SEISMIC TIME-DISTANCE RELATIONSHIPS FROM P-WAVE ARRIVALS AT SOCORRO

by

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ABSTRACT

The arrival times of P-waves from earthquakes ranging in distance from 5 to 45 degrees from three recording stations in New Mexico (Socorro, Albuquerque, Las Cruces) were compared with the standard arrival times in the Jeffreys-Bullen tables. Travel time residuals obtained in the comparison showed a definite variation with distance.

Positive residuals were found for distances centered at 20 and 42 degrees. The positive residuals at 20 degrees were interpreted as indicating a low-velocity layer in the mantle at a depth of about 120km, whereas those at 42 degrees were believed to be due to another discontinuity at a greater depth. Negative residuals found near 6 degrees were believed to be due to errors in the locations of the earthquakes, and not to a zone of high velocity in the crust or mantle.

Slight variations between observed residuals at the three stations were attributed to differences in the average velocity of the crustal and subcrustal structure beneath these stations. The data indicated that the average velocity of the crustal and subcrustal section beneath the stations is highest at Las Cruces, lowest at Socorro, and intermediate at Albuquerque.

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INTRODUCTION

A considerable amount of information about the structure of the earth can be obtained by studying the time-distance relationships for elastic waves propagating through it. If the time-distance relationships for shocks from a given area of the earth are compared with a standard, then areas of anomalous velocity corresponding to areas of anomalous crustal and/or subcrustal structure can be located.

This study concerned the time-distance relationships for P-waves. The P-wave is a compressional elastic wave generated in the earth by earthquakes or explosions. Of the four principal elastic waves, the P-wave has the highest velocity and thus arrives at the recording station first along a least travel time path through the earth.

The standard used in this study was the seismological tables prepared by Harold Jeffreys and K. E. Bullen (1958). Contained in the tables are the travel times of the P-wave for angular distances of 0 to 103 degrees computed for focal depths ranging from the surface to a depth of 0.12 of the earth's radius. These travel times represent the average travel times, prepared in such a way that no change is possible in the basic times without making the agreement with observation worse for at least some earthquakes used in the preparation of the tables.

The actual P-wave travel times from three recording stations, Socorro, Albuquerque, and Las Cruces, New Mexico, were compared with the P-wave travel times given in the Jeffreys-Bullen tables, and the residuals determined. The purpose of this work was to attempt to locate zones of anomalous velocity in the crust and/or mantle on the basis of these observed residuals.

INSTRUMENTATION

The important geographical constants of the stations used in this study are given in Table I, and the locations of the stations are plotted on Figure 1.

Table I. Geographical Constants of Stations

Station	Location	Latitude (N)	Longitude (W)	Elevation (M)	Operator
Soc	Socorro, N.M.	34 04.2	106 56.6	1510	NMIMT
Alb	Albuquerque, N.M.	34 56.5	106 27.5	1853	USCGS
LC	Las Cruces, N.M.	32 24.1	106 36.0	1590	AFTAC

Socorro

Records of earthquakes at Socorro are produced by a seismograph consisting of a short-period vertical Willmore seismometer, a high-gain transistorized amplifier, and a pen and ink helical recorder with a speed of 200mm/min. Minute timing marks on the records are controlled by a Nardin Chronometer. WWV is used as the time standard and is placed directly on the record once each day.

Underlying the station at Socorro are volcanic rocks of Tertiary age (Sanford, personal communication).

Albuquerque

The author had access, through the courtesy of the United States Coast and Geodetic Survey (USCGS), to photographic reproductions of the short-period vertical seismograms from the Albuquerque station. This station is a part of the world-wide standard seismograph system operated by the USCGS. The timing systems, which place minute marks on the records every 60mm, use WWV as a standard.

The type of rock underlying the station at Albuquerque is granite (USCGS, 1963).

Las Cruces

The instrumentation at Las Cruces consists of a three-component Benioff short-period seismograph system, and a three-com-

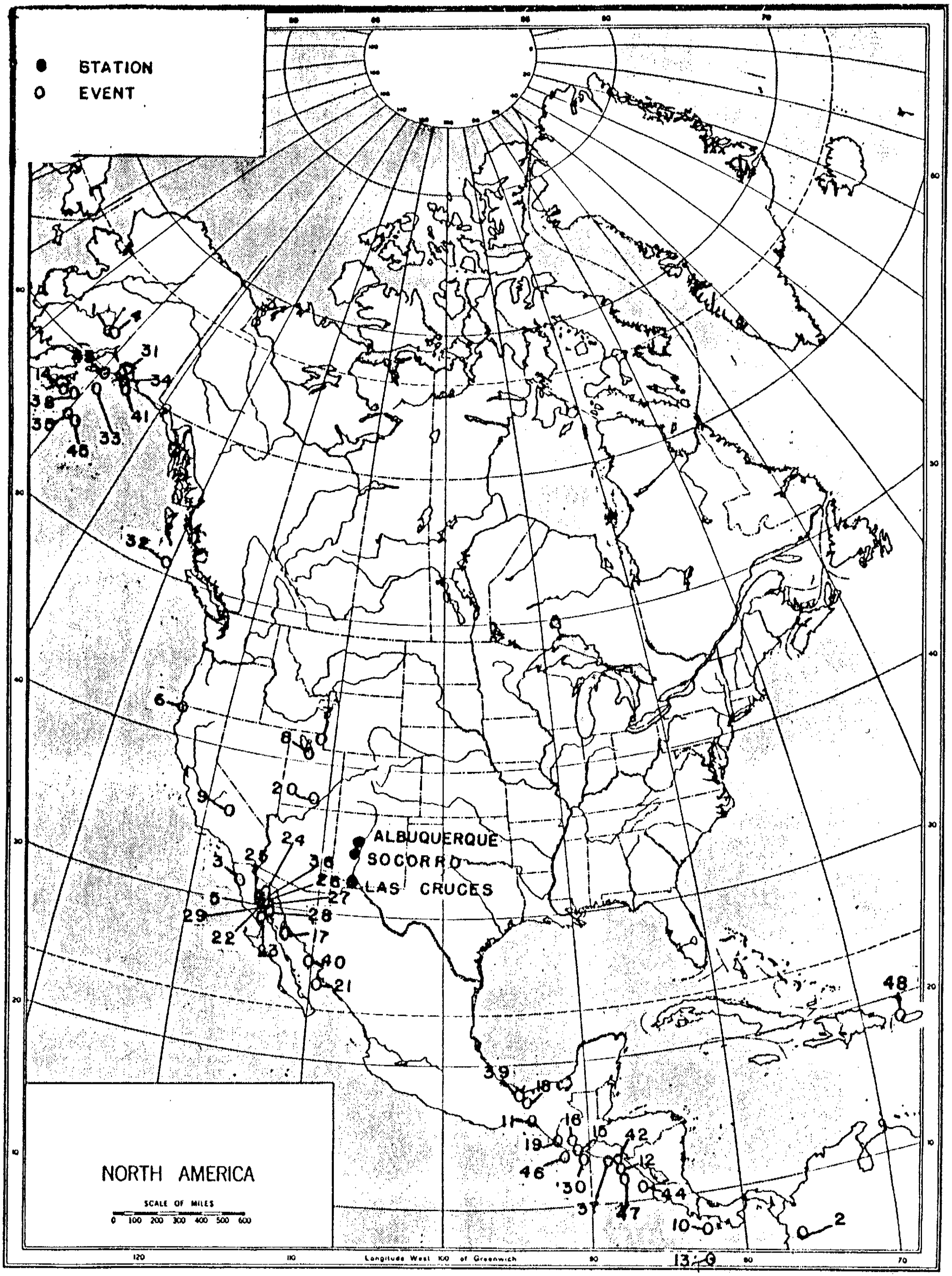


Figure 1. Geographical location of events and recording stations.

ponent Sprengnether long-period seismograph system. Both systems use phototube amplifiers, with 35-mm film and 14-channel magnetic-tape recorders. Geotech Model 5400 or 5400A Precision Timing Systems are used for primary timing, while chronometers are used for secondary time. Both systems use WWV as a time standard.

