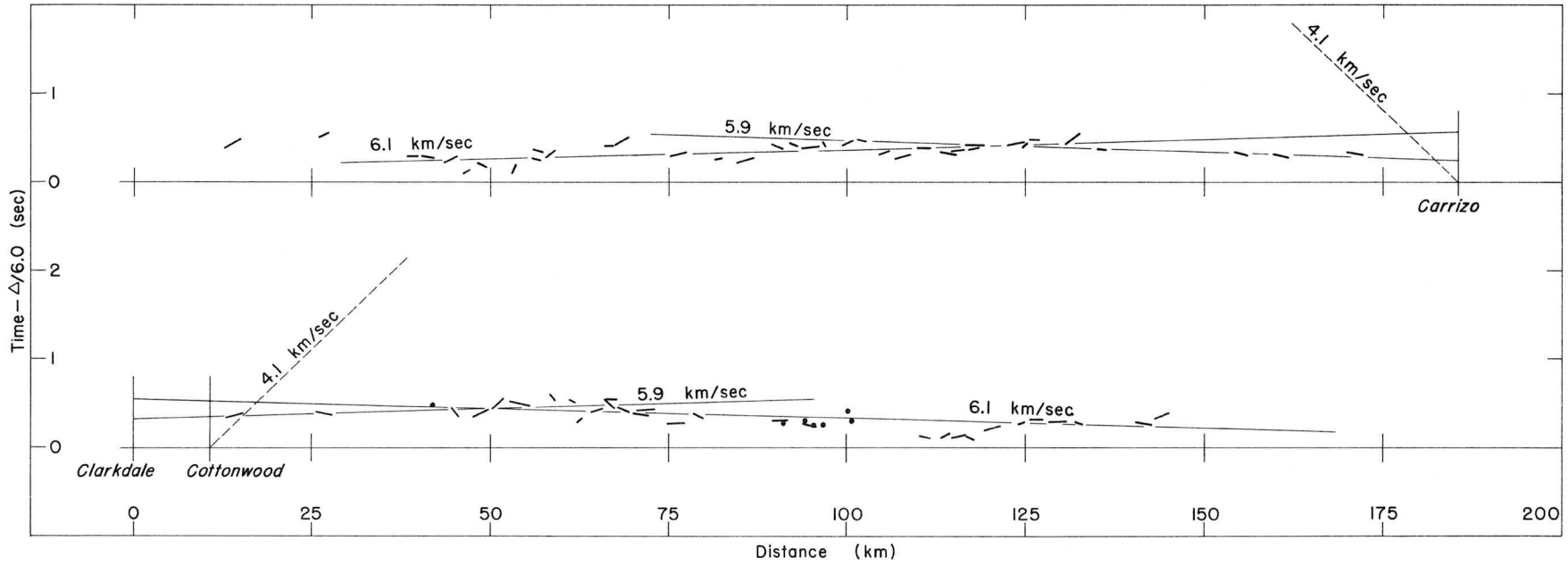

Figure 6.--Time-distance curves from Cottonwood - Carrizo profile.

be represented by two apparent velocities. From near the shotpoint to a distance of 42 km (Figure 7), four seismograms define a line with an apparent velocity of 5.8 km/sec. Beyond 42 km an apparent velocity of 6.2 km/sec is defined by 31 recordings. This line is offset 0.33 sec at a distance of 87 km from Fort McDowell. All recordings beyond 87 km were made on the Colorado Plateau north of the Mogollon Rim. The reversed profile from Winslow shows only one apparent velocity of 6.1 km/sec, which is also offset at the edge of the Colorado Plateau. The velocities and computed layer thicknesses from the intermediate length profiles are shown in Table 5. The upper-layer velocity of 4.1 used in these computations is the average velocity taken from the short profiles (Table 4) rounded to the nearest 0.1 km/sec.

Although the crust is shown in Table 5 as being two discrete layers, the change in velocity from 5.9 km/sec to 6.1 km/sec could be a gradual increase in velocity with depth, and the arrival times could be fitted with a smooth curve.

Long range profiles.--The profile from Blue Mountain to Bylas is parallel to the boundary between the Basin and Range and the Colorado Plateau Provinces (Figure 8). The profile from Gila Bend to Sunrise is at right angles to and crosses this boundary. The purpose of these two profiles was to determine crustal structure and upper-mantle velocities in the vicinity of T.F.S.O. and the immediate area surrounding T.F.S.O. All of these shotpoints are considered to be fair to good, and fair to good quality data on P_n was obtained. Bylas and Gila Bend were slightly better than Blue Mountain, and Sunrise was the poorest of the group.

