CRUSTAL STRUCTURE IN NEW MEXICO

Based on Project Gnome and Microearthquake Data

A Thesis

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ABSTRACT

The crustal structure of eastern and central New Mexico was determined from an analysis of Project Gnome and microearthquake travel time data. Project Gnome data was corrected for the effect of near surface rocks. The total thickness of the crust in eastern New Mexico was found to be 49.5 km with an intermediate discontinuity at a depth of 18.7 km. Compressional wave velocities in the same area were found to be 6.1 km/sec in the upper crustal layer, 6.8 km/sec in the lower crustal layer, and 8.3 km/sec beneath the Mohorovičić discontinuity. A comparison between the crustal models obtained from corrected and uncorrected travel times shows no appreciable effect of near surface rocks on the interpretation of travel time data.

Microearthquakes recorded at Albuquerque were analyzed for the distinct phases other than direct P and S. Reflections, S_iP and S_MS, were found from an intermediate discontinuity (18 km) and the Mohorovičić discontinuity (38 km), respectively. S_MS reflections were used to estimate the average velocity (6.7 km/sec for the P-wave) and thickness of the intermediate layer (19.5 km).

This work in combination with previous studies in New Mexico suggests the state can be divided into "sub-surface provinces" on the basis of crustal thicknesses and sub-crustal velocities observed in different parts of the state.

CRUSTAL STRUCTURE IN NEW MEXICO

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INTRODUCTION

The objective of the work presented in this paper was to investigate the crustal structure of New Mexico using the travel time data from explosions and microearthquakes. Microearthquakes in central New Mexico and a nuclear explosion (Project Gnome) near Carlsbad (Romney, et al., 1962; Westhusing, 1963) were the sources of the elastic waves. The travel time data from these elastic waves was interpreted in terms of crustal structure using seismic refraction and reflection methods of analysis.

In separate sections of this paper, results of Project Gnome refraction profiles, microearthquake crustal reflections, and mining explosion time-distance relations are presented. A brief introduction to the methods of analysis and the results is given below.

An underground nuclear explosion was detonated (December, 1961) approximately 39 km southeast of Carlsbad, New Mexico. This event was well recorded by an extensive network of seismic stations in New Mexico, particularly along a line of stations extending north from ground zero in the eastern part of the state. Two seismic refraction profiles, Gnome to Kilo (north profile) and Gnome to Springerville (northwest profile), were obtained from the published travel time data. Corrections to the observed travel times were made to eliminate the effect of near surface rocks. Since the velocity and thickness of the near surface rocks is known, a correction of this type was possible. Standard methods of interpretation of the corrected travel times gave the crustal models summarized in Tables 3 and 4. A crustal model (Table 5) constructed from uncorrected travel times for the north profile was compared with that obtained from the corrected travel times (Table 3).

Crustal structure of central New Mexico was investigated using the travel time data from shallow foci (5 or 10 km) microearthquakes. Records (from the USCGS station at Albuquerque) of microearthquakes at known epicentral distances and with sharp phases other than direct P and S were analyzed. Strong reflections, S_MS, from the Mohorovičić discontinuity were observed and a suitable crustal model (Fig. 10) for central New Mexico was obtained. Another weaker phase, S_iP, was identified as a reflection from an intermediate discontinuity.

An attempt was made to investigate crustal structure in western New Mexico from the travel time data of Santa Rita and Morenci explosions recorded at Las Cruces (Geo. Tech. Corp.), Socorro (NMIMT) and Albuquerque (USCGS). Because the data were inadequate, no crustal model could be obtained for this region.

The results of the study indicate different crustal thicknesses, and crustal and sub-crustal velocities for different regions of the state. This suggests the state could be separated into different "sub-surface provinces" on the basis of the observed thicknesses and velocities.

NOMENCLATURE AND DEFINITIONS

Basement Rocks: Crystalline igneous and/or metamorphic rocks of Precambrian age underlying sedimentary basins.

Near Surface Rocks: The rocks, Cambrian to Quaternary in age, overlying the basement rocks.

Crust: The portion of the earth which lies between the surface and Mohorovičić discontinuity.

Delay Time: The time for the wave to travel the segment (OA) in Figure 1 minus the time required for the wave to travel the horizontal component (AB) of that segment at the highest velocity (V_1) reached by the wave ($OACS_1$).

P Wave: A compressional wave that travels directly from source to detector.

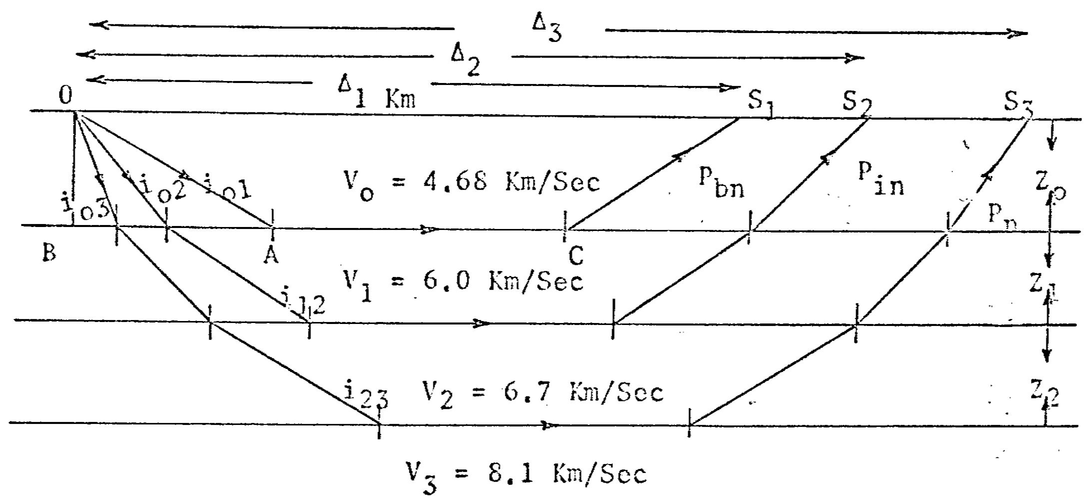
P_{bn} Wave: A conical P-wave generated by a compressional wave critically refracted at the upper part of the basement rocks.

P_{in} Wave: A conical P-wave generated by a compressional wave critically refracted at the upper boundary of the lower portion of the crust.

P_n Wave: A conical P-wave generated by a compressional wave critically refracted at the Mohorovičić discontinuity.

S_iP Wave: A reflection from the top of an intermediate layer involving an incident S-wave and a reflected P-wave.

S_MS Wave: An S-wave reflection from the top of the Mohorovičić discontinuity.



Snell's Law

$$SINi_{o1} = \frac{V_o}{V_1}$$

$$D_{o1} = \frac{2Z_o \ COS \ i_{o1}}{V_o} \qquad SIN \ i_{o1} = \frac{V_o}{V_1}$$

$$D_{mn} = \frac{2Z_m \ COS \ i_{mn}}{V_m} \qquad SIN \ i_{mn} = \frac{V_m}{V_n}$$

Fig. 1. Schematic diagram of refraction ray paths for waves P_{bn}, P_{in} and P_n in a layered crust.

ASSUMPTIONS

Interpretation of the Travel-Time Data:

In the interpretation of the travel-time data the following assumptions were made:

1. The travel-time curve of the first arrivals was divided into straight-line segments. These straight-line segments were interpreted in terms of crustal layering assuming that:

   a. Each layer is represented by a distinct segment of the travel-time curve and the reciprocal slope of each segment represents the velocity of the corresponding layer.

   b. Each layer is horizontal and has a constant velocity.

   c. The velocity of compressional waves in each layer is greater than that in the layer immediately above.

Since the profiles are not reversed, assumptions (b) and (c) are necessary. If the layers are dipping, the velocity in the up dip shooting would be greater than that of down dip shooting. The presence of a low velocity layer in the crust, which is contrary to the assumption (c), would increase total thickness of the crust.

2. The P-wave velocity was computed from the S-wave velocity assuming a Poisson's ratio of 0.25.

SUMMARY OF CRUSTAL STRUCTURE STUDIES IN NEW MEXICO

The first reliable information on the crustal structure of New Mexico was obtained by Tuve and Tatel (1955) who recorded mining and other controlled explosions in western New Mexico and eastern Arizona. The mining explosions were at Santa Rita, New Mexico, and Morenci, Arizona (see Figure 2). From observed travel times, these investigators proposed a single layer crust, 30 km thick, with a velocity of 5.8 km/sec, and an upper-mantle velocity of 8.0 km/sec. Tuve and Tatel also reported reflections, P_xP, probably from the Mohorovičić discontinuity.