The type of rock underlying the station at Las Cruces is limestone (Geotechnical Corporation, 1964).

ANALYSIS OF DATA

Selection of Events

Earthquakes occurring in the distance range of 5 to 45 degrees from Socorro during the period July 1, 1962, to August 1, 1964, were obtained from the seismological bulletins published by Geotechnical Corporation. These bulletins were used to prepare a preliminary list of shocks, because they included data on distances to the epicenters.

After preparation of the preliminary list of events, the records of these shocks at Socorro were examined, and only those events with good P-wave arrivals were retained in the analysis. Events having a combination of high background noise and weak beginnings were rejected because of the difficulties involved in obtaining the correct arrival time. In the final list of shocks, the quality of the P-wave arrivals were graded by designating them either "i" or "e". An "i" designates a P phase with a sharp or sudden beginning. Direction of the first motion is discernible on all "i" phases. An "e" designates a P phase whose beginning may be clear but the initial break is difficult to determine when the quality is "e". The author personally determined the quality of the P-wave arrivals at the Socorro and Albuquerque stations, whereas the quality of the arrivals at the Las Cruces station were obtained from the Geotechnical Corporation's seismological bulletins.

All events selected for analysis are listed in Table II. Also given in Table II are the origin times, locations, and depths of focus, which were obtained from the USCGS seismological bulletins.

Calculation of Distances

The distances to the epicenters were calculated with the following formula:

$$\cos\Delta = \cos C \cos A + \sin C \sin A \cos\alpha$$

where A is the colatitude of the recording station, C is the colatitude of the earthquake, and α is the difference in longitude between the

Table II. List of Events Selected for Study.

Event No.	Date	Origin Time G. C. T.	North Latitude	West Longitude	Depth in Km.	Mag.	Quality of P. Arrival Soc.	Alb.	LC
1	7/16/62	12:54:40.6	62.1	153.1	39	5.22	i	i	e
2	7/30/62	20:18:52.3	5.2	76.4	69	6.75	e	i	e
3	8/ 7/62	22:32:35.1	31.4	116.1	33	4.23	i	i	—
4	8/18/62	16:43:54.3	62.2	152.5	32	5.16	e	e	e
5	8/20/62	10:43:23.2	30.9	114.1	14	5.80	i	i	e
6	8/23/62	19:29:16.0	41.6	124.1	33	6.00	e	i	e
7	8/30/62	13:35:28.7	41.6	111.8	37	5.50	e	e	—
8	9/ 5/62	16:04:29.0	40.5	112.0	14	5.00	i	e	e
9	9/16/62	05:36:15.7	35.6	118.1	10	5.50	i	e	e
10	9/18/62	00:29:05.5	7.4	82.3	33	7.00	i	i	e
11	10/18/62	19:49:56.6	16.1	93.8	138	4.80	e	i	e
12	10/30/62	08:31:51.8	12.4	88.0	80	5.40	i	i	e
13	10/31/62	11:32:28.2	5.4	82.5	33	6.50	i	i	i
14	1/ 1/63	23:39:09.5	56.5	157.5	80	6.50	e	e	i
15	2/13/63	00:22:51.3	13.8	91.0	81	5.00	i	i	e
16	2/24/63	13:34:14.7	14.6	91.3	119	5.70	i	i	i
17	7/26/63	13:40:29.5	28.3	112.0	33	4.00	e	e	e
18	8/17/63	11:34:23.4	17.6	94.3	163	4.90	i	i	e
19	9/29/63	22:44:02.9	14.3	91.9	61	5.00	i	i	e
20	9/30/63	09:17:40.3	37.8	111.1	15	4.50	i	i	e

Table II. Cont.

Event No.	Date	Origin Time G. C. T.	North Latitude	West Longitude	Depth in Km.	Mag.	Quality of P. Arrival Soc.	Alb.	LC
21	11/13/63	20:03:06.6	25.3	109.3	14	4.60	e	—	e
22	11/18/63	16:02:19.9	29.7	113.8	14	4.70	e	i	e
23	11/18/63	19:07:47.7	29.1	114.1	14	4.60	i	i	e
24	11/19/63	01:11:43.2	31.0	113.7	14	4.90	e	e	e
25	11/19/63	08:23:11.6	30.9	113.8	14	5.25	e	e	i
26	11/19/63	10:51:13.8	30.5	114.1	14	4.30	i	e	e
27	11/23/63	07:50:46.3	30.1	114.0	14	6.00	i	e	e
28	11/23/63	08:32:31.0	29.9	114.0	14	5.30	e	e	e
29	11/23/63	08:17:16.6	30.0	113.9	14	4.60	i	e	e
30	3/13/64	11:54:06.1	12.8	90.4	128	4.90	i	—	e
31	3/28/64	03:36:12.7	60.9	147.6	20	8.50	i	i	i
32	3/31/64	09:01:30.2	50.6	130.2	15	6.00	i	e	e
33	4/ 2/64	11:41:10.7	58.6	149.6	20	5.40	i	e	e
34	4/ 5/64	19:28:18.1	60.0	146.7	15	5.80	e	i	e
35	4/14/64	22:55:31.3	57.8	152.6	30	5.40	i	i	e
36	4/16/64	06:20:08.2	30.6	113.9	33	4.87	—	e	e
37	4/24/64	14:40:28.3	13.2	88.8	158	5.10	i	i	e
38	5/ 4/64	12:04:46.1	58.0	152.3	30	5.30	i	i	e
39	7/ 3/64	23:50:23.0	18.1	94.4	10	4.40	i	—	e
40	7/ 5/64	19:07:57.8	26.1	110.2	29	6.00	i	—	e

Table II. Cont.

Event No.	Date	Origin Time G. C. T.	North Latitude	West Longitude	Depth in Km.	Mag.	Quality of P. Arrival Soc.	Alb.	LC
41	7/11/64	20:25:40.3	59.5	146.2	40	5.60	e	–	e
42	7/21/64	07:01:59.3	13.0	88.4	68	4.70	e	–	e
43	7/23/64	19:08:06.6	59.7	149.2	55	5.40	i	–	e
44	7/30/64	05:16:03.3	11.0	86.2	42	5.70	i	–	e
45	8/ 2/64	08:36:16.9	56.0	149.9	31	6.00	e	–	e
46	8/ 7/64	15:31:18.0	13.9	91.9	89	5.00	i	–	e
47	8/ 8/64	15:45:10.9	12.4	87.8	63	5.80	–	–	e
48	8/10/64	01:10:12.4	19.0	67.3	33	5.00	i	–	i

station and earthquake (see Figure 2). The calculations were carried out with the aid of five-place logarithm tables.

Since the latitudes of epicenters given by the USCGS are geodetic, a conversion to geocentric latitudes was made before the calculation of distances (Richter, 1958). The calculated distances were rounded off to the nearest tenth of a degree, since the coordinates of the earthquakes given by the USCGS were to the nearest tenth of a degree.