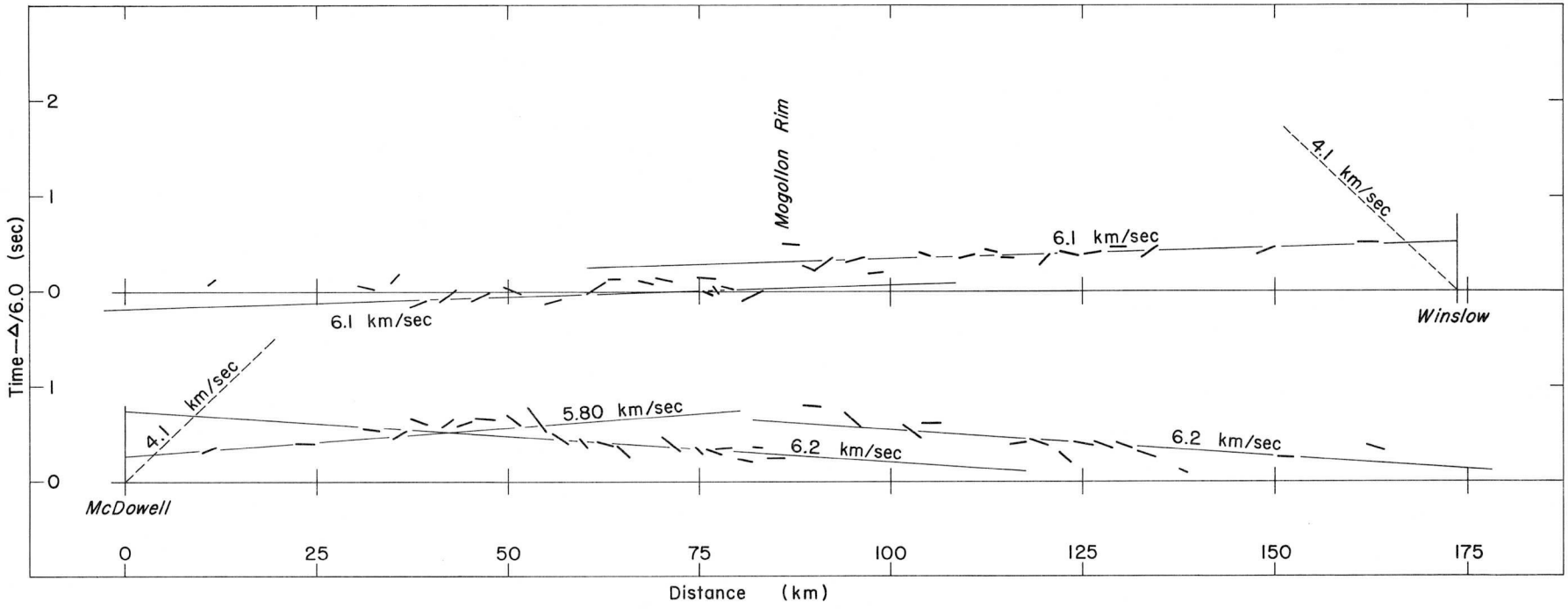

Figure 7.--Time-distance curves from McDowell - Winslow profile.

Table 5.--Velocities and depths from profiles of intermediate length.

Shot Point	Velocity P_{g1}	Velocity P_{g2}	H_0* km	H_1**
Cottonwood	5.9	6.1	0.95	3.60
Carrizo	5.9	6.1	0.69	3.70
McDowell	5.8	6.2	0.76	3.77
Winslow	- -	6.1	1.44	- -

* Assuming V_0 = 4.1 km/sec.

** Thickness of layer with velocity near 5.9 km/sec.

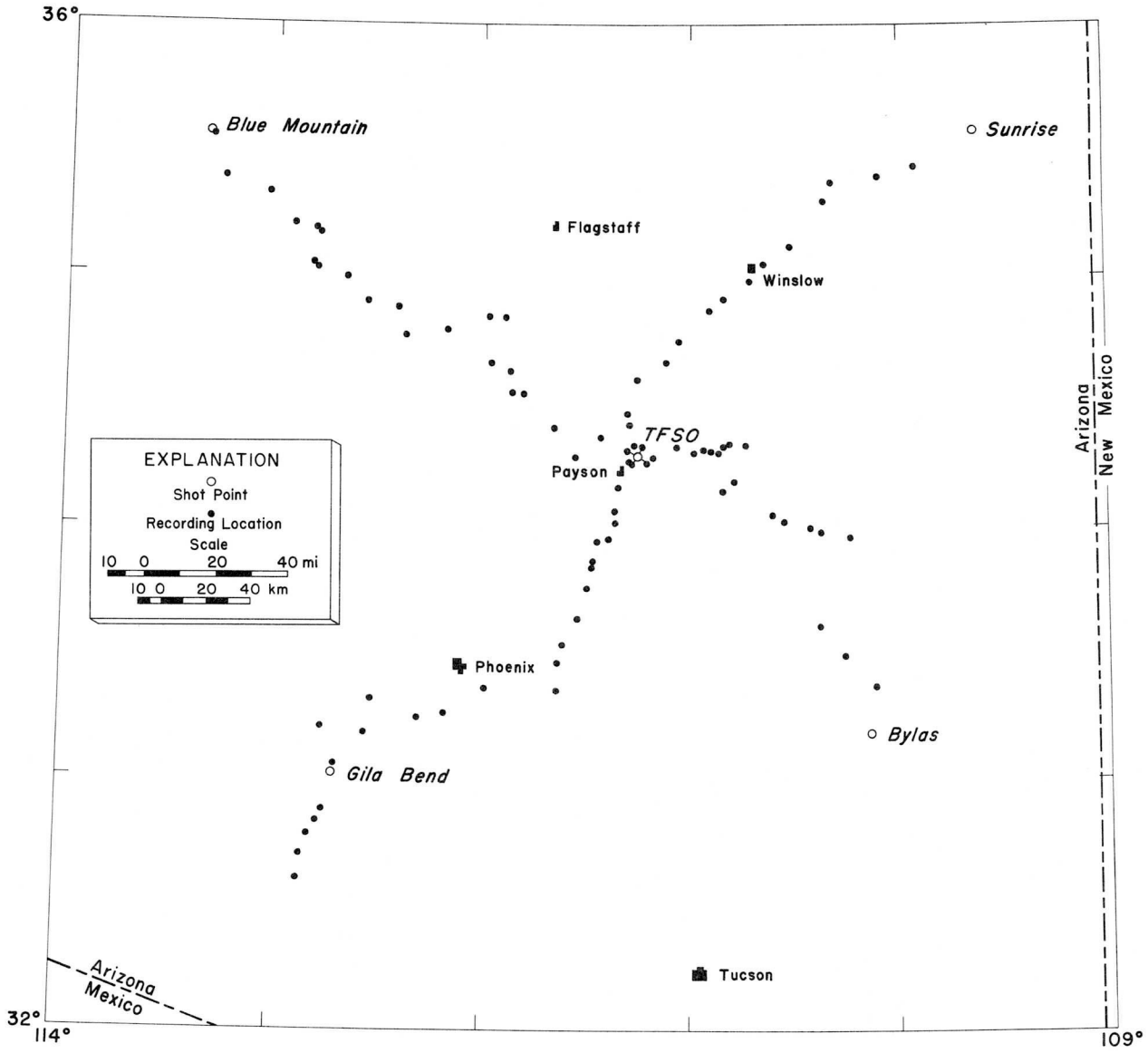

Figure 8. Index map of long-range profiles.

First arrivals from the Blue Mountain shotpoint can be represented by three straight-line segments (Figure 9). Five recordings define an apparent velocity of 5.9 km/sec for a distance of 90 km. An apparent velocity of 6.1 is defined by 7 recordings from 90 km to the P_g-P_n crossover at 182 km. Beyond 182 km an apparent P_n velocity of 7.7 km/sec is defined by 7 recordings. Six other arrivals which are late are plotted in this distance range, probably because of weak energy which obscured the true first arrivals.