After the investigations of Tuve and Tatel, no significant work on crustal study of New Mexico was done until Project Gnome. Seismic waves generated by the Gnome nuclear explosion (December 10, 1961) in southeastern New Mexico were recorded at many locations in the state, particularly along a 350 km long line extending north from the explosion. The observations of this experiment were published in a special issue of the Bulletin of the Seismological Society of America (December, 1962) and in the journal of Geophysics (February, 1963). The interpretations of travel time data obtained in eastern New Mexico resulted in three different crustal models. The crustal models proposed by Stewart and Pakiser (1962), by Romney, et al. (1962), and by Carder (1962) are summarized in Figure 3. Noteworthy is the fact that with the same observational data three different crustal models have been proposed for the same area. In these interpretations of travel-

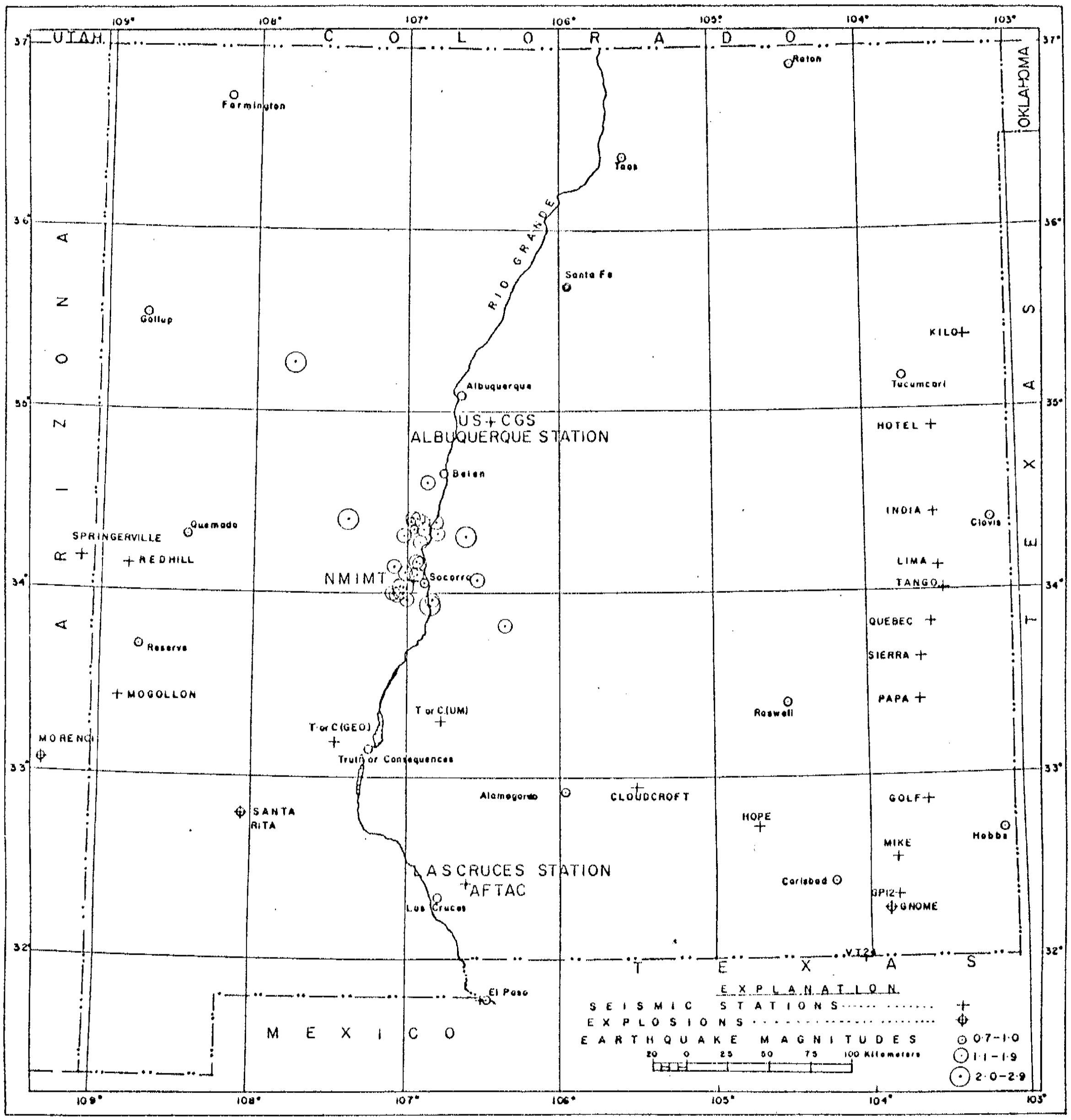


Fig. 2. Map of New Mexico showing locations of seismic stations, Gnome explosion, microearthquakes, and mining explosions (microearthquake locations from Sanford, 1965).

time data, the effect of the near surface rocks overlying the basement rocks was neglected.

On crustal structure of central New Mexico, no information was published until 1964. Phinney (1964), from an analysis of spectral behavior of long-period body waves recorded at Albuquerque, obtained a crustal thickness of 40 km. His results also indicated the possible existence of an intermediate layer in the depth range of 18 to 22 km with a velocity somewhere between 6.6 and 7.0 km/sec.

Another significant contribution to the crustal structure study of central New Mexico was by Sanford and Long (1965). They have reported microearthquake crustal reflections, S_xP and S_xS, from the top of an intermediate layer at a depth of 18 km.

Figure 3 summarizes the crustal models obtained in previous work. This summary reveals a variety of crustal models, particularly for the eastern part of the state.

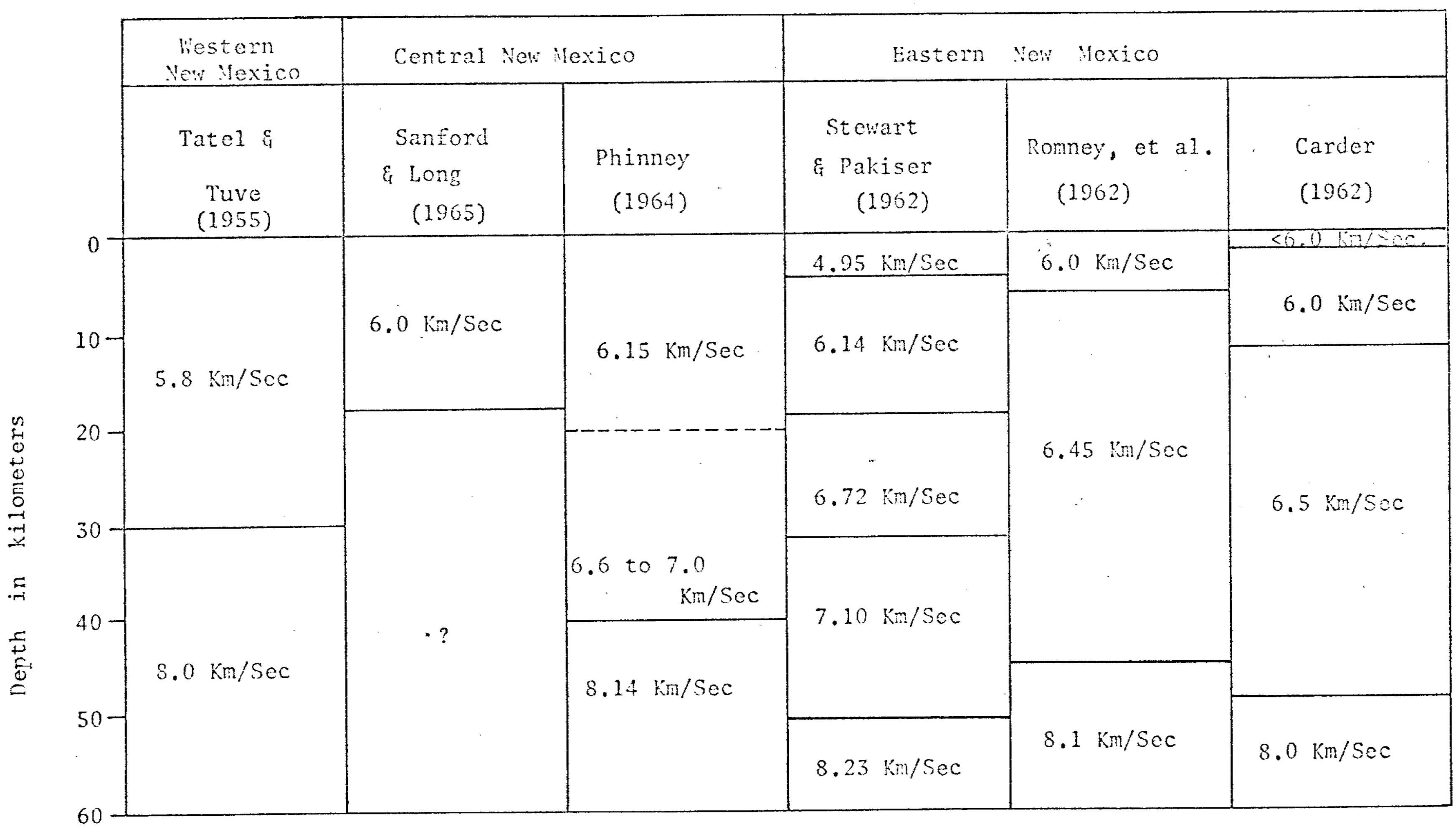


Fig. 3. Summary of Crustal Structures in New Mexico.

REINTERPRETATION OF PROJECT GNOME DATA

Introduction

A variety of possible crustal models for eastern New Mexico have been determined by several investigators using the Gnome explosion data (Fig. 3). The multiple solutions may be due in part to variations in arrival times (Figs. 7 and 8) arising from differences in the thickness and velocity of the near surface rocks. In this work, a correction was applied to the travel times to eliminate the effect of the sedimentary section at the shot and the detectors. As shown later, this correction proved to be ineffective in some respects. Locations of seismic recording units, whose data from Project Gnome were used in this study, are shown in Figure 2. These seismic stations constitute two profiles, Gnome to Kilo (North Profile) and Gnome to Springerville (Northwest Profile).

Effect of Near Surface Rocks

Thickness of Near Surface Rocks:

Figure 4 shows the basement relief (Foster and Stipp, 1961) along the Gnome north profile. The thickness of near surface rocks at the Gnome explosion site is about 5.1 km whereas at the farthest seismometer location, Kilo, the thickness is about 1.0 km.