The distance of each event from the three recording stations appears in Table III.

Travel Times for P-Waves

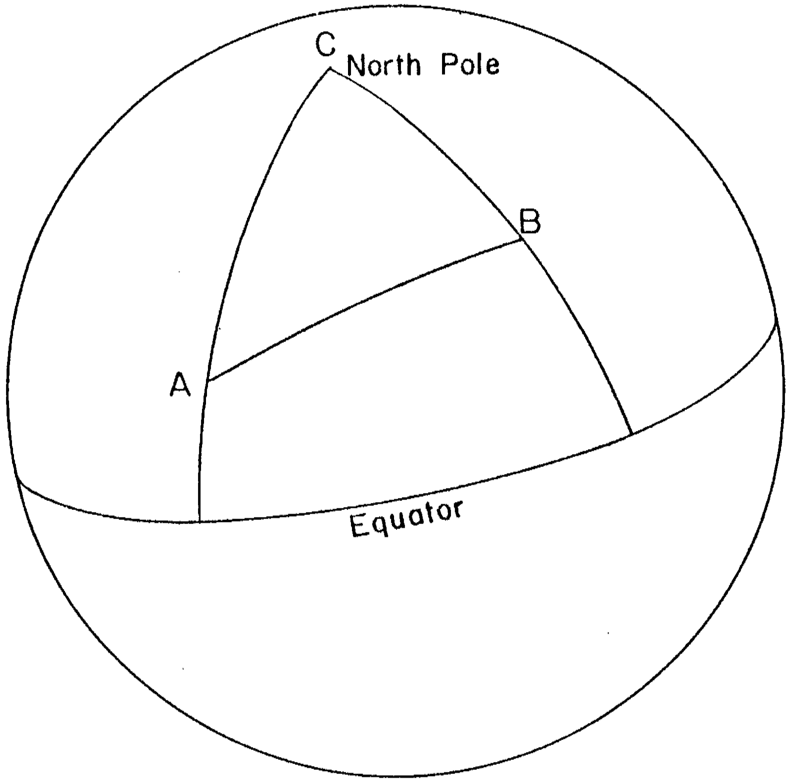
The arrival times of the P-waves at the Socorro and Albuquerque stations were taken directly from the records, while those recorded at Las Cruces were obtained from the seismological bulletins published by the Geotechnical Corporation. The travel time of the P-wave from the epicenter to each recording station was then obtained by subtracting the origin time from the arrival time.

The origin times obtained from the USCGS were given to the nearest tenth of a second, and if extreme care was taken, the arrival times could be obtained from the Socorro and Albuquerque records to the nearest one or two tenths of a second. Arrival times for the Las Cruces station were also given to the nearest tenth of a second, so that the travel times calculated for the three stations were computed to the nearest one tenth of a second.

Knowing the distance of each event from the recording station and the focal depth, it was then possible to obtain the travel time from the Jeffreys-Bullen tables. The focal depths given in the tables are listed at intervals of 0.01 of the earth's radius. Interpolations between listed values were made by plotting the travel times on large scale graph paper. The travel times from the Jeffreys-Bullen tables were thus obtained and compared with actual travel times obtained for each station.

Determination of Residuals

The residuals obtained from the comparisons of actual travel



$$\overline{CA} = a$$

$$\overline{CB} = c$$

$$\alpha = < ACB$$

$$\Delta = \overline{AB}$$

Figure 2. Formula used for calculation of distances.

Table III. Distances of Events from Stations and J-B Residuals.

Event No.	Δ in degrees Soc	Alb	LC	Residuals in seconds Soc	Alb	LC
1	40.2	39.7	41.8	4.2	3.4	3.6
2	40.4	40.7	39.2	-7.1	-8.6	-0.6
3	8.2	8.7	—	-30.6	3.0	—
4	40.1	39.5	41.6	1.9	1.3	7.8
5	6.9	7.5	6.5	-5.2	-0.8	-2.8
6	15.5	15.3	16.7	3.2	2.7	3.1
7	8.5	7.9	—	0.3	0.5	—
8	7.6	7.1	9.2	4.8	-0.2	9.9
9	9.3	9.5	10.0	-0.7	1.6	2.5
10	35.0	35.4	33.7	0.8	0.2	-2.1
11	21.5	22.0	20.0	2.8	1.5	-0.1
12	26.9	28.1	26.3	7.0	-1.0	-2.2
13	36.5	36.9	35.2	0.5	-0.9	-2.0
14	40.8	40.4	42.2	2.5	2.3	2.4
15	24.9	25.3	23.4	1.0	1.0	0.3
16	24.1	24.5	22.6	3.4	2.5	2.0
17	7.3	8.1	6.2	-2.8	-0.7	-1.0
18	20.0	20.4	18.5	3.9	4.2	1.7
19	24.0	24.4	23.8	3.4	1.8	7.4
20	5.0	4.7	6.5	1.5	0.8	5.7
21	9.0	—	7.6	-17.0	—	-9.3

Table III. Cont.

Event No.	Δ in degrees Soc	Alb	LC	Residuals in seconds Soc	Alb	LC
22	7.3	8.1	6.7	-1.0	-1.9	-0.7
23	7.9	8.7	7.2	-4.0	-3.2	-2.9
24	6.6	7.2	6.2	-0.7	1.8	-0.7
25	6.6	7.3	6.3	-1.0	0.7	-0.9
26	7.0	7.8	6.7	-0.3	5.4	-1.1
27	7.2	7.9	6.7	-1.7	-0.2	-1.1
28	7.3	8.0	6.9	-1.6	0.7	-3.1
29	7.2	7.9	6.7	-1.4	0.6	-0.8
30	26.1	—	25.5	1.0	—	1.0
31	37.3	36.8	38.9	3.6	2.0	2.0
32	23.7	23.3	25.4	3.2	0.1	-2.0
33	37.3	36.8	38.8	3.2	0.6	2.3
34	36.5	36.0	38.2	3.0	2.7	1.9
35	38.5	38.1	40.0	13.6	0.8	2.0
36	—	7.6	6.4	—	-0.4	-0.1
37	26.6	27.0	25.2	2.3	0.2	1.3
38	38.4	38.0	39.9	2.8	1.8	2.4
39	19.5	—	18.0	0.8	—	0.5
40	8.6	—	7.1	-4.8	—	-2.7
41	36.1	—	37.6	4.5	—	4.4
42	27.0	—	25.6	0.2	—	-0.9

Table III. Cont.

Event No.	Δ in degrees Soc	Alb	LC	Residuals in seconds Soc	Alb	LC
43	37.6	—	39.1	3.8	—	4.7
44	29.8	—	28.5	1.7	—	-0.2
45	36.6	—	38.0	2.5	—	2.3
46	24.3	—	22.9	4.0	—	-0.3
47	—	—	26.5	—	—	-2.9
48	38.2	—	37.6	1.0	—	0.5

times to the three recording stations with the travel times in the Jeffreys-Bullen tables are listed in Table III. Positive residuals are to be interpreted as meaning that it took the P-wave longer to travel from the source to the recording station than it should have taken according to the Jeffreys-Bullen tables, whereas a negative residual indicates the reverse.

The residuals plotted against distance for the individual stations appear in Figures 3, 4, and 5. A composite plot of residuals at all three recording stations is given in Figure 6. The latter graph is restricted to residuals of less than eight seconds. A discussion of these figures will be given in a later section.