First arrivals from Bylas can be represented by two straight-line segments. P_g with an apparent velocity of 6.1 km/sec is defined by 10 recordings to the P_g-P_n crossover at 170 km. Beyond the crossover P_n is defined by 10 recordings that lie within less than 0.1 sec of an apparent-velocity line of 7.9 km/sec. A strong event that follows P_n by 0.3 sec and also has an apparent velocity of 7.9 km/sec appears as the recognizable first arrivals on many of the records. P_n is very emergent on this profile and is obscured in the noise on several records. Two first arrivals, at 165 km and 190 km, are early and possibly suggest that a refracted wave from an intermediate layer in the crust becomes the first arrival in this distance range. Recordings were made from an intermediate shotpoint at Strawberry. An apparent P_g velocity of 6.1 km was recorded to the southeast toward Bylas and an apparent P_g velocity of 6.0 km/sec was recorded to the northwest to Blue Mountain.

First arrivals from the Gila Bend shotpoint can be represented by five straight-line segments (Figure 10). A near-surface velocity of 3.6 km is indicated by one recording. From near the shotpoint to a distance of 108 km

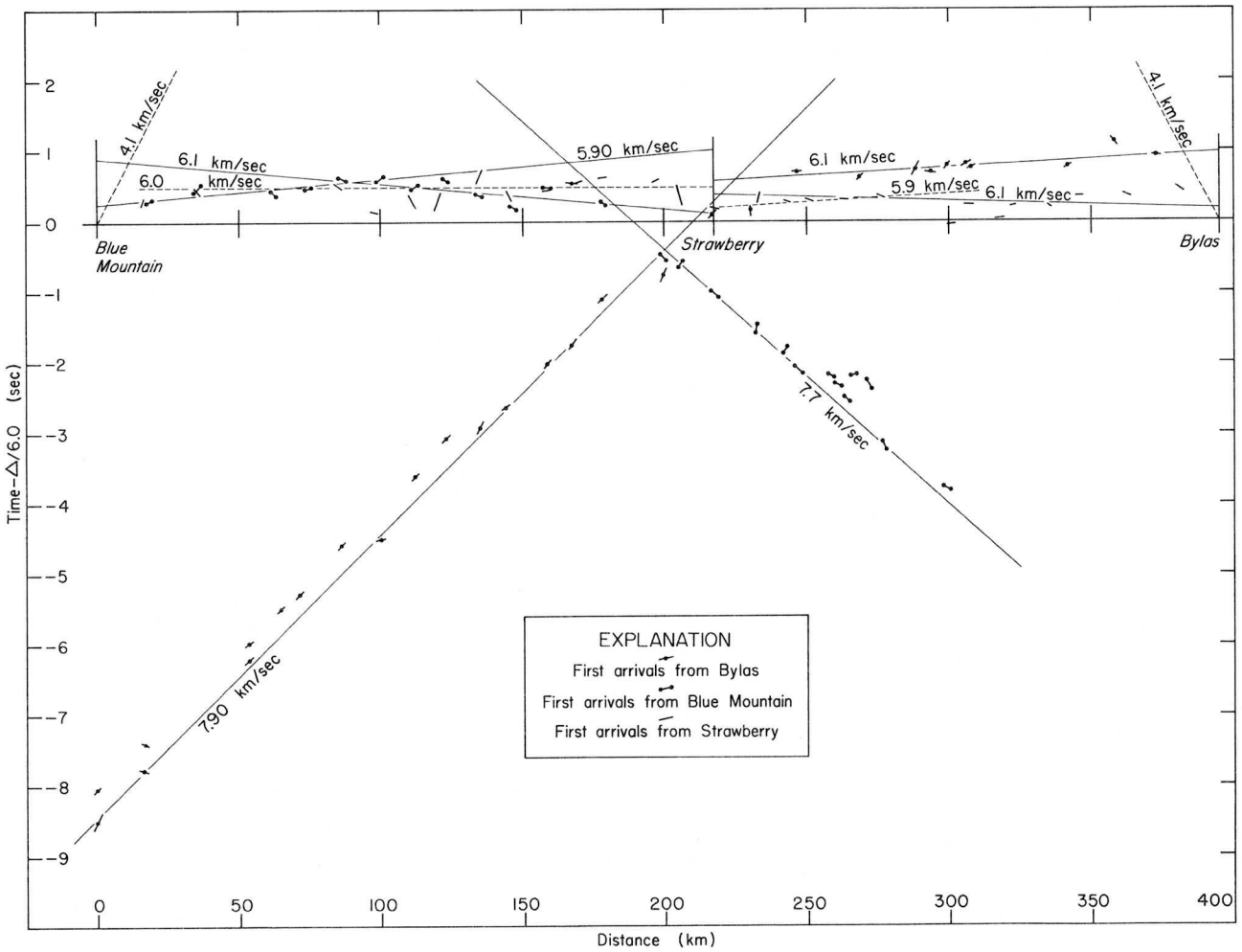

Figure 9.--Time-distance curve from Blue Mountain - Bylas profile.