Velocity of Near Surface Rocks:

The average velocity in near surface rocks along the north profile in eastern New Mexico was obtained from the velocity logs of wells in this area. Lists of velocity logged wells in New Mexico

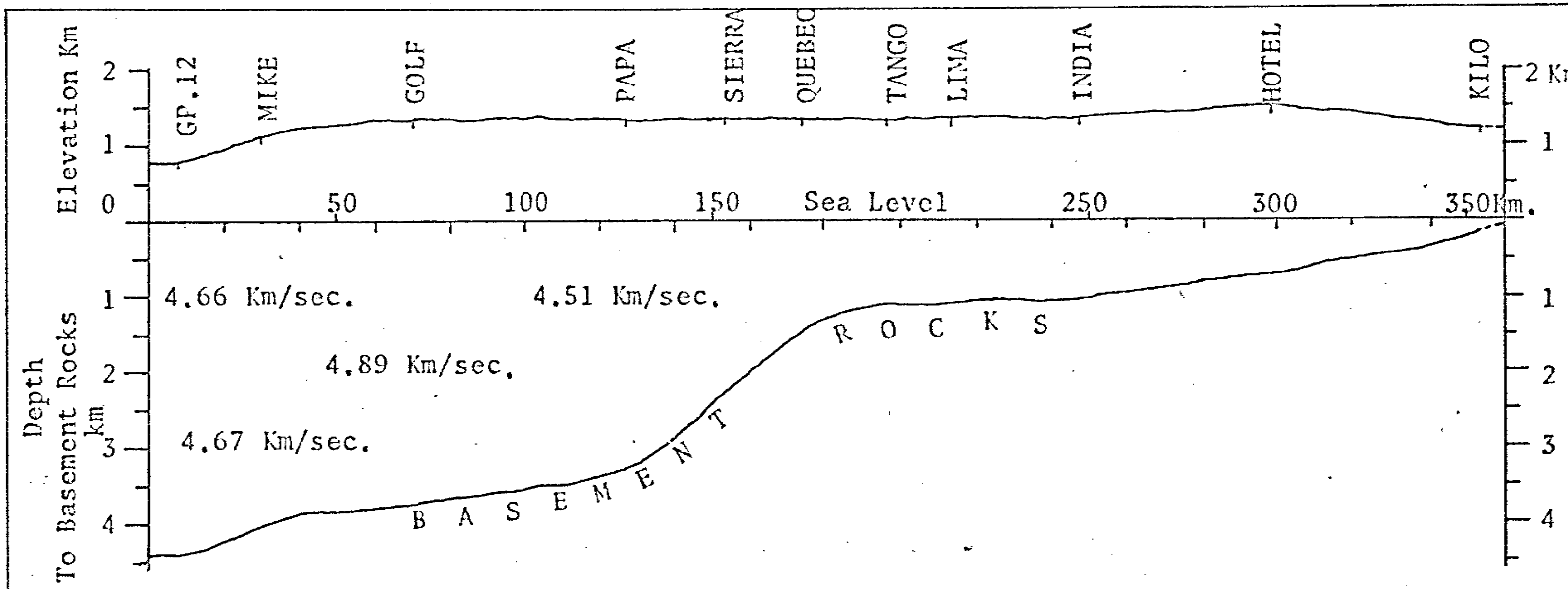


Fig. 4. Basement Relief along the North profile in Eastern New Mexico.

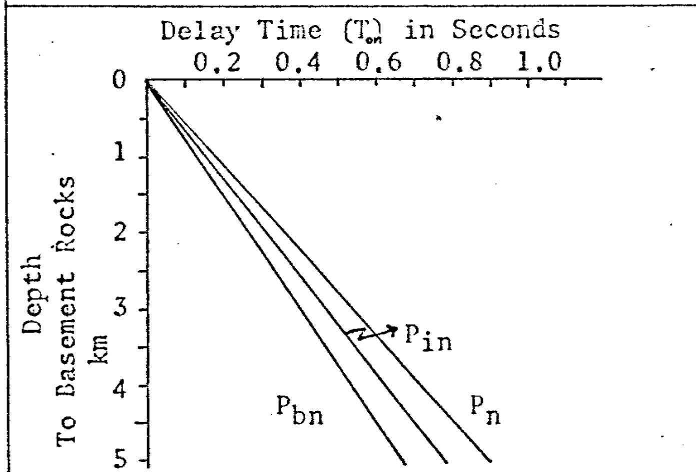


Fig. 5. Travel-time delays in near surface rocks.

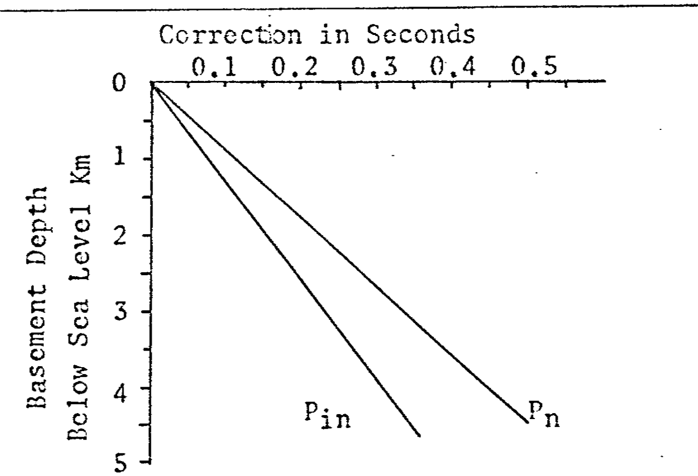


Fig. 6. Basement relief correction.

have been published in the journal Geophysics (1944-1963). The wells with velocity information located within 6 km of the Gnome seismic stations were selected with special emphasis on the deep wells. Through the courtesy of several oil companies (Conoco, Pan American, Phillips, and Shell) velocities in the sedimentary rocks near four seismic stations along the north profile of eastern New Mexico were obtained. An average velocity in the sedimentary section at each of these four stations was determined from the well velocity data nearest to the stations. These average velocities are indicated in the Figure 4. An average of the average velocities at the four locations was found to be 4.68 km/sec. This value was adopted as the velocity of the near surface rocks along the north profile and for the first four stations of the northwest profile.

Procedure for Correction:

With the thickness and average velocity of near surface rocks known, the travel times in these rocks could be computed. The concept of delay-time (Nettleton, 1940; pp. 248-254) was used to compute the travel time of waves P_{bn}, P_{in}, and P_n in the sedimentary section.

Consider the multiple layer crust of Figure 1 in which the refraction ray paths of P_{bn}, P_{in}, and P_n waves are shown schematically. The travel times of the P_{bn}, P_{in}, and P_n arrivals can be written in terms of delay-times as follows:

$$T_1 = \Delta_1/V_1 + T_{01},$$

$$T_2 = \Delta_2/V_2 + T_{02} + T_{12}, \text{ and}$$

$$T_3 = \Delta_3/V_3 + T_{03} + T_{13} + T_{23},$$

where the Δ's are distances between shot point and seismometer locations;

$T_{01} = 2Z_0 \cos i_{01}/V_0$ is the delay time of P_{bn} in Z_0 layer;
$T_{02} = 2Z_0 \cos i_{02}/V_0$ and $T_{12} = 2Z_1 \cos i_{12}/V_1$ are delay times of P_{in} in Z_0 layer and Z_1 layers, respectively; and $T_{03} = 2Z_0 \cos i_{03}/V_0$, $T_{13} = 2Z_1 \cos i_{13}/V_1$, and $T_{23} = 2Z_2 \cos i_{23}/V_2$ are delay times in Z_0, Z_1, and Z_2 layers, respectively.

As stated earlier, the main objective was to eliminate the effect of near surface rocks on the observed travel times using the delay time concept. Computations of T_{01}, T_{02}, and T_{03} were made with the following assumptions:

1. The velocity in the sedimentary section is constant, without any lateral variations.
2. The velocities of waves P_{bn}, P_{in}, and P_n are constant in their respective crustal layers all along the profile.
3. Crustal structure along the profiles is approximately that shown in Figure 1.

The correction procedure was to subtract the delay times T_{01}, T_{02}, and T_{03} (travel times in Z_0 layer) from the observed travel-time. As a result of this correction, the observed travel-times were reduced to the basement level. An added correction for the elevation differences of stations was also made.

Reduction of Travel Times:

The delay times (T_{01}, T_{02}, and T_{03}) of waves P_{bn}, P_{in}, and P_n in the Z_0 layer (in this case near surface rocks) were plotted with respect to the thickness of the near surface rocks (Fig. 5). Travel-time in the near surface rocks was obtained from Figure 5 for each recording station. For example, at the seismic station MIKE, the observed travel time (T_0) is 6.21 sec. The travel time T_{01} in the near surface rocks was 1.35 sec. The time T_{01} = 1.35 sec, is the sum of delay times 0.65 sec at the site of the explosion and 0.70 sec at the seismic station MIKE. The reduced time $T = T_0 - T_{01} = 4.9$ sec puts the shot point (Gnome explosion site) and the seismic station (MIKE) at the level of basement rocks. A similar procedure was followed in the reduction of observed travel times at other stations of the north profile.

Since the basement surface is irregular (Fig. 4), an added correction for differences in basement elevation along the profile was necessary. Figure 6 is a graph of the correction time (T_b) in seconds versus basement depth below sea level. T_b is computed (in a manner similar to computations of the delay time in near surface rocks) for P_{in} and P_n waves assuming a velocity of 6.0 km/sec in the basement rocks. No correction to P_{bn} is required for a change in basement elevation. Finally, the quantity $T + T_b$ gives the corrected travel time, T_c, for the first arrival at each station as if the shot and all the seismometers along the profile were located at sea level on basement rocks.

The reduced travel-times of the north profile (Gnome to Kilo, Fig. 2) and the northwest profile (Gnome to Springerville, Fig. 2) are listed in Table 1 and Table 2, respectively.

Results

Profile Gnome to Kilo:

The corrected travel times were plotted (Fig. 7) with respect to the distance between the seismic recording unit and the shot point.

Table 1. Correction of Observed Travel Times, Gnome to Kilo, to Eliminate the Effect of Near Surface Rocks.

Station	Δ Km.	T_o Sec.	Depth to basement rocks at station* Km.	Delay time T_{on} Sec.	Reduced travel time $T = T_o - T_{on}$ Sec.	Sea level to basement +depth Km.	Basement elevation correction T_b Sec.	Corrected time $T_c = T + T_b$ Sec.	Remarks
Mike	30.9	6.21	5.3	1.35	4.9	4.0	-	4.9	P_{bn} is used
Golf	69.6	12.3	5.1	1.32	10.98	3.8	-	10.98	"
Papa	127.1	21.7	3.6	1.12	20.58	2.3	-	20.58	"
Sierra	153	26.0	3.45	1.27	24.73	2.1	0.58	25.33	P_{in} is used
Quebec	176	29.1	2.5	1.12	27.98	1.2	0.40	28.38	"
Tango	195.8	32.2	2.35	1.1	31.1	1.05	.39	31.49	"
Lima	209.4	34.3	2.35	1.1	33.2	1.05	.39	33.59	"
India	241.4	38.7	2.35	1.26	37.44	1.05	.56	38.00	P_n is used
Hotel	295.2	45.5	2.25	1.25	44.25	0.75	.53	44.78	"
Kilo	351.6	51.8	1.35	1.1	50.7	0.15	0.46	51.16	"

* Basement depth at Gnome 4.8 Km.