Errors in Analysis

Errors in analysis arise from errors in locations, depth of focus, and timing. The final determinations of location, depth of focus and origin times published by the USCGS were used for events 1 through 29, while the preliminary determinations were used for events 30 through 48 which occurred in 1964. Final determinations of locations for the year 1964 have not been published. A comparison of preliminary and final locations for events 1 through 29 showed no more than two tenths of a degree difference in latitude and longitude, but in a few cases as much as four seconds difference in origin times. In no cases did the value of the focal depth given in the preliminary bulletin change in the final determination.

Errors in timing arise from several sources. The major error arrises in picking the beginning of the event. Since only those shocks with the best P-wave arrivals were retained in the analysis, it is hoped this error was kept to a minimum. An additional error arises in reading the times. Since the arrival times were determined by measuring with a millimeter scale from the nearest minute mark on the records to the beginning of the event, the accuracy is a function of the chart speed and how well one can read the scale. For P-waves with good beginnings the error should not exceed one tenth of a second for the Socorro records, and no more than two or three tenths of a second for the Albuquerque records. The errors involved in the timing at Las Cruces should not exceed one tenth of a second (Geotechnical Corporation, 1964).

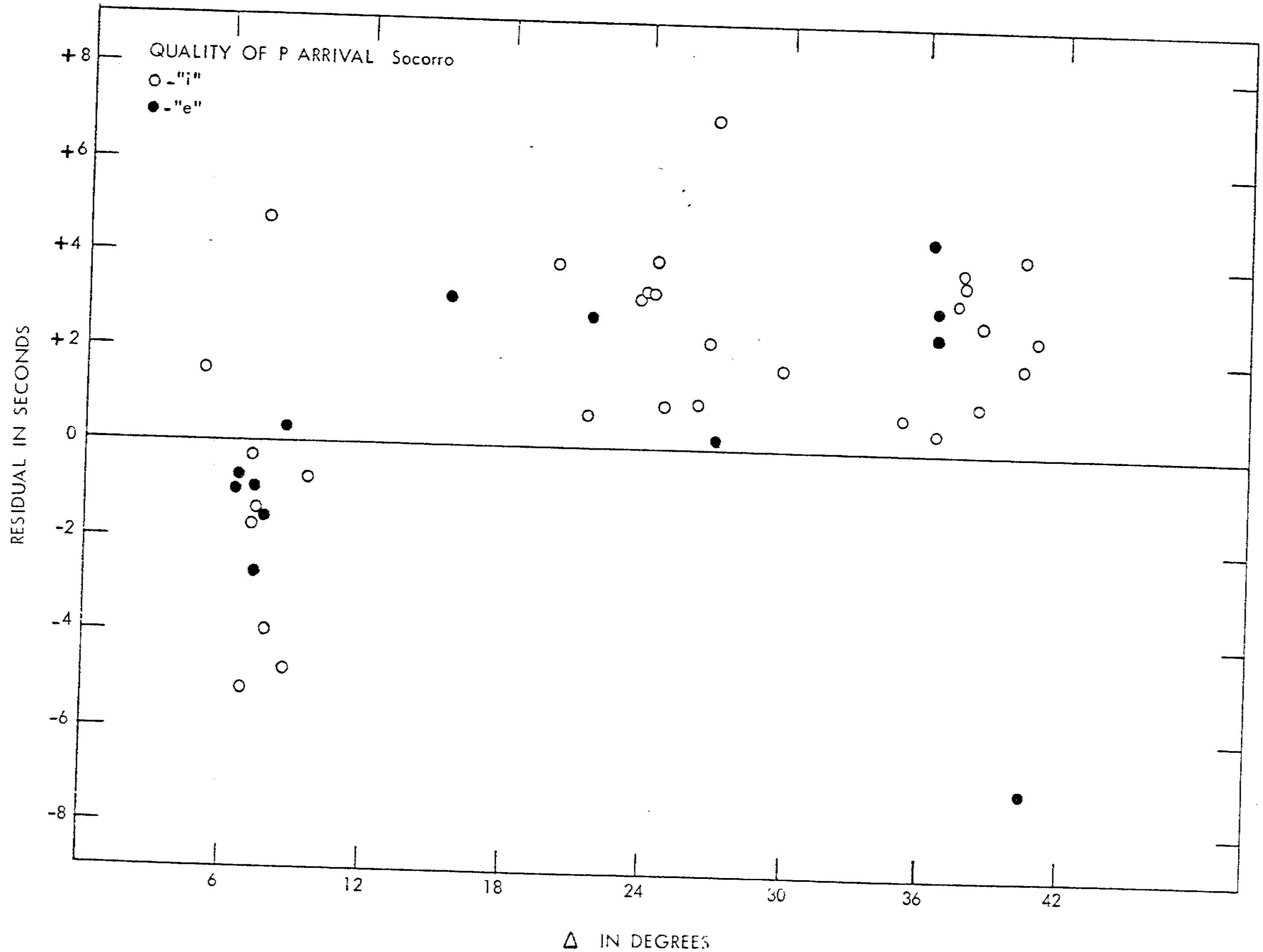


Figure 3. Travel time residuals for Socorro.