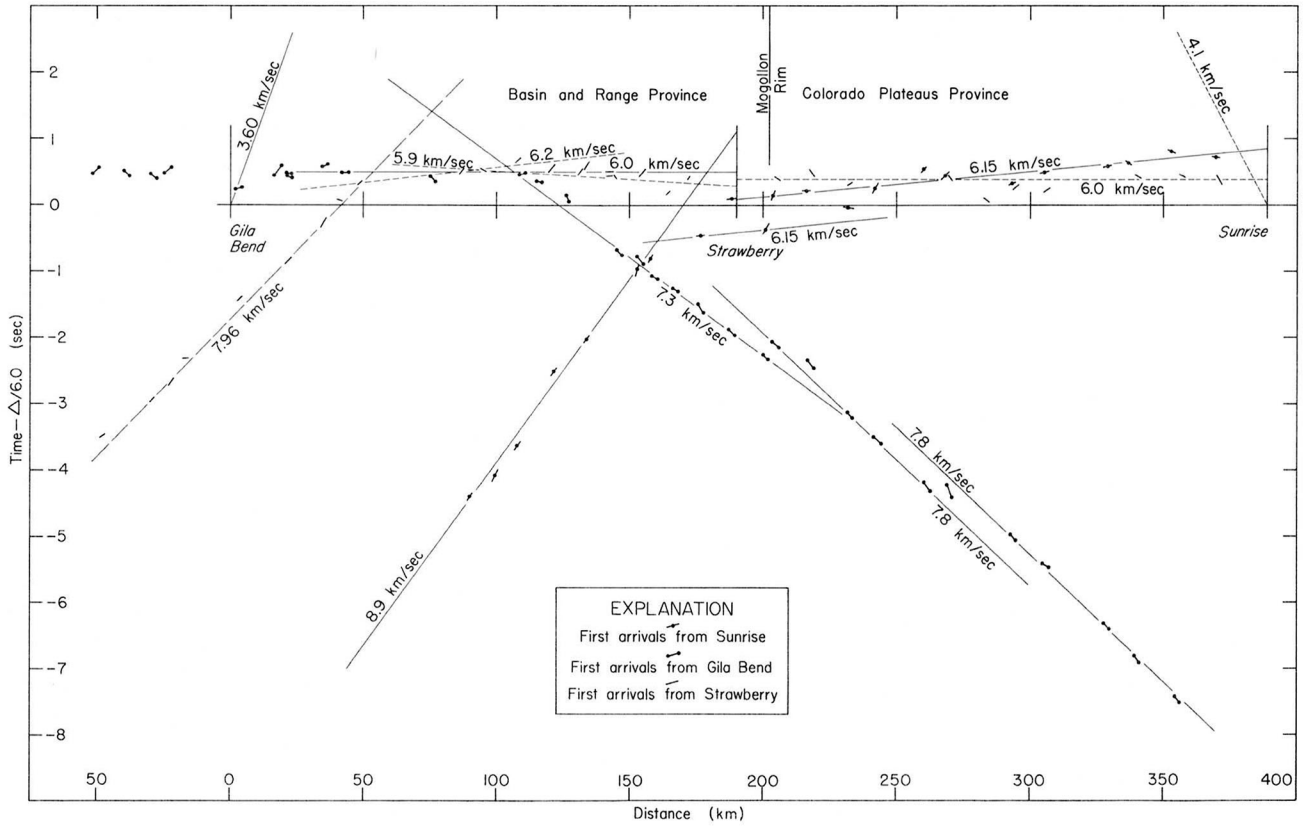

Figure 10.--Time-distance curve from Gila Bend - Sunrise profile.

an apparent P_g velocity of 6.0 km/sec is defined by six recordings. From 108 to 202 km, an apparent P_n velocity of 7.3 km/sec is defined by nine records. At 202 km, the line crosses the Basin and Range-Colorado Plateau boundary at the Mogollon Rim. At this boundary, P_n arrivals are offset and the velocity increases to 7.8 km/sec as defined by 5 recordings. At 275 km, P_n line is again offset, but shows no velocity change. This offset is not expressed in the P_g traveltime and must be due to changes in deep crustal layers. The most probable explanation is an abrupt change of crustal thickness at the boundary of the Colorado Plateau.

The first arrivals from Sunrise are fitted by three straight-line segments. From near the shotpoint to a distance of 187 km an apparent P_g velocity of 6.15 km/sec is defined by 11 recordings. Beyond 187 km to the P_g-P_n crossover at 229 km, the P_g arrival times are offset by 0.50 sec where the profile crosses the Mogollon Rim. Beyond 229 km an apparent P_n velocity of 8.9 km/sec is defined by seven recordings.

The first arrivals from the intermediate shotpoint at Strawberry southwest toward Gila Bend show P_g velocities of 5.9 and 6.2 km/sec and an apparent P_n velocity of 7.96 km/sec beyond the P_g-P_n crossover at 140 km. To the northeast, a P_g velocity of 6.0 km/sec is defined by 9 recordings.

Crustal thickness at 28 km at Bylas and 33 km at Blue Mountain were computed from the first arrival data (Table 6). These thicknesses are minimums, for if an intermediate layer is present, but no refracted waves from that layer appear as first arrivals, the above depths are too shallow.

Table 6.--Velocities and depths from long-range profiles.

Shot point	V_0 (km/sec)	H_0 (km)	P_g (km/sec)	P_n (km/sec)	z (km)	Z (km)
Bylas	4.1*	2.7	6.1	7.9	28.3	32
Blue Mountain	4.1*	0.7	5.9 & 6.1	7.7	32.8	37
Gila Bend	3.6	1.7	6.0	7.3	20	33
Sunrise	4.1*	2.4	6.15	8.9	35	40
Strawberry (SW)	3.1	0.5	5.9 & 6.2	7.96	30	35

* Assumed from average V_0 measured on short profiles.

z Total thickness of crust computed from first arrivals.

Gila Bend P_n and T_2 and Sunrise T_1 are for first segments of the curves.

Z With assumed intermediate layer.

The total crustal thickness would be 32 km at Bylas and 38 km at Blue Mountain if it is assumed that an intermediate layer with a velocity of 6.8 km/sec is present and that its thickness is the maximum that can be present so the refracted waves from this layer do not become first arrivals. The velocity of 6.8 was chosen because this velocity has been observed in preview work in the western United States.

The complicated structure prevents the use of formulas based on plane boundaries to compute the crustal thickness along the profile from Gila Bend to Sunrise, but some preliminary observations can be made from the first arrivals.

An apparent P_n velocity of 7.96 km/sec was derived from recordings in the vicinity of Gila Bend from the Strawberry shotpoint. This apparent velocity is slightly higher than average velocity on profiles in the Basin and Range Province. This apparent velocity could indicate a slight up-dip southwestward or nearly a horizontal Mohorovicic discontinuity near Gila Bend. An apparent P_n velocity of 8.9 km/sec was derived from recordings from the Sunrise shotpoint toward the southwest, and a reverse apparent P_n velocity of 7.3 km/sec was derived from recordings from the Gila Bend shotpoint in the distance range of 90 to 200 km northeast of Gila Bend. A true P_n velocity of 7.97 km/sec with a dip to the northeast of 6.7° can be computed from these updip and downdip velocities. These data would indicate a thickening of the crust of approximately 10 km from Gila Bend to Strawberry.