\+ Basement depth at Gnome from sea level 4.0 Km.

Table 2. Correction of Observed Travel Times, Gnome to Springerville, to Eliminate the Effect of Near Surface Rocks.

Station	Δ Km.	T_o Sec.	Basement level at station *B.S.+A.S.	Elev. at the station +A.S.	Thickness of sediments Km.	Delay time T_{on}	Reduced time $T = T_o - T_{on}$ Sec.	Basement level at detector with ref. to sea level Km. *B.S.+A.S.	Correct. to sea level T_b Sec.	Correct. time $T_c = T + T_b$	Remarks
V. T. 24	33.9	6.95	4.25	0.9	5.15	1.33	5.72	4.25	-	5.72	P_{bn} used
Hope	95.3	16.3	1.54	0.5	2.04	0.96	15.34	1.54	+0.47	15.81	P_{in} used
Cloud-croft	190.1	31.9	1.69	≈2.0	≈0.3	0.70	31.2	1.69	+0.18	31.38	
T or C (UM)	296	45.4	0.34	1.5	1.16	0.84	44.56	0.34	+0.40	44.96	P_n used
Socorro	350.1	51.8		1.6				1.6	+0.17	51.97	
T or C (Geo)	352.2	52.3		1.5				1.5	+0.18	52.48	"
Mogollon	482.4	68.3		1.6				1.6	+0.17	68.47	"
Red Hill	506.5	72.5		0.5 ?				0.5 ?	+0.39	72.64	"
Springer-ville	535.9	75.5		2.1				2.1	+0.22	75.72	"

* Below sea level. + Above sea level.

Straight-line segments were drawn through the travel-time data using the least-squares method. The best fitting straight-line segments and the corresponding standard deviations were as follows:

$$T_1 = (0.163 \pm 0.0008)\Delta_1,$$

$$T_2 = (0.147 \pm 0.0035)\Delta_2 + (2.7 \pm 0.074), \text{ and}$$

$$T_3 = (0.120 \pm 0.0040)\Delta_3 + (9.35 \pm 0.184),$$

where the Δ's are distances in kilometers between shot point and seismometer locations and T's are the corrected travel-times in seconds. The standard deviations are negligible except for the intercept time in the T_3 segment, which results in ± 0.8 km change in total thickness of the crust.

Using the intercept times 2.7 sec and 9.35 sec, depths to the intermediate layer and Mohorovičić discontinuity were found to be 18.7 and 49.5 km, respectively, from sea level. The crustal model for eastern New Mexico obtained from the time-distance curve in Figure 7 is summarized in Table 3.

Table 3. Summary of Crustal Model for Eastern New Mexico Based on Corrected Arrival Times.

Layer No.	Compressional wave velocity km/sec	Cross over distance km	Intercept time sec	Layer thickness km	Depth to bottom of layers km
1	6.1			18.7	18.7
2	6.8	170	2.7	30.8 ± 0.8	49.5 ± 0.8
3	8.3	240	9.35 ± 0.18	-	

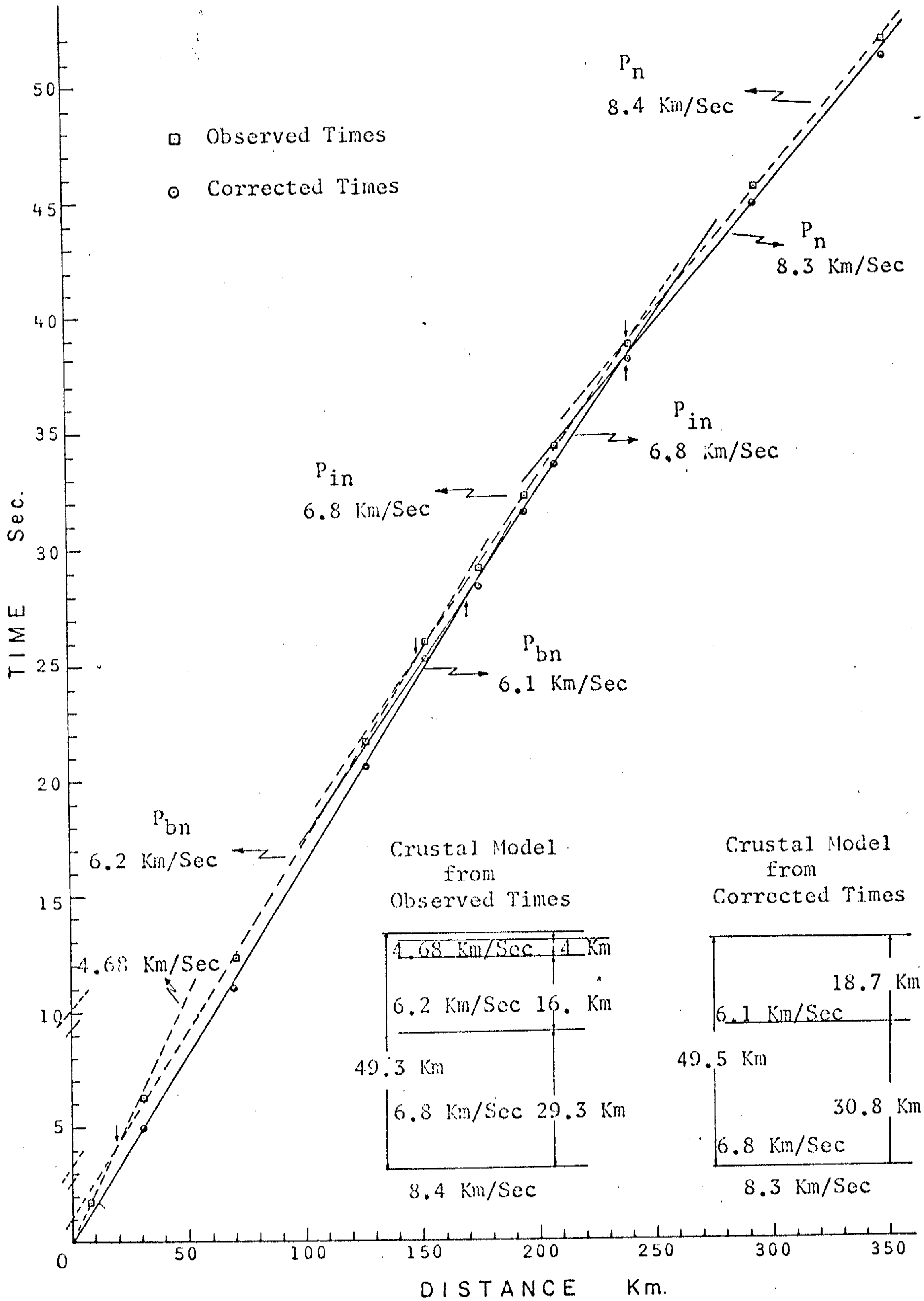


Fig. 7. Travel-times of first arrivals for the Gnome explosion, Gnome to Kilo profile.

Profile Gnome to Springerville:

In the northwest profile, corrections to the observed travel-times, similar to those of north profile were applied to the following seismic stations: Volunteer Team 24 (V.T. 24), Hope; Cloudcroft; and Truth or Consequences (UM). For the remaining seismic stations (Table 2), corrections were not applied, since the depth to the basement rocks was not known. However, a correction was made for the elevation differences (Table 2).

Figure 8 is the time-distance plot of the northwest profile data. The data fit two straight-line segments, drawn with the least-squares method. The equations of straight lines with corresponding standard deviations are:

$$T_1 = (0.164 \pm 0.00325)\Delta_1,$$

$$T_3 = (0.128 \pm 0.0018)\Delta_3 + (7.05 \pm 0.165).$$

The depth to the Mohorovičić discontinuity calculated from the intercept time (7.05 ± 0.16 sec) and velocities (6.09 km/sec and 7.81 km/sec) was 34.3 ± 0.7 km. The intermediate layer along this profile is not evident from the data. If an intermediate layer with a velocity of 6.8 km/sec did exist at a depth of 18 km, all first arrivals for Δ's between 148 and 240 km would lie on the dotted line segment in Figure 8. Only one observation station, Cloudcroft, is within the distance range of 148 to 240 km, and therefore the existence of the intermediate layer northwest from Gnome is uncertain. However, because the calculated depth to the "Moho" without the intermediate layer was less than the depth in central and eastern New Mexico, a crustal model with an intermediate layer was constructed and the