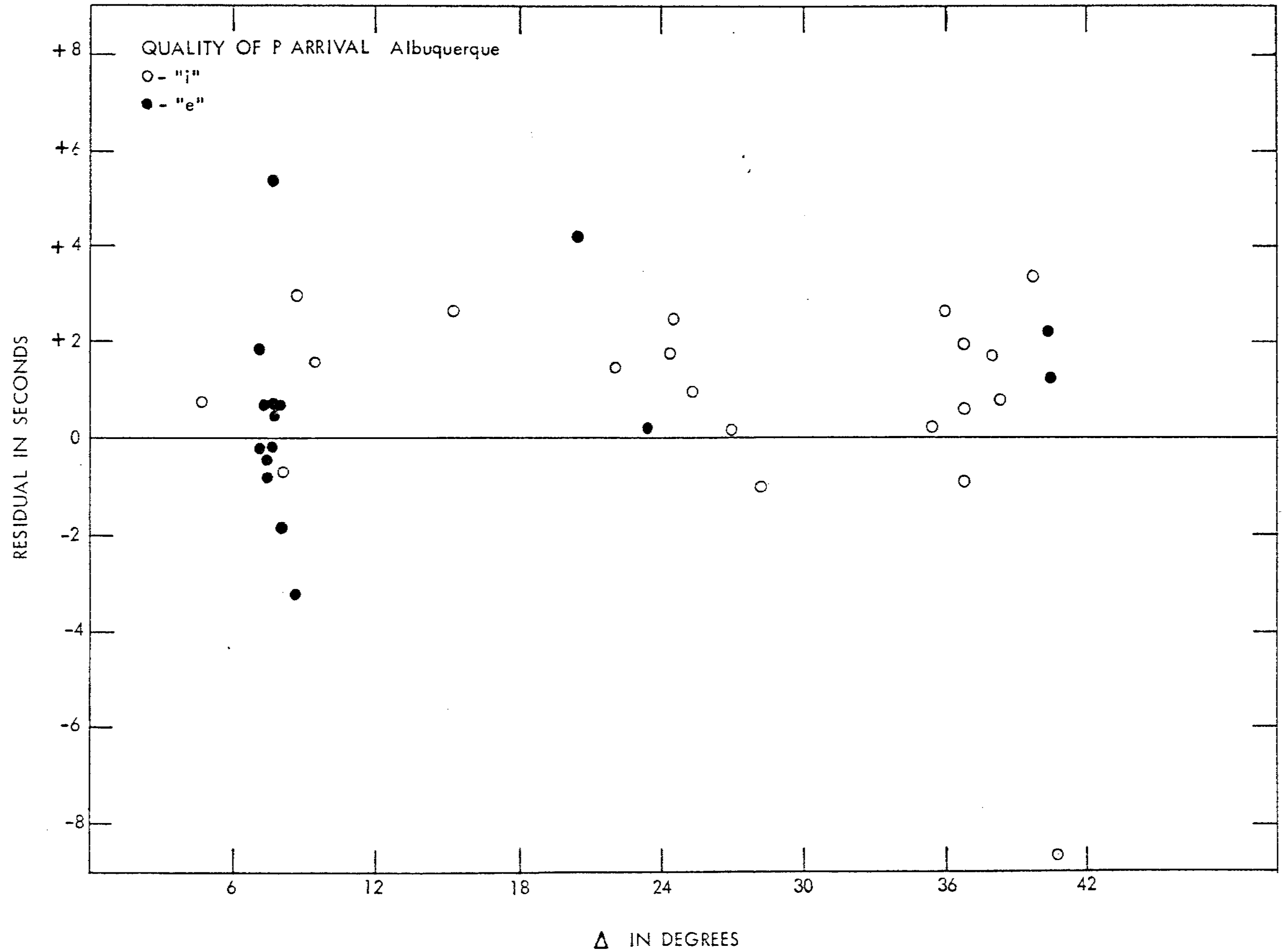


Figure 4. Travel time residuals for Albuquerque.

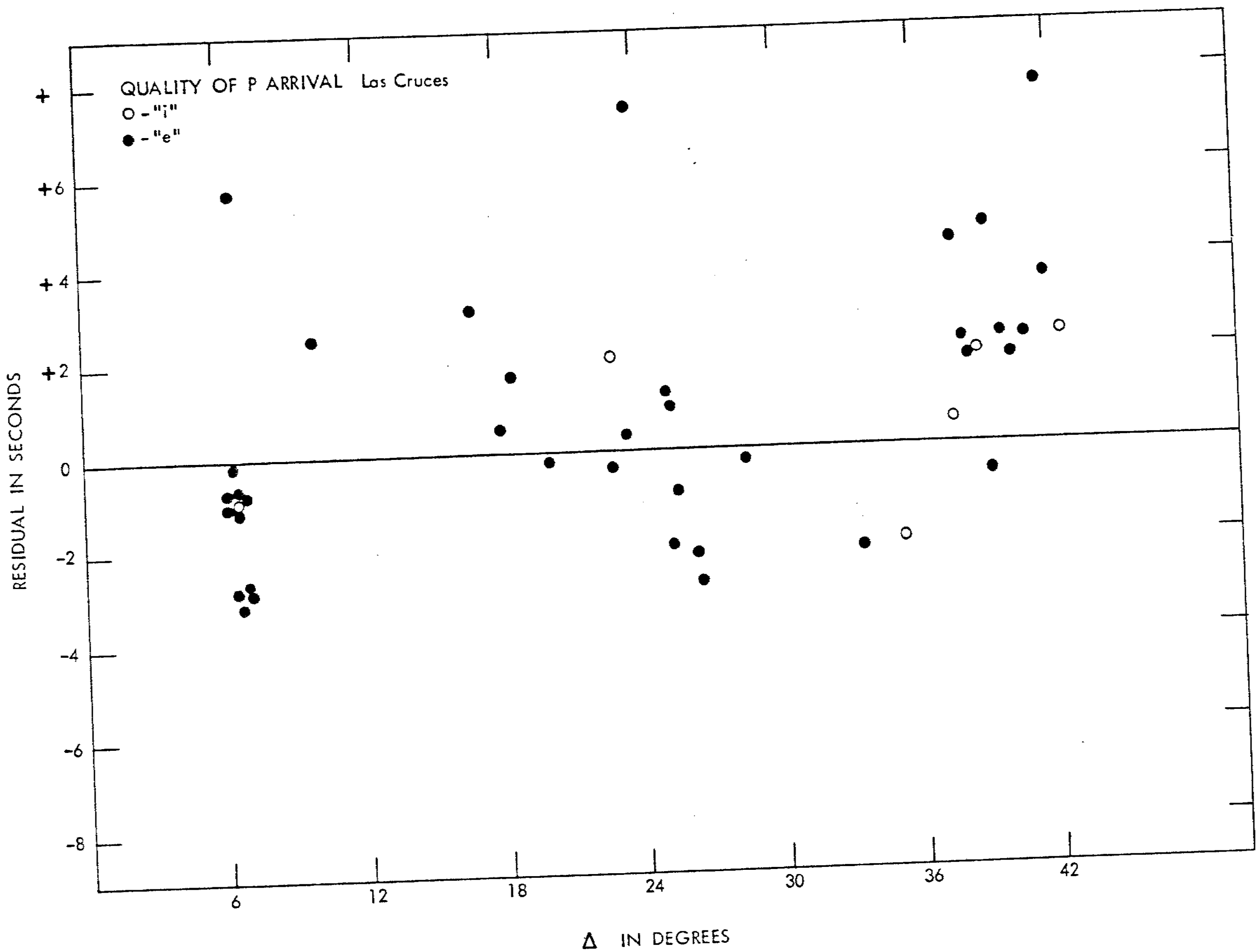


Figure 5. Travel time residuals for Las Cruces.