A crustal thickness of approximately 30 km was computed along the Blue Mountain-Bylas profile, which passes through the Strawberry shotpoint; therefore, the thickness of the crust is probably about 20 km at Gila Bend.

The P_n arrivals from the Gila Bend shotpoint are delayed approximately 0.3 sec 10 km northeast of Strawberry where the profile crosses the Mogollon Rim. The P_g arrivals from Sunrise are delayed by 0.5 sec at this same location. The sedimentary section increases in thickness by at least 2000 feet at the Rim; therefore, all of this delay in P_n arrivals is probably due to surface geology. However, the apparent P_n velocity beyond 210 km northeast of Gila Bend is 7.8 km/sec, and this indicates that the Mohorovicic discontinuity is, with one exception, essentially horizontal from the Mogollon Rim northeast to the Sunrise shotpoint. There is another delay of 0.5 sec in the P_n arrivals from the Gila Bend shot 275 km northeast of Gila Bend, and there is no corresponding delay in P_g at this point. This delay is probably caused by an abrupt thickening of the crust. The P_n waves recorded at 275 km would be refracted from the Mohorovicic discontinuity at a distance 50 km closer to the Gila Bend shotpoint, if the angle of incidence is 50° and the crustal thickness is about 35 km. This indicates that the abrupt thickening of the crust is 225 km northeast of the Gila Bend shotpoint or very near the Mogollon Rim. This delay of 0.5 sec in P_n arrivals requires an increase of approximately 5 km in the crustal thickness.

The crust is at least 30 km thick at Strawberry from data recorded on the Blue Mountain-Bylas line; therefore, the crust is probably at least 35 km thick at Sunrise, assuming no other factors such as dip are involved between Strawberry and Sunrise.

SUMMARY

During a four-week seismic field program, a total of 1200 km of reversed refraction profiles were recorded from 44 large explosions.

The velocity of seismic waves in the near-surface rocks was measured at 4 locations near T.F.S.O. and found to range between 3.12 km/sec and 5.34 km/sec, with an average velocity of 4.13 km/sec. The average thickness of these near-surface rocks is 0.58 km.

The upper part of the crust in the Basin and Range Province near T.F.S.O. has a velocity of 5.9 km/sec to 6.2 km/sec. The thickness of the crust, as determined from first arrival data is at least 30 km at T.F.S.O. The Mohorovicic discontinuity is essentially horizontal along a northwest-trending profile parallel to the province boundary, and increases from approximately 20 km in the southwest at Gila Bend to at least 35 km in the northeast under the Colorado Plateau at Sunrise. The velocity of P_n waves is about 7.9 km/sec over the entire area surveyed. The thickness of the crust increases rapidly under the boundary between the Basin and Range and the Colorado Plateau Provinces, and may even contain a vertical discontinuity of as much as 5 km.

Mathematical expressions of the time-distance curves are shown in Table 7.

Acknowledgements.--The authors wish to express their appreciation to Mr. Allen M. Rugg, Jr., Project Manager, T.F.S.O., and his staff for their assistance during the field operations, which included providing office space, secretarial services, and many other helpful assists and suggestions.

C. B. Forbes of U.E.D. prepared Tables 1 and 2 and a portion of Appendix 2.

Table 7.--Mathematical expressions of time-distance curves

Shot point	P_0 sec	P_g sec	P_n sec	Remarks
Rye Creek	$\Delta/3.62$	$0.08 + \Delta/5.98$	- - - -	
Chase Ranch	$\Delta/4.43$	$0.11 + \Delta/5.84$	- - - -	
Kohl Ranch	$\Delta/5.34$	$0.26 + \Delta/6.00$	- - - -	
Strawberry	$\Delta/3.12$	$0.17 + \Delta/5.86$	- - - -	SE towards Kohl Ranch
McDowell	- - - -	$0.26 + \Delta/5.8$	- - - -	
		$0.74 + \Delta/6.2$		To 87 km
		$1.07 + \Delta/6.2$		Beyond 87 km
Winslow	- - - -	$0.52 + \Delta/6.1$	- - - -	To 89 km
		$0.24 + \Delta/6.1$		Beyond 89 km
Cottonwood	- - - -	$0.32 + \Delta/5.9$	- - - -	Includes data from Clarkdale
		$0.64 + \Delta/6.1$		
Carrizo	- - - -	$0.24 + \Delta/5.9$	- - - -	
		$0.57 + \Delta/6.1$		
Gila Bend	$0.0 + \Delta/3.6$	$0.44 + \Delta/6.0$	$3.61 + \Delta/7.3$	P_n to 202 km
	- - - -		$5.64 + \Delta/7.8$	P_n beyond 202 km
	- - - -		$6.26 + \Delta/7.8$	P_n beyond 275 km
Sunrise	- - - -	$0.84 + \Delta/6.15$	$12.20 + \Delta/8.9$	
	- - - -	$0.34 + \Delta/6.15$		P_g beyond 188 km
Strawberry	- - - -	$0.30 + \Delta/5.9$	$6.18 + \Delta/7.96$	Toward Gila Bend
	- - - -	$0.98 + \Delta/6.2$		

Table 7.--Mathematical expressions of time-distance curves (cont'd)

Shot point	P_0 sec	P_g sec	P_n sec	Remarks
Strawberry	- - - -	0.40 + Δ/6.0		Toward Sunrise
Bylas	- - - -	0.98 + Δ/6.1	6.42 + Δ/7.9	
Blue Mountain	- - - -	0.25 + Δ/5.9	6.84 + Δ/7.7	
	- - - -	0.90 + Δ/6.1		
Strawberry	- - - -	0.49 + Δ/6.0		Toward Blue Mountain
Strawberry	- - - -	0.20 + Δ/5.9		Toward Bylas
	- - - -	0.39 + Δ/6.1		

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Appendix 1.--Longitude, latitude, and elevation of recording locations.