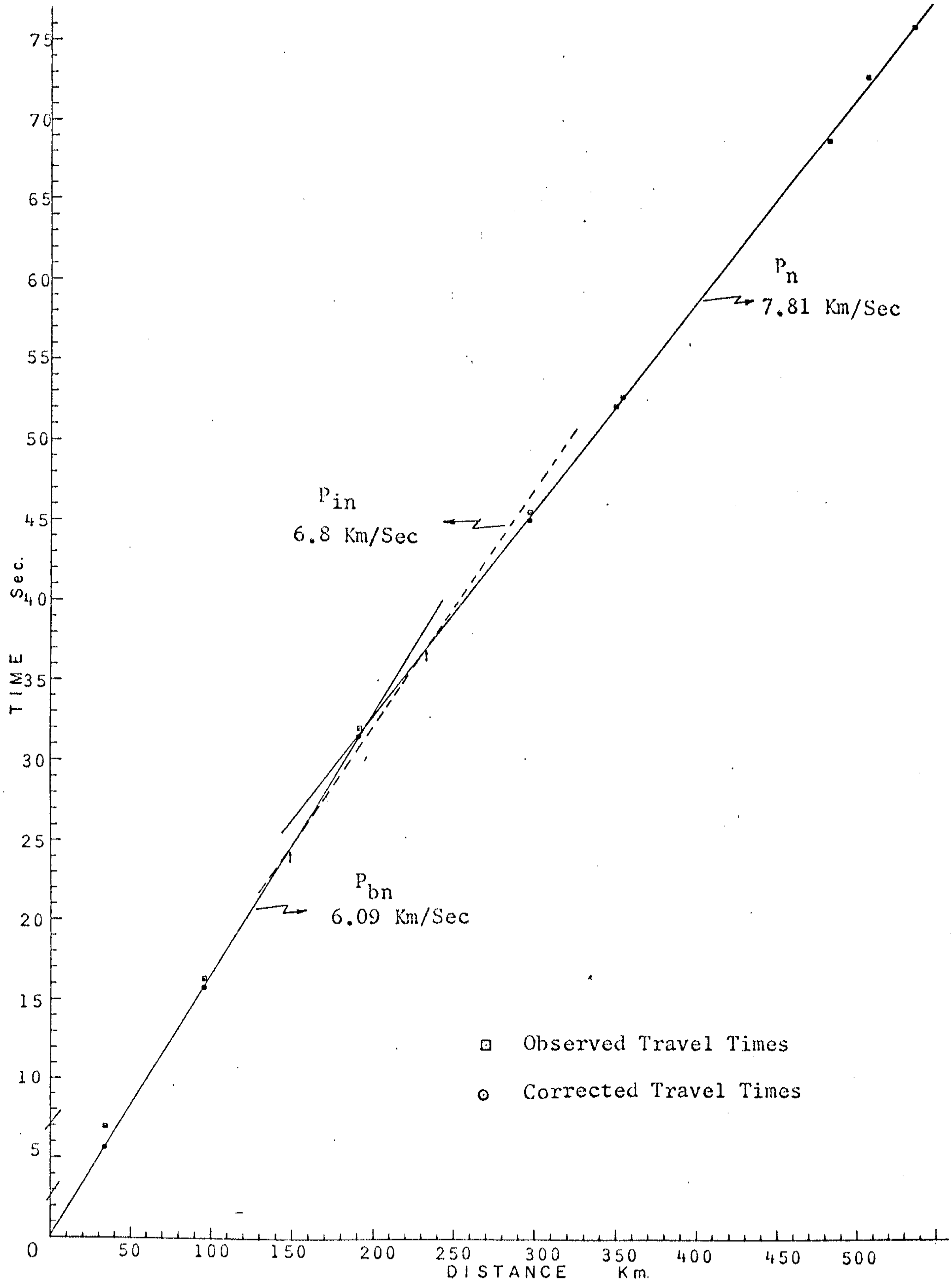


Fig. 8. Travel-times of first arrivals for the Gnome explosion, Gnome to Springerville profile.

results are summarized in Table 4.

Table 4. Summary of Crustal Model Along the Northwest Profile From Gnome.

Layer No.	Compressional wave velocity km/sec	Cross over distance km	Intercept time sec	Layer thickness km	Depth to bottom of layers km
1	6.09		-	18	18
2	6.8	148	2.6	22	40
3	7.81	240	7.05	-	-

Comparison of the Results:

A comparison was made between the crustal models obtained from corrected times and observed times. The purpose of the comparison was to establish whether or not the near surface rocks had any appreciable effect on the interpretation of the travel-time data.

Straight-line segments were drawn to the uncorrected observed travel-time data for the north profile using the least-squares method. The straight-line segments obtained are given below with the corresponding standard deviations.

$$T_0 = (0.214)\Delta_0$$

$$T_1 = (0.161 \pm 0.0016)\Delta_1 + (1.13 \pm 0.065)$$

$$T_2 = (0.147 \pm 0.001)\Delta_2 + (3.29 \pm 0.068) \quad \text{and}$$

$$T_3 = (0.119 \pm 0.003)\Delta_3 + (10.15 \pm 0.13)$$

where the Δ's are distances in km between shot point and the recording station and the T's are the uncorrected travel times.

The crustal model obtained from the time-distance curves (Fig. 7 dotted lines) is summarized in Table 5.

Table 5. Crustal Model for Eastern New Mexico, Constructed From Uncorrected Observed Travel Times (North Profile).

Layer No.	Compressional wave velocity km/sec	Cross over distance km	Intercept time sec	Layer thickness km	Depth to bottom of layers*km
0	4.68			4	4
1	6.2	20	1.13	16.0	20
2	6.8	148	3.29	29.3	49.3
3	8.4	240	10.15	-	-

* The depth is given with respect to the mean surface elevation along the profile.

The total thickness of the crust in eastern New Mexico is 48 km (obtained by taking the mean elevation of this region to be 1.3 km above sea level). A comparison between the results summarized in Table 3 (the crustal model from corrected times) and Table 5 (the crustal model from uncorrected times) indicates the following features (see also Figure 7):

1. The total thickness obtained in both cases differs by only 1.5 km, individual layers by, at most, 2.7 km.
2. The velocities differ by, at most, 0.1 km/sec.

The conclusion from this comparison is that the near surface rocks have only a minor effect on the determination of thicknesses and velocities.

A comparison of the results obtained in this paper (with both corrected and uncorrected times) for eastern New Mexico (Table 3) with the results obtained by Stewart and Pakiser (Figure 3) is of significance. In the writer's interpretation of project Gnome travel-time data, no evidence was found to support the existence of a 7.1 km/sec layer in the lowest part of the crust.

REFLECTIONS FROM MOHOROVIČIĆ DISCONTINUITY

Microearthquakes of central New Mexico recorded at Albuquerque have several sharp well-defined phases in addition to the primary P and S phases. A suitable crustal model was obtained for central New Mexico from the observed travel times of the secondary phases, S_iP and S_MS, on the Albuquerque records. The most prominent and consistent of these phases was the reflected S-phase (S_MS) from the top of the Mohorovičić discontinuity.

Distribution of Microearthquakes

Figure 2 shows the distribution of the microearthquakes analyzed for the crustal structure study. These shocks are located within a distance range of 54 to 123 km from Albuquerque. Seismograms of the located shocks from the U. S. Coast and Geodetic Survey station at Albuquerque, New Mexico (34° 56.5' N; 106° 27.5' W), were analyzed for prominent phases (other than direct S) after the first P arrival. The two principal criteria adopted in selecting later phases were distinct changes in amplitude and frequency. The travel times of these phases are listed in Tables 6 and 7. Shocks listed in Table 6 were located by using three or more stations whereas those of Table 7 were located by using only two stations. The shocks were graded excellent (E), good (G), fair (F) and poor (P) on the sharpness of the beginning of the event and the clarity of the later phases on the seismogram. The locations of microearthquakes were determined by assuming a depth of focus of 5 or 10 km and a P-wave velocity of 6.0 km/sec (Sanford, 1965).

Table 6. Observed Travel Times and Amplitudes of Reflected Phases for Microearthquakes Located by Three or More Stations.

No.	Date & origin time GCT	Δ Km	(S-P) Sec	(P-O)= 1.37 x (S-P) Sec	(P-O) observed Sec	Phase 1 T_1 Sec	Phase 1 Ampli.* Mm	Phase 2 T_2	Phase 2 Ampli.*	* Ampli. S - wave	Grade
1	24 Jan 62 15:12:45.3	110	13.0	17.8	17.8	20.8	6.0	35.8	20.0	38.0	G
2	24 Jan 62 15:53:15.5	110	13.0	17.8	18.1	-	-	36.1	12.0	14.5	G
3	3 Mar 62 18:16:48.1	123	14.8	20.3	20.7	22.8	4.2	38.6	4.5	6.5	F
4	22 Mar 62 04:23:53.6	83	9.5	13.0	13.0	17.2	14.5	28.8	22.5	26.0	G
5	25 Jun 62 10:00:45.8	123	14.2	19.5	20.5	-	-	37.5	4.0	3.5	G
6	15 Dec 62 20:20:34.0	118	14.1	19.3	19.9	22.7	10.5	37.9	19.0	23.0	E
7	19 Dec 62 13:04:05.2	75	9.0	12.3	12.6	15.1	2.5	27.6	5.5	6.0	G
8	2 Jun 63 05:07:36.2	71	8.0	11.0	11.8	15.2	43.0	27.8	39.0	55.5	E

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Table 6 continued:

No.	Date & origin time GCT	Δ Km	(S-P) Sec	(P-0)= 1.37 x (S-P) Sec	(P-0) observed Sec	Phase 1		Phase 2		* Ampli. S - wave	Grade
						T_1 Sec	Ampli.* Mm	T_2	Ampli.*		
9	3 Jul/63 19:08:00.6	117	14.0	19.2	19.9	22.9	9.5	37.9	16.0	10.5	E
10	27 Aug/63 05:18:17.0	123	14.1	19.3	20.5			37.5			F
11	30 Dec/63 08:48:14.6	97	12.2	16.7	16.7	19.7	1.5	32.9	4.5	4.5	G
12	29 Jun/64 08:11:11.6	117	14.2	19.5	19.6			37.0	3.5	2.8	F

* Amplitude of phase on record.

Phase 2 is identified as a reflected, S_MS, phase.

Phase 1 is identified as a reflected, S_iP, phase.

Table 7. Observed Travel Times and Amplitudes of Reflected Phases for Microearthquakes Located Using Socorro and Albuquerque Stations Only.