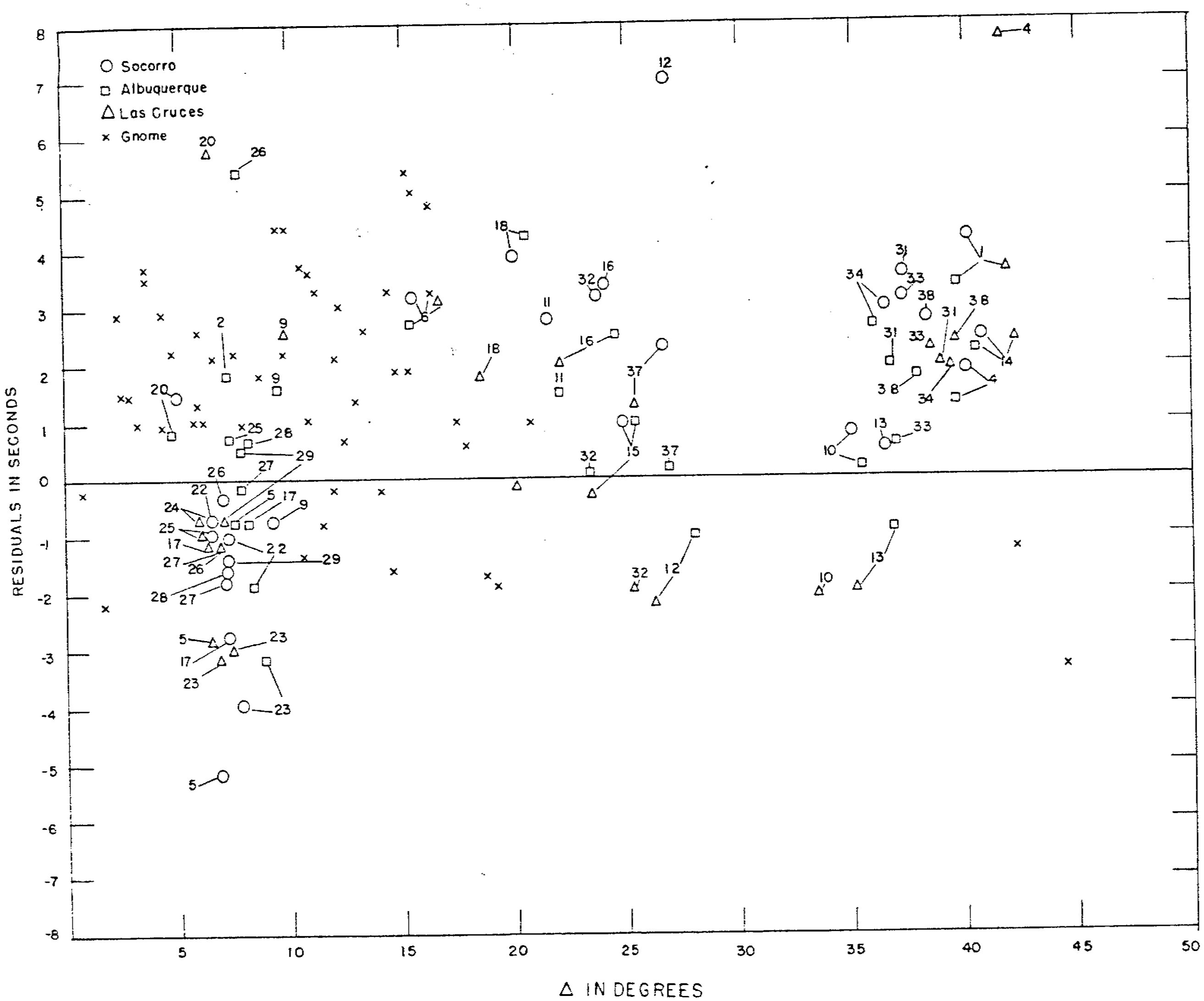


Figure 6. Travel time residuals for the Socorro, Albuquerque, and Las Cruces stations and the Gnome explosion.

PRESENTATION OF DATA

Geographical Location of Events

The geographical location of all events used in this work are plotted on Figure 1. As is evident from Figure 1, most events occur more or less along a northwest-southeast line passing through the stations. The major exceptions are those events which occurred in the Gulf of California and event number 48, which were in a southwesterly and southeasterly direction from the stations, respectively. Those events which occurred in Alaska are approximately the same distance from the recording stations as those events that occurred in Colombia.

Distribution of Events with Distance

The distribution of all shocks with respect to distance from all three recording stations is shown in Figure 7. There exist two ranges of distances, 10 to 14 and 30 to 32 degrees, in which there were no shocks of good enough quality for this work. With these two exceptions the distribution of shocks with distance is relatively good. Although the number of shocks for a given distance are not equally composed of events from the northwest and southeast, there are few cases where the shocks in a given distance interval are totally from the northwest or the southeast.

Residuals

Although the values of the residuals differ slightly from station to station, there is the same relative pattern of the residuals with distance for all three recording stations (see Figures 3, 4, and 5). The majority of the residuals at all three recording stations are negative between 5 and 10 degrees. The residuals then tend to become positive and reach a maximum centered at 20 degrees. Between 25 and 38 degrees the residuals have small positive or negative values at all three stations. A large number of the residuals at the Las Cruces station become negative in this range, while at the other two stations

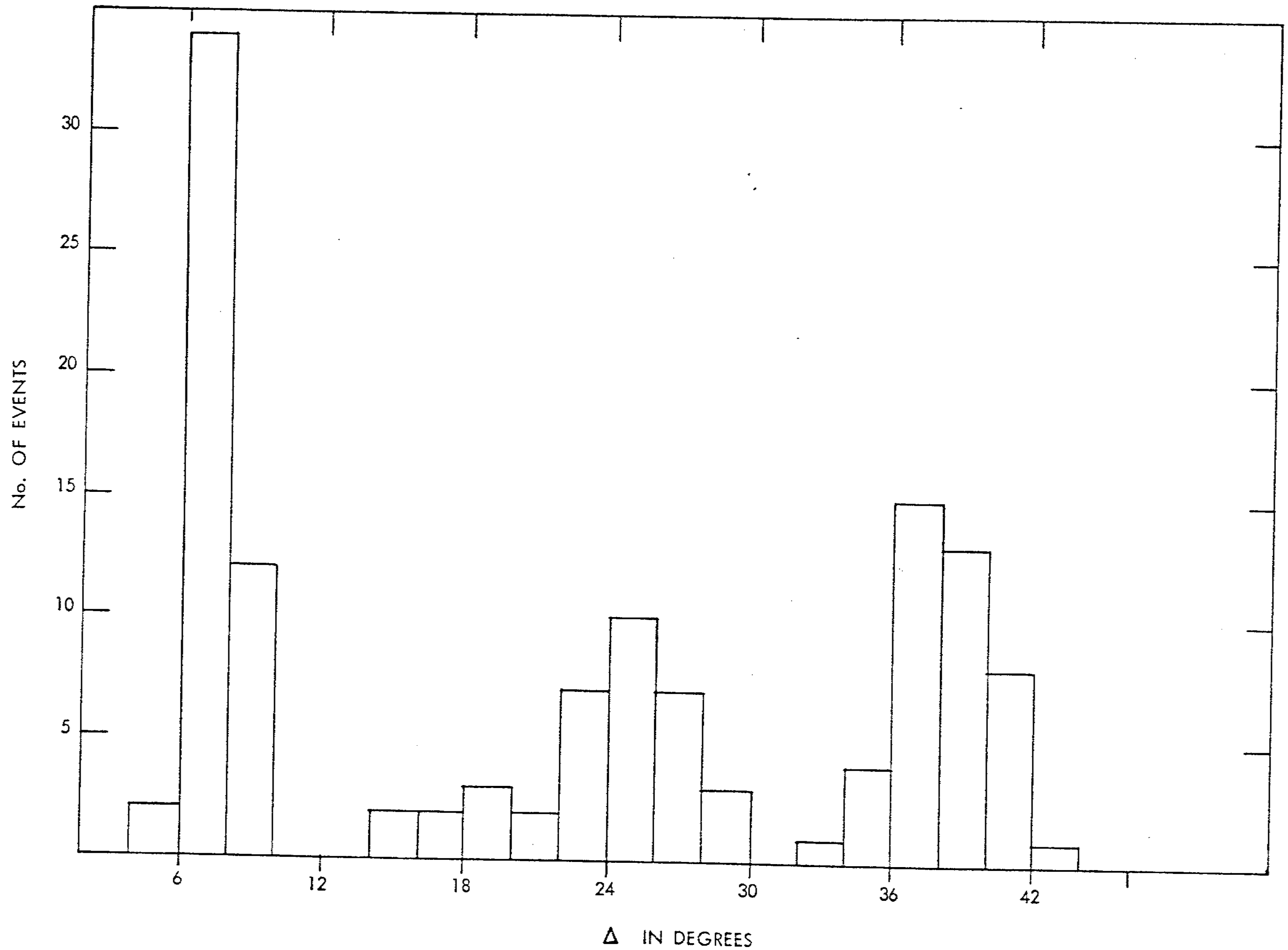


Figure 7. Distribution of events with distance.

the majority of the residuals are positive. Near 30 degrees the residuals reverse their trend and tend to become more positive, reaching another positive maximum centered near 42 degrees.

Although the same general pattern of residuals can be seen at all three stations, there is a variation in the values of the residuals from station to station. This variation is evident in Figure 8, where average residuals over intervals of 4 degrees are plotted against distance for each station. (Only residuals of six seconds or less are included in these averages.) In general, Socorro has more and larger positive residuals than the other stations. The negative residuals for the near events are also larger at Socorro. Albuquerque has as many positive residuals as Socorro, but of lower magnitude; whereas Las Cruces has the least number of positive residuals and the greatest number of negative ones. In the range of 25 to 35 degrees, residuals at Las Cruces become negative, while at the other two stations the residuals, for the most part, remain positive.