Shot: Bylas 1, Strawberry 1, Blue Mountain 1.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°47.03'	112°10.30'	1580
I	34°45.89'	112°22.14'	1350
J	34°52.25'	112°24.65'	1300
K	34°54.04'	112°33.26'	1270
L	34°59.32'	112°39.48'	1280
P	35°01.33'	112°48.42'	1480
Q	35°10.93'	112°48.59'	1360
R	No Record		
S	35°19.32'	113°02.58'	1590
T	35°23.32'	113°15.53'	1570

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Bylas 3, Strawberry 3.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	33°22.42'	110°06.89'	1390
I	33°29.17'	110°15.52'	1260
J	33°36.38'	110°22.51'	1660
K	33°58.23'	110°14.43'	1470
L	33°59.28'	110°22.79'	1510
P	33°59.97'	110°25.93'	1460
Q	34°01.20'	110°32.79'	1460
R	34°02.86'	110°36.51'	1670
S	34°08.69'	110°50.74'	1770
T	34°18.31'	110°56.22'	1750

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Strawberry 2, Bylas 2, Blue Mountain 2.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°19.22'	111°03.97'	1720
I	34°16.39'	111°10.63'	1440
J	34°19.55'	111°16.24'	1480
K	34°21.61'	111°25.45'	1610
L	34°24.33'	111°33.00'	1670
P	34°23.57'	111°39.20'	1020
Q	34°31.88'	111°48.54'	910
R	34°36.83'	111°51.98'	960
S	34°39.34'	111°57.78'	980
T	34°50.17'	111°58.13'	1190

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Carrizo 1, Blue Mountain 3, Clarkdale 1.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°19.52'	110°44.66'	2160
I	34°10.98'	110°47.52'	1870
J	34°19.67'	110°48.90'	2210
K	34°19.18'	110°50.67'	2180
L	34°17.90'	110°51.84'	2150
P	33°59.97'	110°25.93'	1420
Q	34°01.20'	110°32.79'	1530
R	34°02.86'	110°36.51'	1650
S	34°18.03'	110°54.17'	1980
T	34°18.31'	110°56.22'	1760

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Cottonwood 3.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°20.16'	110°44.44'	2130
I	34°19.80'	110°46.67'	2140
J	34°19.67'	110°48.90'	2150
K	34°19.18'	110°50.67'	2150
L	34°17.90'	110°51.84'	2130
P	34°17.68'	110°37.44'	2120
Q	34°20.68'	110°42.63'	2080
R	34°21.89'	110°41.36'	2010
S	34°17.98'	110°54.23'	2040
T	34°18.31'	110°56.22'	1770

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Carrizo 3.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°16.47'	111°19.27'	1400
I	34°17.68'	111°21.01'	1330
J	34°18.97'	111°23.71'	1380
K	34°21.55'	111°23.73'	1520
L	34°21.86'	111°25.83'	1590
P	34°24.82'	111°29.35'	1750
Q	34°23.82'	111°28.08'	1590
R	34°24.32'	111°33.21'	1500
S	34°15.22'	111°16.79'	1340
T	34°24.42'	111°31.47'	1570

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Carrizo 2, Clarkdale 2.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°17.77'	110°57.89'	1750
I	34°17.82'	110°58.98'	1840
J	34°19.10'	111°00.86'	1640
K	34°18.69'	111°02.86'	1620
L	34°19.42'	111°04.83'	1540
P	34°17.56'	111°08.01'	1535
Q	34°16.93'	111°09.44'	1510
R	34°16.11'	111°11.22'	1420
S	34°15.82'	111°13.20'	1390
T	34°15.74'	111°15.19'	1340

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Bylas 4.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°47.03'	112°10.30'	1753
I	34°16.39'	111°10.63'	1509
J	34°37.07'	111°52.38'	1585
K	34°80.17'	111°58.13'	1272
L	34°39.32'	112°39.48'	1402
P	35°02.26'	112°49.31'	1707
Q	35°10.01'	112°47.59'	1463
R	35°12.13'	112°55.06'	1524
S	34°17.99'	110°59.18'	1859
T	35°33.23'	113°19.29'	1585

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Clarkdale 3, Carrizo 4.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°43.39'	111°56.68'	965
I	34°24.41'	111°36.42'	1077
J	34°23.57'	111°39.20'	1155
K	34°25.81'	111°41.23'	1126
L	34°27.27'	111°42.16'	1070
P	34°28.10'	111°43.16'	1011
Q	34°29.47'	111°44.51'	969
R	34°30.39'	111°45.91'	934
S	34°24.48'	111°35.18'	1413
T	34°37.07'	111°52.38'	913

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Chase Ranch 1, Rye Creek 1, Winslow 1, McDowell 1.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°24.25'	111°16.78'	1661
I	34°21.89'	111°16.87'	1646
J	34°20.38'	111°17.38'	1509
K	34°17.46'	111°16.43'	1600
L	34°09.49'	111°19.34'	1295
P	34°15.15'	111°17.37'	1463
Q	34°12.42'	111°19.41'	1524
R	34°12.14'	111°19.36'	1478
S	34°16.16'	111°16.33'	1524
T	34°09.12'	111°20.63'	1219

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Strawberry 4, Kohl Ranch 1.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°16.89'	111°09.87'	1570
I	34°18.65'	111°02.71'	1730
J	34°17.36'	111°06.81'	1722
K	34°21.52'	111°23.94'	1646
L	34°15.87'	111°11.73'	1527
P	34°19.08'	111°22.49'	1433
Q	34°16.12'	111°19.28'	1509
R	34°17.76'	111°21.26'	1417
S	34°15.22'	111°16.79'	1448
T	34°15.85'	111°13.91'	1494

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Cottonwood 1.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°24.70'	111°29.38'	1829
I	34°23.60'	111°27.60'	1676
J	34°24.43'	111°31.75'	1829
K	34°21.52'	111°23.94'	1646
L	34°21.86'	111°25.83'	1608
P	31°19.08'	111°22.49'	1448
Q	34°16.12'	111°19.28'	1509
R	34°17.76'	111°21.26'	1417
S	34°15.22'	111°16.79'	1448
T	34°24.32'	111°33.21'	914

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Cottonwood 2.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°17.77'	110°57.89'	1890
I	34°17.82'	110°58.98'	975
J	34°19.10'	111°00.86'	1783
K	34°24.82'	111°29.35'	1821
L	34°21.86'	111°25.83'	1638
P	34°17.84'	110°39.22'	2210
Q	34°23.82'	111°28.08'	1768
R	34°24.32'	111°33.21'	1783
S	34°15.22'	111°16.79'	1173
T	34°24.42'	111°31.47'	1403