No.	Date & origin time GCT	Δ Km	(S-P) Sec	(P-0)= 1.37 x (S-P) Sec	(P-0) observed Sec	Phase 1 T_1 Sec	Phase 1 Ampli.* Mm.	Phase 2 T_2	Phase 2 Ampli.*	* Ampli. S - wave	Grade
13	18 Mar/62 11:37:55.6	120	14.6	20.0	20.0	-	-	38.1			F
14	15 May/62 04:02:06.8	106	12.8	17.5	17.7	-	-	34.8	1.5	4.5	P
15	12 Jun/62 19:10:21.2	85	10.0	13.7	14.3	17.8	3.2	29.8	7.0	16.5	G
16	16 Jun/62 09:49:31.4	70	8.5	11.6	11.6	14.1	2.6	26.6	5.5	4.0	E
17	16 Jun/62 16:15:39.6	74	9	12.3	12.4	14.7	3.5	27.4	4.5	5.0	G
18	27 Jun/62 04:47:16.0	114	13.1	18.0	19.0	22.2	6.0	36.6	12.5	27.0	E
19	29 Jul/62 04:59:03.1	75	8.9	12.2	12.5	15.7	1.5	27.8	4.5	9.5	G
20	29 Jul/62 07:40:40.6	77	8.5	11.6	12.9	16.4	2.8	28.2	5.5	12.0	E

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Table 7, page 2

No.	Date & origin time GCT	Δ Km	(S-P) Sec	(P-0)= 1.37 x (S-P) Sec	(P-0) observed Sec	Phase 1 T_1 Sec	Phase 1 Ampli.* Mm.	Phase 2 T_2	Phase 2 Ampli.*	* Ampli. S - wave	Grade
21	29 Jul/62 17:25:12.6	80	8.8	12.1	13.4	16.9	1.0	29.2	2.0	4.0	P
22	24 Aug/62 00:25:55.3	105	12.8	17.5	17.6	20.9	2.5	35.0	7.6	7.2	G
23	27 Sep/62 02:56:36.8	68	8.4	11.5	11.3	14.8	1.8	26.8	2.5	12.0	F
24	23 Dec/62 11:38:15.7	77	9.1	12.5	12.8	15.8	0.5	28.5	1.0	1.0	F
25	6 Jan/63 04:33:42.5	75	9.0	12.3	12.5	15.5	0.08	28.3	1.5	1.0	F
26	18 May/63 08:20:36.8	115	13.7	18.8	19.2	-	-	36.2	14.5	5.8	G
27	3 Jul/63 19:12:06.2	118	14.0	19.2	19.8	22.8	1.5	36.8	7.5	3.0	F
28	13 Aug/63 04:26:14.3	97	11.7 ?	16.0 ?	16.2	-	-	33.7	2.8	4.5	F

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Table 7, page 3

No.	Date & origin time GCT	Δ Km	(S-P) Sec	(P-0)= 1.37 x (S-P) Sec	(P-0) observed Sec	Phase 1 T_1 Sec	Phase 1 Ampli.* Mm.	Phase 2 T_2	Phase 2 Ampli.*	* Ampli. S - wave	Grade
29	15 Sep 63 07:21:37.1	97	11.7	16.0	16.2	19.6	?	32.4	5.2	4.5	G
30	7 Oct 63 08:32:50.0	104	12.9	17.7	17.4	-	-	34.4	2.4	2.5	F
31	7 Oct 63 20:43:37.8	87	11.1	15.2	14.5	16.5	4.0	30.5	2.5	4.5	G
32	13 Dec 63 14:40:25.0	54	7.0	9.6	9.0			23.8	3.0	6.0	F

Phase 2 is identified as a reflected, S_MS, phase.

Phase 1 is identified as a reflected, S_iP, phase.

* Amplitude of phase on record.

Identification of Phases

The most prominent secondary phases (Fig. 9) are well separated from the direct P and S waves. A sharp phase (phase No. 2 on Fig. 9) of large amplitude follows S-phase by a few seconds at epicentral distances of 54 to 100 km from the recording station at Albuquerque. On the seismograms this event is frequently as strong or stronger than the direct S-phase. A weaker secondary phase (phase No. 1 on Fig. 9) appears on the records at about 3 seconds after the initial P arrival. Travel times (T_1 and T_2) and record amplitudes of phases (1) and (2) are listed in Tables 6 and 7.

Figure 10 is a plot of the travel times of the P, (1), S, and (2) phases with respect to the epicentral distance (Δ_x). Theoretical calculations indicate that phase (1) is a S_iP reflection from the top of an intermediate layer at a depth of 18 km (Sanford and Long, 1965). The theoretical arrival times for the S_iP phase (computed using P- and S-wave velocities of 6 km/sec and 3.46 km/sec) are also plotted on Figure 10. The curvature of the line defined by the arrival times of phase (2) and the relation of this line to the direct S-phase arrivals indicates that phase (2) is most likely an S-wave reflection from a deep interface.

Velocity and Depth Measurements Using T_2 Times

By assuming phase (2) was an S-phase reflection, estimates of the average velocity and total depth to the reflecting surface could be made. The reflection time T_2 can be expressed as

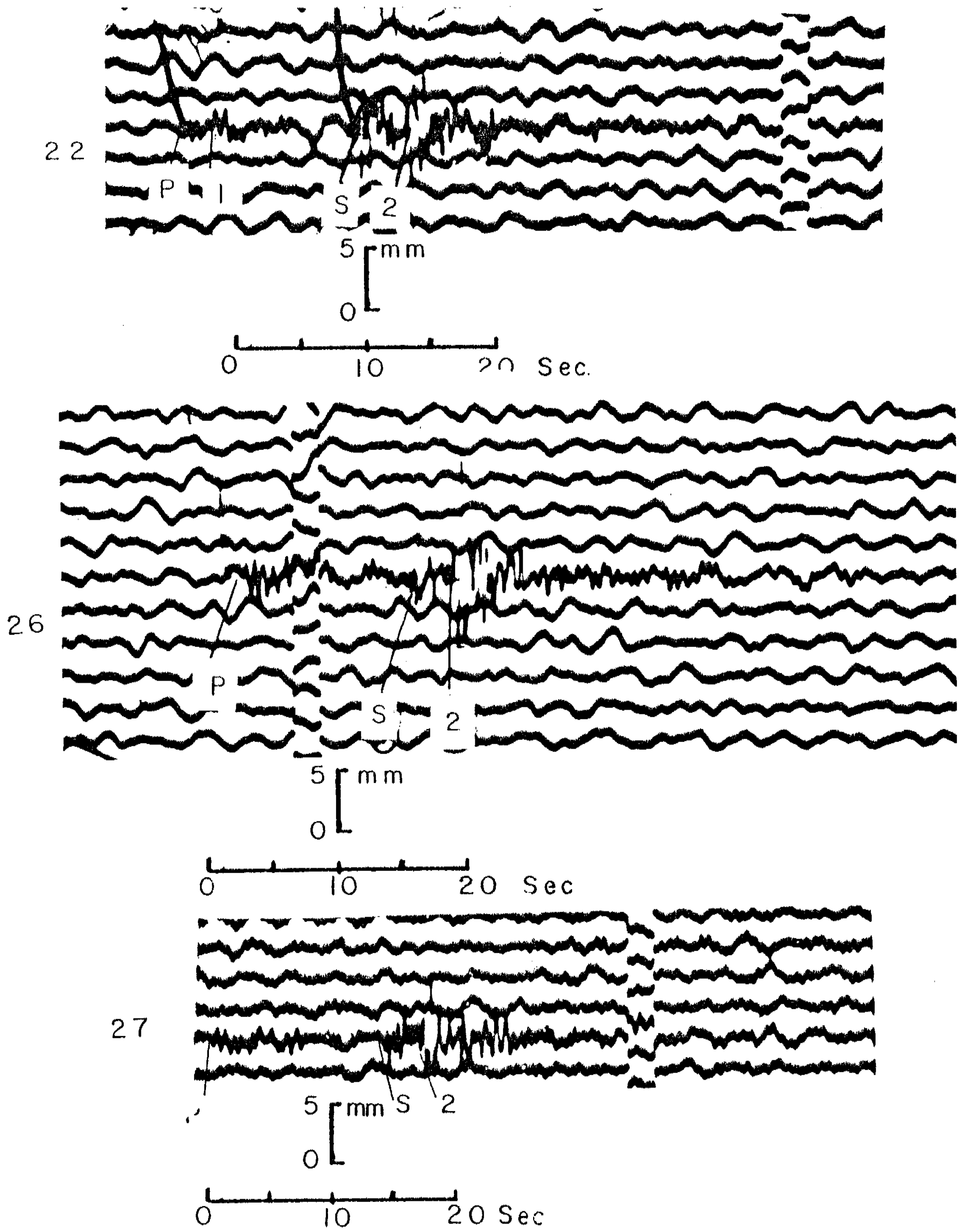

Fig. 9. Microearthquakes recorded at Albuquerque showing the phases P, 1 (S_iP) S, and 2 (S_MS).

$$T_2 = t_2 + \Delta t_2, \qquad (1)$$

where t_2 is the reflection time for vertical incidence at the epicenter (i.e. at $\Delta_x = 0$) and $\Delta t_2 = (T_2 - t_2)$ is the time difference between a reflection detected at a Δ equal to Δ_x and Δ equal to zero. A T_2^2 vs. Δ_x^2 plot of the observed data yielded an intercept time of 19.1 sec and an average velocity of 3.66 km/sec (square root of the reciprocal of slope of the line in T_2^2 vs. Δ_x^2 plot). From the average velocity and intercept time, a depth to the reflecting interface of about 38 km was found.