INTERPRETATION

Variation of Residuals from Station to Station

The residuals are a function of the entire path the energy travels from source to recording station, and not just a function of the crustal and subcrustal structure beneath the recording station. The structure at either end of the path may contribute to the residual, but there is no way of telling how the effects of the structure at the two ends of the path are contributing to the residual. On the other hand, the variation in residuals from station to station, for a given event, must arise from the differences in the average velocity of the crustal and subcrustal structure beneath the stations. The differences in residuals shown in Figure 8 indicate that the average velocity of the crustal and subcrustal section beneath the stations is lowest at Socorro, highest at Las Cruces, and intermediate at Albuquerque.

Negative Residuals at a Distance of 6 Degrees

Nearly all the negative residuals near 6 degrees in Figures 3, 4, and 5 are the result of a group of shocks which occurred in the Gulf of California during the month of November 1963 at a focal depth of 14km. Since these shocks originated a relatively short distance from the recording stations, the path the energy followed did not dip very deep into the mantle. The energy probably traveled a path just below the Mohorovicic discontinuity. The velocity for this path should be near 7.9km/sec (Herin and Taggart, 1962; Pakiser, 1963), and with this velocity one would expect positive residuals instead of the negative ones obtained.

Four other shocks in the analysis, three from Utah and one from northern California, occurred at about the same distance as the Gulf of California shocks. The residuals from these shocks were positive or slightly negative. The velocity for the P-waves from these shocks should be about the same as for those shocks that occurred in the Gulf of California (Herrin and Taggart, 1962; Pakiser, 1963). In addition, the residuals for the Gnome explosion data in the western half of the United States (see Figure 6) indicate that the residuals at a

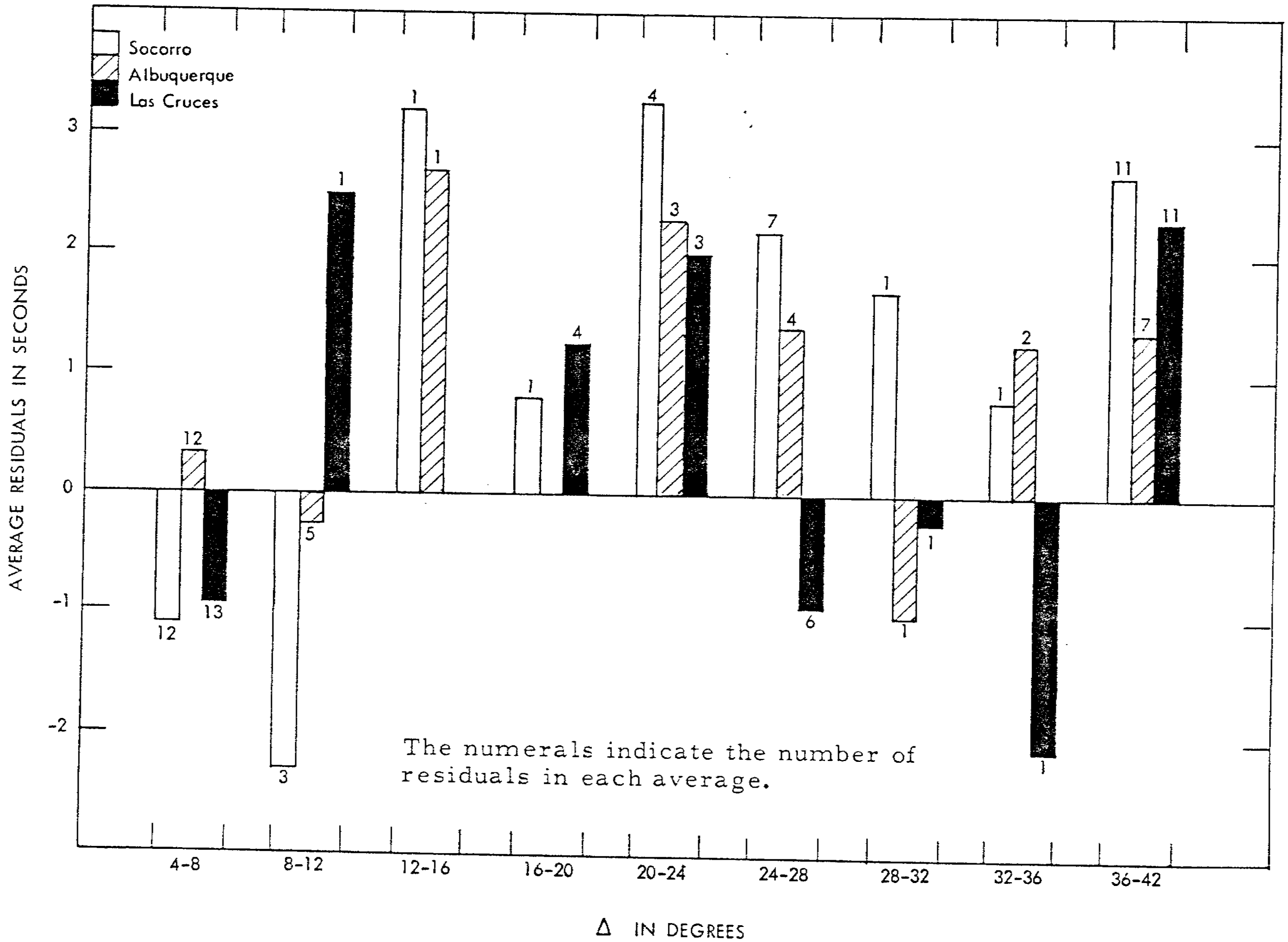


Figure 8. Average residuals taken at distance intervals of 4 degrees.

distance of 6 degrees should be positive (Romney, et al., 1962). (The locations of the stations used from the Gnome explosion data appear in Table IV.)

A possible explanation for the large negative residuals for the Gulf of California shocks is errors in epicenter locations. If stations to the west of these events were to pick the P-wave arrivals late, the epicenters of the events would be placed too far west and the calculated distances to the New Mexico stations would be greater than the true distances. Since travel times from the Jeffreys-Bullen tables are based on the computed distance, the travel time from the tables would be too great and the resultant residuals negative.

Positive Residuals at a Distance of 20 Degrees

Jeffreys and Bullen (1958) indicate there is evidence for positive residuals of about three seconds at distances near 20 degrees for earthquakes in North America. Nuclear explosion travel times from the Central Pacific compared with the Jeffreys-Bullen tables indicate a trend of the residuals toward the positive near 20 degrees (Carder, 1964). Although all of these residuals are negative from 15 to 95 degrees, the important thing is the variation of the residuals with distance. Carder believes these variations are real and are the result of layers of different velocities in the mantle.

The positive residuals observed in this study are possible evidence for lower velocities in the mantle than those predicted by the Jeffreys-Bullen tables. Gutenberg (1954) proposed a low-velocity layer in the mantle for P-waves at a depth ranging from 60 to 150 km. Using data from underground atomic explosions, Dowling and Nuttli (1964) obtained depths to the top of this low-velocity layer of 70±km in central New Mexico and 105±km in northern Utah and southern Wyoming. The average residuals observed in this study become positive beyond a distance of 10 degrees. Assuming that a ray for a shock at 10 degrees just grazes the upper surface of the low velocity layer, one can calculate the depth to this layer using relations derived by Bullen (1963). The velocity function for these calculations is

$$V = a - br^2,$$

Table IV. Gnome Explosion Data (Romney and others, 1962).