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Winslow 3, McDowell 3.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°37.63'	111°07.43'	2073
I	34°36.81'	111°11.28'	1950
J	34°35.44'	111°15.02'	2195
K	34°34.21'	111°16.30'	2195
L	34°33.20'	111°18.79'	2134
P	34°29.95'	111°16.89'	2195
Q	34°28.75'	111°17.82'	2210
R	34°27.26'	111°18.31'	2271
S	34°18.88'	111°14.53'	1524
T	34°23.00'	111°21.11'	1463

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Winslow 2, McDowell 2.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°58.33'	110°43.76'	1554
I	34°39.81'	111°06.61'	1798
J	34°48.67'	110°58.21'	1716
K	34°46.91'	110°59.93'	1829
L	34°45.59'	111°01.30'	1829
P	34°44.53'	111°03.09'	1890
Q	34°43.73'	111°04.64'	1830
R	34°42.36'	111°05.76'	1863
S	34°39.59'	111°06.59'	2042
T	34°54.22'	110°50.83'	1640

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Sunrise 1, Gila Bend 1, Strawberry 5.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°44.53'	111°03.09'	1815
I	34°39.31'	111°06.61'	1932
J	34°35.11'	111°15.40'	2195
K	34°27.50'	111°18.31'	2225
L	34°24.25'	111°16.78'	1676
P	34°15.15'	111°17.37'	1507
Q	34°09.12'	111°20.63'	992
R	34°00.96'	111°21.48'	1051
S	33°56.56'	111°26.93'	1402
T	33°50.83'	111°28.02'	914

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Winslow 4, McDowell 4.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	34°06.21'	111°21.18'	954
I	34°05.73'	111°21.18'	880
J	34°03.75'	111°21.62'	945
K	34°00.94'	111°21.45'	975
L	33°59.68'	111°22.24'	1051
P	33°59.12'	111°22.99'	975
Q	33°57.61'	111°23.42'	975
R	33°56.79'	111°26.71'	1128
S	33°52.04'	111°28.06'	1097
T	33°45.12'	111°29.73'	670

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Strawberry 7, Gila Bend 3.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	33°14.79'	112°18.59'	420
I	33°18.99'	112°31.31'	304
J	33°10.99'	112°33.17'	426
K	33°12.41'	112°45.72'	244
L	33°03.61'	112°41.53'	204
P	32°52.90'	112°45.23'	256
Q	32°49.95'	112°46.89'	289
R	32°46.88'	112°48.62'	305
S	32°41.95'	112°50.93'	335
T	32°36.02'	112°56.16'	366

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Strawberry 6, Gila Bend 2, Sunrise 2.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	33°38.49'	111°32.36'	670
I	33°32.03'	111°36.56'	487
J	34°03.75'	111°21.62'	975
K	33°27.42'	111°37.93'	554
L	33°21.01'	111°38.09'	429
P	33°21.82'	111°58.81'	518
Q	33°57.61'	111°23.42'	304
R	33°15.39'	112°10.01'	350
S	33°52.04'	111°28.06'	1005 Sunflower
T	33°45.12'	111°29.73'	853

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Tonto 1.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	35°56.43'	109°34.36'	1770
I	35°34.93'	109°46.93'	1829
J	36°43.61'	115°54.83'	1131
K	36°52.11'	116°09.54'	1457
L	38°22.02'	110°53.53'	1402
P	33°03.74'	112°41.75'	208
Q	35°19.49'	114°01.92'	1112
R	36°09.94'	114°54.78'	487
S	35°34.00'	113°19.29'	1646
T	33°10.76'	110°09.01'	803

Appendix 1.--Longitude, latitude, and elevation of recording locations (cont'd)

Shot: Strawberry 8, Sunrise 3, Gila Bend 4.

Unit	Latitude, North	Longitude, West	Elevation (meters)
H	35°26.34'	109°55.36'	1768
I	35°23.57'	110°05.21'	1768
J	35°22.49'	110°19.24'	1798
K	35°17.77'	110°21.52'	1768
L	No Record		
P	35°06.81'	110°31.25'	1617
Q	35°02.62'	110°37.51'	1510
R	34°59.01'	110°43.02'	1532
S	34°54.51'	110°50.52'	1622
T	34°51.68'	110°54.82'	1707

Locations are given for most westerly seismometer.

Appendix 2.--Shotpoint Information

Shot Point	Shot No.	Shot Time (MST)	Date	Total Charge Size (lb)	Drill Hole No.	Charge	Depth (ft) Top	Depth (ft) Bottom	Typical drill log	Shot Point Latitude	Shot Point Longitude	Altitude (meters)
Blue Mountain	1	07:00:00.40	4-15-64	2000	A-1	2000	70	140	0-55 clay & gravel 55-210 cavernous limestone.	35°33.42'	113°19.92'	1580
Blue Mountain	2	06:30:00.41	4-16-64	6690	A-4	3360	70	210				
Blue Mountain	3	07:30:00.45	4-18-64	7360	A-5	3330	70	180				
					A-2	2000	150	152				
					A-3	2000	70					
					A-6	3360	70					
Bylas	1	06:00:00.17	4-15-64	9970	A	1170	130	150	0-50 gravel & sand 50-220 red clay W.T. - 50 ft	33°10.76'	110°08.01'	795
					B	1520	75	140				
					C	2000	86	150				
					F	2000	96	180				
					G	2280	80	170				
					H	1000	114	150				
Bylas	2	07:28:56.87	4-16-64	8000	C*	2000	95	170				
					D	500	160	180				
					E	2000	97	180				
					F-1*	1500	70	130				
					G-1*	2000	70	153				
Bylas	3	07:00:00.02	4-17-64	2000	A-1*	1000	93	135				
					B-1*	1000	93	135				
Bylas	4	06:29:59.95	4-21-64	10,000	A-2*	2000	84	120				
					B-2*	2000	70	120				
					C-1*	4000	80	110				
					I-1*	2000	84	120				

Appendix 2.--Shotpoint Information (continued)