On the assumption that an intermediate layer exists in central New Mexico (Sanford and Long, 1965), the T_2 reflection times were used to calculate V_2 and Z_2, the velocity and thickness of the lower portion of the crust. The velocity V_2 and thickness Z_2 can be estimated from the expressions (Grant and West, 1965, pp. 141-144)

$$V_2^2 = \frac{\Delta_x^2}{2\,\Delta t_2(t_2 - t_1)} - \frac{2\,V_1^2\,t_1}{(t_2 - t_1)} \quad \text{and} \qquad (2)$$

$$Z_2 = 1/2\;V_2(t_2 - t_1) \qquad (3)$$

where t_2, Δt_2 and Δ_x are the same quantities as in equation (1) and t_1 is the vertical reflection time from an intermediate discontinuity, assuming an 18 km depth (Z_1) and an S-phase velocity of 3.46 km/sec (V_1). For vertical incidence, t_1 is obtained from the expression

$$t_1 = \frac{2Z_1 - h}{V_1} \qquad (4)$$

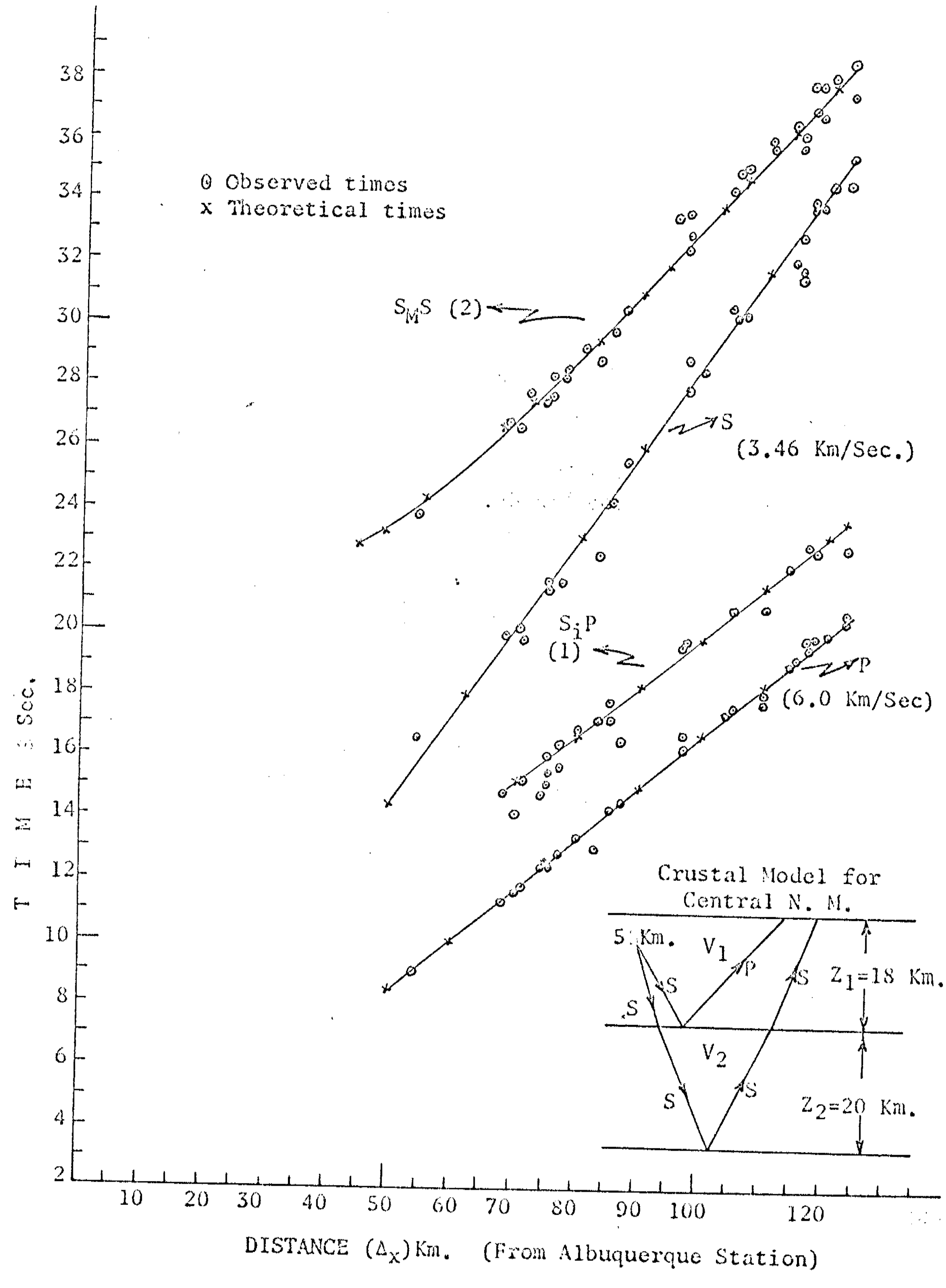

Fig. 10. Observed and theoretical travel times for the phases P, S_iP(1), S and S_MS(2), recorded at Albuquerque, plotted with respect to the epicentral distance.

where h is the depth of focus. In the equation (2) for V_2, the parameters t_2, Δt_2, t_1, Δ_x and V_1 are known. The calculated values of V_2 and Z_2 from the data of several shocks are given in Table 8.

Table 8. Sample Estimations of Velocity (V_2) and Depth (Z_2) Based on S_MS Reflection Times.

Earthquake No. from Tables 6 & 7	Δ_x km	Δ_x^2	$T_2 = (t_2 + \Delta t_2)$	Δt_2	V_2	Z_2
2	110	12100	36.1	17.0	3.75	19.0
4	83	6889	28.8	9.7	3.85	19.54
5	123	15129	37.5	18.4	4.41	22.38
11	97	9409	32.9	13.8	3.55	18.02
13	120	14400	38.1	19.0	4.04	20.50
22	105	11025	35.0	15.9	3.63	18.42
30	104	10816	34.4	15.3	3.71	18.83

The average of the V_2 and Z_2 values listed in Table 8 are 3.86 km/sec and 19.5 km, respectively. The crustal model obtained from the reflection data is summarized schematically in Figure 10. A theoretical curve (Fig. 10) for the phase S_MS was calculated using the crustal model given in Figure 10. The data of phase (2) fit the theoretical curve in Figure 10. This identifies the phase (2) as an S_MS reflection.

Discussion of the Results

The time differences between observed and theoretical reflections is about ± 1 second. These differences may be due to the following:

1. Identification of the beginning of a phase,

2. Errors in the epicentral location of microearthquakes,

3. Local variations in the crustal structure at the epicenter.

A total of 22 S_iP reflections and 17 strong S_MS reflections were found out of 32 events analyzed. The amplitudes listed in Tables 6 and 7 indicate that S_MS reflections recorded at Albuquerque are very strong. The S_MS becomes even stronger after about Δ_x = 100 km. This may be due to simultaneous arrival of S_MS and S_n phases, the reflected and refracted from "Moho."

SANTA RITA AND MORENCI EXPLOSIONS

Introduction

Mining explosions at Santa Rita (32° 47.5' N; 108° 04.4' W) and Morenci (33° 04.75' N; 109° 22.0' W) are recorded regularly at Albuquerque (U.S.C.G.S.), Socorro (NMIMT), and Las Cruces (Geo Tech.). A travel time analysis of these explosions was made. However, because Santa Rita and Morenci explosions were observed at only three recording stations at large distances from the shot points, no crustal model for western New Mexico could be obtained.

Time-Distance Curves

The large amplitudes of Santa Rita and Morenci explosions on the seismograms at Socorro suggest the detonation of considerable explosive charge. The amount of explosive at Santa Rita probably ranges between 5000 to 25,000 pounds, whereas at Morenci the amounts range to twice as much (estimates by R. Dimock and G. Griswold).

Origin times of a few selected Santa Rita and Morenci explosions were calculated using the procedure outlined by Richter (1958, pp 693-700). Table 9 is a list of events with corresponding origin times. The explosions were graded excellent (E), good (G) and fair (F) on the basis of the sharpness of the beginning of the event. The small error involved in the origin times at Las Cruces, Socorro and Albuquerque was due to the difficulty in identifying the exact beginning of the S-phase. Knowing the origin time of a particular event, the travel time of the first P arrival at each of the above stations was calculated. Figure 11

Table 9. Arrival Times at Albuquerque, Socorro, Las Cruces for Morenci and Santa Rita Explosions Used in the Analysis.

Date	Shot point	Station	*ΔKm	(S-P) Sec	1.37 (S-P) Sec	Origin time GCT	Grade
Mar 24,63	Morenci	LC	261	30.0	41.0	20:54:58.0	
	"	Soc	250	28.8	39.5	20:54:57.6	E
Mar 28,63	"	Alb	339	-	58.1	-	F
	"	LC	261	30.4	41.7	16:40:04.9	
	"	Soc	250	-	39.4	-	F
May 7,63	Santa Rita	LC	144	19.0	26.0	21:41:13.0	
	"	Soc	177	22.5	30.9	21:41:13.1	G
	"	Alb	282	34.0	46.6	21:41:13.4	G
Jun 16,63	Morenci	LC	261	31.0	42.5	17:29:41.5	
	"	Soc	250	30.0	41.2	17:29:41.0	E
	"	Alb	339	37.5	51.4	17:29:41.4	G
Jun 22,63	Santa Rita	LC	144	18.2	25.0	19:49:07.8	
	"	Soc	177	22.5	30.9	19:49:06.6	E
	"	Alb	282	34.5	47.3	19:49:07.8	G
Aug 4,63	"	Soc	177	22.5	30.9	22:01:02.1	E
	"	Alb	282	34.3	47.0	22:01:02.0	G
Sep 15,63	"	LC	144	19.3	26.4	19:57:27.3	
	"	Soc	177	22.5	30.9	19:57:27.0	E
	"	Alb	282	35.0	48.0	19:57:27.3	F

*Δ: The distance between shot point and the recording station is calculated using Richter's method (Richter, 1958, pp 701-705) for computing short distances.