Station	Coordinates North Latitude °	'	"	West Longitude °	'	"	Distance in degrees	Residuals in seconds
Hope	32	43	36	104	43	12	.86	-0.2
Cloudcroft	32	56	56	105	43	23	1.71	-2.2
Las Cruces	32	24	08	106	35	58	2.32	2.9
Vol. Team 31	32	15	24	106	53	14	2.56	1.55
Truth/Conseq.	33	18	06	106	46	36	2.67	1.6
Socorro	34	04	06	106	56	42	3.15	1.0
Truth/Conseq.	33	11	03	107	27	42	3.18	1.0
Frustration	34	57	30	106	26	19	3.44	3.7
Sandia	34	56	30	106	27	30	3.45	3.5
Albuquerque	34	56	30	106	27	30	3.45	3.5
Magdalena	33	45	00	107	47	12	3.62	–
Mogollon	33	24	53	108	50	11	4.35	2.9
Red Hill	34	08	36	108	49	06	4.56	0.9
Springerville	34	10	32	109	08	49	4.83	2.2
Tucson-T	32	20	06	110	43	24	5.82	1.0
Tucson	32	14	48	110	50	06	5.92	1.3
Snowflake	34	26	19	110	30	52	5.98	2.6
Durango	37	27	53	107	47	00	6.12	0.9
Flagstaff	35	04	09	111	18	34	6.83	2.1
Williams	35	25	04	112	12	54	7.65	2.2
Glen Canyon	36	58	25	111	35	35	7.93	0.9
Kanab	37	01	22	112	49	39	8.80	1.8
Climax Claim	35	56	18	114	06	36	9.28	–
Vernal	40	30	31	109	34	45	9.45	4.4
Fillmore	39	13	06	112	12	25	9.72	2.1
Flaming Gorge	40	55	36	109	23	10	9.74	2.3
Lake Meade	36	34	10	114	33	03	9.84	4.2
Pioche	38	06	27	114	37	19	10.58	3.7
Campo	32	43	44	116	22	16	10.60	-1.4

Table IV. Cont.

Station	Coordinates North Latitude °	'	"	West Longitude °	'	"	Distance in degrees	Residuals in seconds
Barrett	32	40	48	116	40	18	10.86	1.1
Test Site	36	38	00	115	58	59	10.94	3.6
Tippipah	37	12	01	116	13	34	11.33	3.3
Riverside	33	59	36	117	22	30	11.49	-0.8
Mount Wilson	34	13	24	118	03	30	12.08	-0.2
Darwin	36	16	37	117	35	37	12.07	2.1
Eureka	39	29	00	115	58	12	12.20	3.0
Isabella	35	38	36	118	28	36	12.63	0.7
Woody	35	42	00	118	50	48	12.93	1.4
Mina	38	26	10	118	08	53	13.21	2.6
Hailey	43	38	52	114	16	02	14.04	-0.2
Winnemucca	41	21	02	117	27	30	14.20	3.3
Bozeman	45	40	01	111	02	43	14.53	-1.6
Paraiso	36	19	54	121	22	12	14.66	1.9
Vineyard	36	45	00	121	23	18	15.16	5.4
Butte	46	00	48	112	33	48	15.33	1.9
Mount Hamilton	37	20	30	121	38	30	15.49	5.0
Mineral	40	20	42	121	36	18	16.44	4.9
Calistoga	38	38	12	122	35	06	16.56	3.1
Shasta	40	41	36	122	23	30	17.14	1.0
Hungary Horse	48	20	58	114	01	39	17.86	0.6
Mabton	46	09	12	120	09	42	18.76	-1.8
Toppenish	46	15	48	120	31	00	19.01	-1.9
Penticton	49	19	00	119	37	00	20.78	1.0
College-O	64	54	00	147	47	36	42.32	-1.3
Mould Bay	76	14	00	119	20	00	44.78	-3.4

where a and b are constants and r the distance from the center of the earth to any point in the mantle. By choosing the appropriate constants, namely a = 18.20km/sec and b = 2.6 X 10^{-7}, this velocity function is a good fit to the velocities predicted by the Jeffreys-Bullen tables to at least a depth of 300km. Since the crust of the earth does not fit this velocity function, it cannot be included in the calculation. Using this method, the depth calculated for the top of the low-velocity layer is about 120km, which is within the depth range found by other investigators (Dowling and Nuttli, 1964; Gutenberg, 1954; Westcott, 1963). The depth of 120 km is for the regions which lie 5 degrees northwest or 5 degrees southeast of the stations in New Mexico.

Positive Residuals at a Distance of 42 Degrees

The peak in the residuals near 42 degrees is observed at all three recording stations in New Mexico, and is also a prominent feature of the residuals from the nuclear explosion data in the central Pacific (Carder, 1964). As before, the positive residuals indicate a zone of lower velocity in the mantle than the Jeffreys-Bullen tables predict. The positive residuals do not necessarily imply a zone in the mantle with a velocity less than the velocity of the zone directly above it. To have observed travel times longer than those predicted by the tables, there need only be a discontinuity in the velocity at this depth such that the Jeffreys-Bullen curves do not quite fit. The simplifying assumptions made in the depth calculation to the top of the first discontinuity are no longer true because of the presence of that low-velocity layer. Therefore it would be very difficult on the basis of the data obtained in this work to make a calculation to the top of this discontinuity. Carder in his work placed this discontinuity at a depth of 866km, and reflection data obtained from large quarry blasts in northern Utah give evidence of a possible discontinuity at a depth of about 910km. (Hoffman, et al., 1961). This would tend to imply that the residuals found in this work near 42 degrees are due to a discontinuity somewhere near these depths.

The shocks involved at distances near 42 degrees occurred mostly in a northwesterly direction from the stations, mainly in laska. However, a few shocks occurred in Colombia at about the ame distance and they also showed positive residuals. This would mply that the peak in the residuals at 42 degrees is not the result f errors in the location of the shocks, but the result of structure in he mantle.

CONCLUSIONS

When observed travel times at Socorro, Albuquerque, and Las Cruces were compared with travel times obtained from the Jeffreys-Bullen tables, there was a definite variation of the time residuals with distance. At all three recording stations two peaks of positive residuals between the distances of 5 and 45 degrees were observed. The first of these peaks occurred near a distance of 20 degrees from the recording stations, and was believed due to a low-velocity layer at a depth of about 120km. The second of these peaks occurred at a distance of 42 degrees, and was believed due to a discontinuity at a greater depth in the mantle. No calculation of the depth to the latter discontinuity was possible on the basis of the data obtained in this work. The second discontinuity is not necessarily one of lower velocity, even though the residuals are positive. There need only be a discontinuity in the velocity such that the Jeffreys-Bullen time-distance curves are early with respect to actual travel times.

Negative residuals were found for a series of shocks that occurred in the Gulf of California at distances of 5 to 10 degrees from the recording stations. These residuals were believed to result from errors in the locations of the earthquakes, and not from anomalous velocities in the crust or mantle. Earthquakes from other geographical locations at the same distance had either positive or small negative residuals.

The differences in the values of residuals between the three stations was believed to be due to differences in the average velocity of the crustal and subcrustal structure beneath the stations. The data indicated that the average velocity of the crustal and subcrustal section beneath the stations is highest at Las Cruces, lowest at Socorro, and intermediate at Albuquerque.

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