Shot Point	Shot No.	Shot Time (MST)	Date	Total Charge Size (lb)	Drill Hole No.	Charge	Depth (ft) Top	Depth (ft) Bottom	Typical drill log	Shot Point Latitude	Shot Point Longitude	Altitude (meters)
Strawberry	1	06:30:00.80	4-15-64	3000	4	1500	90	145		34°22.16'	111°26.02'	1690
					6	1500	90	145				
Strawberry	2	07:00:00.20	4-16-64	2500	3	1000	55	115	0-150 ls., mudstone & shale			
					7	1500	90	137				
Strawberry	3	06:30:00.16	4-17-64	6000	5	1500	95	145				
					8	1500	100	140				
					9	3000	50	150				
Strawberry	4	06:30:00.18	4-22-64	5400	11	540	75	100				
Strawberry	5	07:15:00.21	4-30-64	2000	10	2000	59	133				
Strawberry	6	06:30:00.19	5-4-64	3000	6*	3000	111	140				
Strawberry	7	06:00:00.07	5-5-64	6000	7*	4000	92	115				
Strawberry	8	07:00:00.20	5-6-64	4000	1	1500	68	125				
					8*	2500	105	142				
Carrizo	1	07:00:00.06	4-18-64	1000	E-4	1000	102	144	0-50 sand, gravel & boulders	34°01.77'	110°17.54'	1520
Carrizo	2	07:00:00.01	4-19-64	2000	E-2	2000	102	190	50-150 shale w/ledges of ss & gypsum			
Carrizo	3	13:29:59.97	4-19-64	2000	E-1	2000	102	190	150-200 ls with stringer ss & shale			
Carrizo	4	06:29:59.96	4-20-64	3000	E-3	1500	101	164				
					E-2A*	1500	101	164				

Appendix 2.--Shotpoint Information (continued)

Shot Point	Shot No.	Shot Time (MST)	Date	Total Charge Size (lb)	Drill Hole No.	Charge	Depth (ft) Top	Depth (ft) Bottom	Typical drill log	Shot Point Latitude	Shot Point Longitude	Altitude (meters)
Clarkdale	1	06:30:00.15	4-18-64	3000	4	1500	90	150	0-200 clay with layers hard ls W.T. - 45 ft	34°48.01'	112°04.98'	1285
					2	1500	100	200				
Clarkdale	2	07:15:00.16	4-19-64	2000	3	2000	110	200				
Clarkdale	3	08:00:00.43	4-20-64	3000	4*	2000	107	200				
					1	1000	89	150				
Kohl Ranch	1	07:30:00.18	4-22-64	310	1	310	30	42	0-47 ls bottom quartzite	34°19.38'	111°03.99'	1680
Rye Creek	1	13:30:00.23	4-23-64	560	1	560	130	150	0-150 granite	34°08.22'	111°21.60'	1060
Chase Ranch	1	14:00:00.02	4-23-64	960	A	960	88	121	0-40 ls 40-96 ss 96-125 ls	34°23.49'	111°17.20'	1655
Fort McDowell	1	07:00:00.06	4-24-64	3000	A	3000	65	240	0-35 gravel & boulders 35-250 volcanic rock & well cemented conglomerate W.T. - 35 ft	33°40.08'	111°34.62'	500
Fort McDowell	2	06:30:00.22	5-1-64	6000	2	3000	65	240				
					3	3000	85	240				
Fort McDowell	3	06:00:00.40	5-2-64	4000	3	2000	90	245				
					4	2000	65	245				
Fort McDowell	4	06:30:00.29	5-3-64	2000	5	2000	85	235				

Appendix 2.--Shotpoint Information (continued)

Shot Point	Shot No.	Shot Time (MST)	Date	Total Charge Size (lb)	Drill Hole No.	Charge	Depth (ft) Top	Depth (ft) Bottom	Typical drill log	Shot Point Latitude	Shot Point Longitude	Altitude (meters)
Winslow	1	06:30:00.12	4-24-64	4000	A	2000	115	200	0-90 shale & clay	35°01.44'	110°38.02'	1500
					B	2000	115	200	90-230 shale w/ss & gypsum layers			
Winslow	2	07:00:00.00	5-1-64	2040	4	2040	100	180				
Winslow	3	06:29:59.97	5-2-64	4080	1	2040	118	200				
					5	2040	105	230				
Winslow	4	05:59:59.99	5-3-64	6000	3A*	3000	160	190				
					4A*	3000	160	190				
Cottonwood	1	06:30:00.41	4-23-64	3000	1	1500		90	0-200 clay w/hard ls & ss layers	34°45.49'	111°58.59'	1080
					2	1500		150				
Cottonwood	2	07:00:00.15	4-29-64	4000	3	2000	106	200				
					4	2000	106	200				
Cottonwood	3	13:00:00.27	4-29-64	6000		2000						
						2000						
Gila Bend	1	07:40:00.23	4-30-64	7000	1	3000			0-50 loose clay	33°01.28'	112°42.23'	205
					2	2000		175	50-200 hard conglomerate			
					3	2000	135	175				
Gila Bend	2	07:00:01.44	5-4-64	4000					W.T. - 50 ft			
Gila Bend	3	07:35:00.21	5-5-64	2000								
Gila Bend	4	06:00:00.69	5-6-64	10,000	3							
					4							
					5							

Appendix 2.--Shotpoint Information (continued)

Shot Point	Shot No.	Shot Time (MST)	Date	Total Charge Size (lb)	Drill Hole No.	Charge	Depth (ft) Top	Depth (ft) Bottom	Typical drill log	Shot Point Latitude	Shot Point Longitude	Altitude (meters)
Sunrise	1	06:49:59.99	4-30-64	8000	A	2000	98	200	0-80 sand, gravel	35°34.51'	109°48.46'	1830
					B	2000	100	200	80-105 hard ss			
					C	2000	100	200	105-200 red sandy			
					D	2000	101	200	shale w/ss ledges			
									W.T. - 35 ft			
Sunrise	2	05:59:59.95	5-4-64	10,020	2A*	3360	86	110				
					4A*	3360	100	110				
					5A*	3300	90	110				
Sunrise	3	06:29:59.93	5-6-64	4020	3A	4020	90	105				
Tonto	1	05:30:00.20	5-8-64	23,320	1*	8220		148	0-50 hard shale	34°18.42'	111°14.72'	1650
					2*	7020		150	50-145 ls			
					3*	8100		150	145-158 soft brown shale	Note: Holes sprung with 500# each before loading.		
									158 - very hard rock			

* Denotes reused drill hole.

W.T. = Water Table (holes were dry where no water table is given).