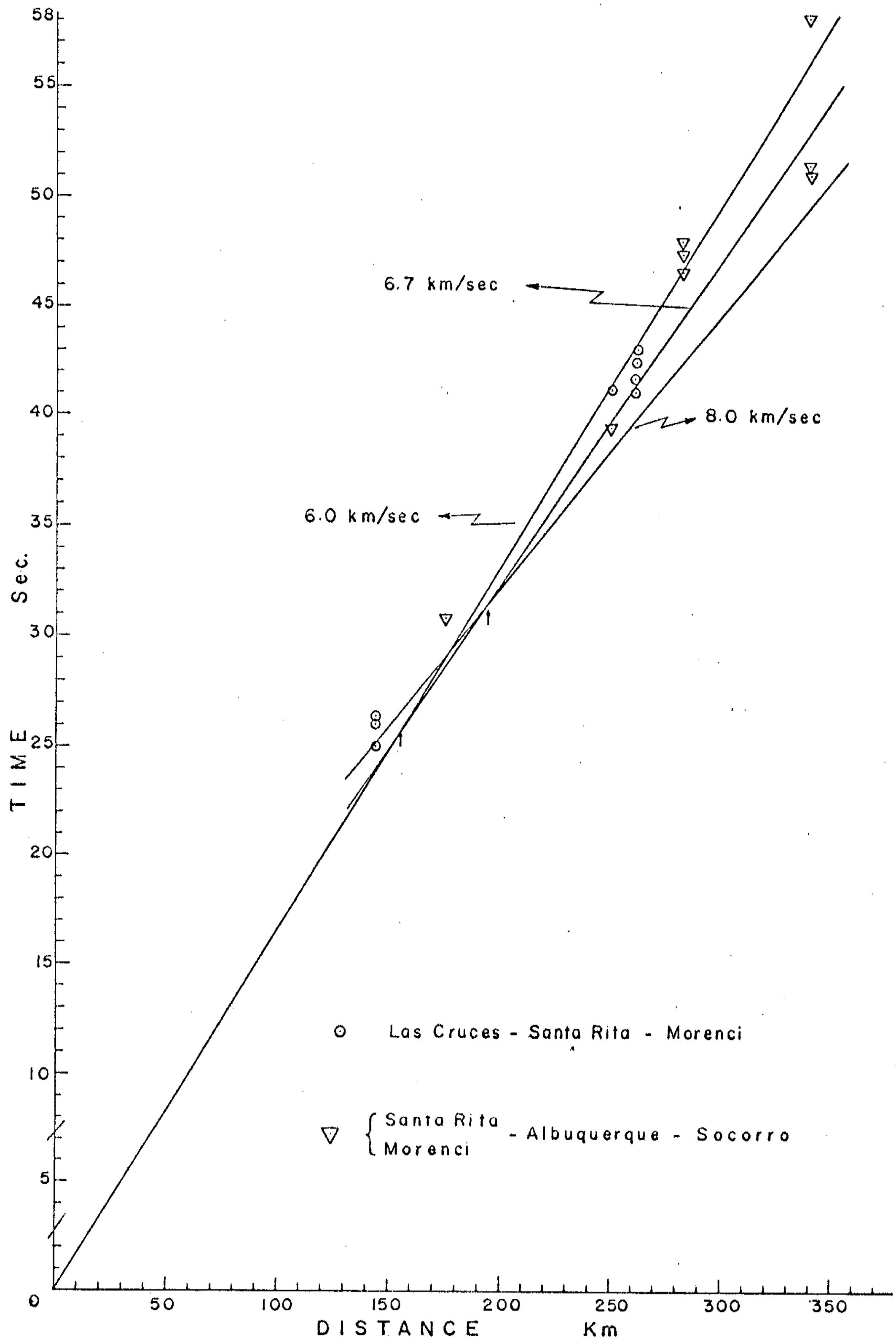

Fig. 11. Travel Times of Santa Rita and Morenci Explosions Compared with the Crustal Model of Central New Mexico.

is a plot of the time-distance relations. No definite information on the crustal structure can be obtained from Figure 11. Figure 11 also shows straight-line segments drawn assuming the crustal model of central New Mexico. A velocity of 8.0 km/sec (Tuve and Tatel, 1955) for upper mantle rocks was used. There is no apparent agreement between the Santa Rita and Morenci explosion data and the theoretical arrival times for the central New Mexico crustal model. This indicates that the crustal structure in western New Mexico is different from that of the central region.

CONCLUSIONS AND SUGGESTIONS FOR FURTHER STUDY

Conclusions

The crustal structure of New Mexico determined in this study, in combination with previous work in the area, reveals certain characteristic features of the crust. The important features are the variations in the upper mantle velocity and the thickness of the crust in different regions of the state.

The thickness of the crust in the eastern part of the state is about 49 km, whereas in the central and western regions it is 38 km and 30 km, respectively (Tuve and Tatel, 1955). The upper mantle velocities in eastern, central and western regions are, respectively, 8.3 km/sec, 8.1 km/sec (Phinney, 1964) and 8.0 km/sec (Tuve and Tatel, 1955).

On the basis of crustal thickness and velocity of the upper mantle, the state of New Mexico can be divided into "sub-surface provinces" (or seismic provinces). Accordingly, there will be at least three such sub-surface provinces which correspond to the eastern, the central, and the western regions of the state.

A crustal cross section (along 34° north latitude, Figure 12) which traverses the Eastern Plains and Basin and Range provinces is of particular interest. The crust is thicker below the Eastern Plains and thinner below the Basin and Range provinces. Since the average elevation is greater in the Basin and Range provinces than the Eastern Plains, observed crustal thicknesses contradict Airy's concept of isostasy, provided the level of isostatic compensation is at the base of the crust.

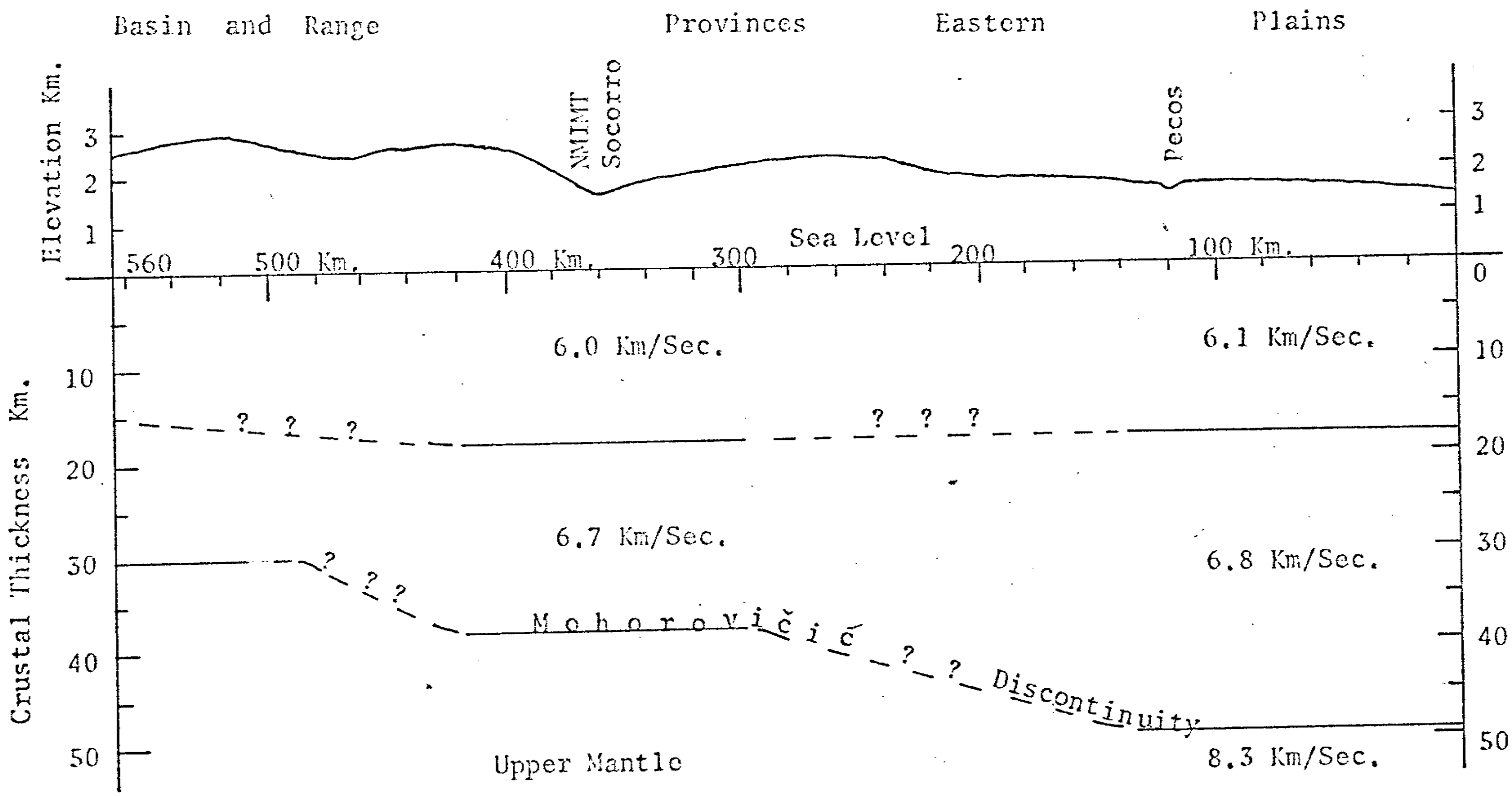

Fig. 12. Crustal cross section of New Mexico along an East-West line (565 Km.) passing through Socorro (≈ 34° N. Latitude). Elevations are approximate.

Suggestions for Further Study

A complete study of crustal structure in New Mexico is needed to investigate the apparent discrepancy between Airy's concept of isostatic equilibrium and crustal thicknesses. The distinct physiographic provinces in New Mexico, such as the Basin and Range provinces and the Eastern Plains, provide a unique combination for this study.

Detailed crustal structure (for example the existence of an intermediate discontinuity) in western New Mexico could be investigated using Santa Rita and Morenci explosions. Requirements for this study would be additional seismic stations at appropriate locations, and good control on the explosion times.

The crustal structure of northern and northwestern New Mexico could be investigated using the proposed underground nuclear explosion in the Farmington area. Extensive seismic station networks recording an explosion of this nature would provide the necessary travel time data for a crustal structure study of these areas.

The quality and quantity of microearthquake travel-time data in central New Mexico could be improved by using high-magnification and high frequency response instruments (with magnetic tape recording) at several locations.

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