A STUDY OF TIME RESIDUALS IN THE SOCORRO AREA FOR P_n ARRIVALS FROM MINING EXPLOSIONS AT SANTA RITA, TYRONE, NEW MEXICO, AND MORENCI, ARIZONA

by

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ABSTRACT

Seismic energy from daily explosions at Santa Rita (SR) and Tyrone (TR), New Mexico, and Morenci (MR), Arizona open pit copper mining operations was used to determine variations in crustal structure within the Socorro, New Mexico, area. Arrival times of mining explosions at a total of eleven stations in the vicinity of Socorro were used.

The basic measurement in this study was the difference in arrival times of P_n phases from the mining explosions between ten stations and a reference station (WT). These time differences were converted to time residuals by applying three corrections; (1) a correction for differences in distance to the mining explosions, (2) a correction for differences in elevation of stations, and (3) a correction for differences in the geologic section beneath each station. After these corrections, three residual maps were constructed. The maps based on data from the Tyrone and Morenci mining explosions are similar in appearance with contours having a NW-SE orientation and the residuals becoming more negative to the southwest.

The increasing negative residuals to the southwest cannot be explained by crustal thinning because apparent P_n velocities (8.12 to 8.28 km/sec) for the explosions relative to the true velocity (7.9 km/sec) indicate that crustal thickening is more probable. A possible explanation for the distribution of residuals is that for stations to the northeast, the P_n phases pass through an extensive magma body at a depth of about 18 km or through small isolated magma bodies at depth of less than 18 km.

INTRODUCTION

The purpose of the study described in this report was to use seismic energy from large daily explosions at Santa Rita and Tyrone, New Mexico, and Morenci, Arizona open pit copper mines to determine variations in the crustal structure of the Rio Grande rift near Socorro, New Mexico.

Arrival times of mining explosions at a total of eleven recording stations in the vicinity of Socorro were used. Figure 1 shows the geographic locations of these recording stations with respect to the rift and to the mines. The distance travelled by the seismic waves on a direct line from pit to recording station ranged from 162 to 261 km.

This report is divided into four sections: (1) review of previous work, (2) instrumentation, (3) analysis of data and (4) discussion of results.

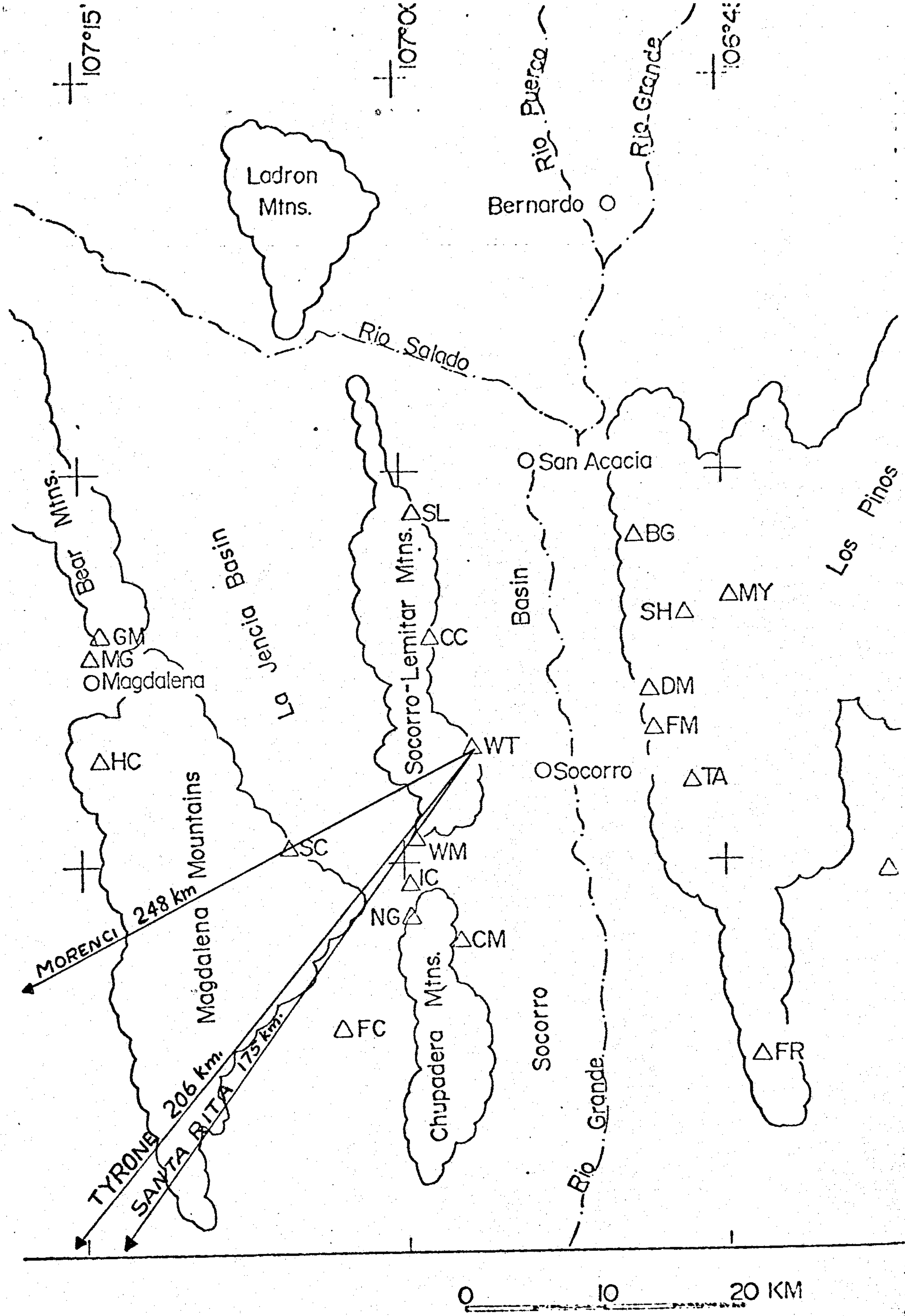


Figure 1. Geographic locations of the recording stations with respect to the mines.

REVIEW OF PREVIOUS WORK

Socorro, New Mexico, is located within the Rio Grande rift, a major north-south continental rift extending about 1000 km from central Colorado through New Mexico (see Figure 2). The rift is characterized by normal faulting which has produced a series of basins and mountain ranges arranged an echelon with a general north trend (Chapin and Seager, 1975). Near Socorro, the rift is expressed as elevated blocks separated by structural basins (see Figure 1). The structurally high areas are (1) La Joyita Hills, (2) the Socorro-Lemitar Mountains, (3) the Chupadera Mountains, (4) the Bear Mountains and, (5) the Magdalena Mountains. The structurally low features are the Socorro and La Jencia basins.

Detailed studies of microearthquake activity in the Socorro region began in early 1960. The bulk of the seismic activity is concentrated to the south and west of Socorro (Sanford and Holmes, 1962; Sanford, 1963; Sanford and Long, 1965; Sanford et al., 1972; Mott, 1976; Shuleski, 1976; and Rinehart, 1976). These studies suggest that the concentration of seismic activity near Socorro may be related to recent igneous intrusions or to current magmatic activity at depth.

An 18 km deep magma body beneath Socorro has been mapped by Sanford and Long (1965), Sanford et al. (1973), and Rinehart (1976), using reflected SxS and SxP phases. The minimum areal extent of the magma body is approximately 1200 square kilometers. The body is located in the central part of the Rio Grande rift at depths of 18 km to 20 km. The southern end of the magma body appears to have the shape of an elongated laccolith with a NNE-SSW trend.

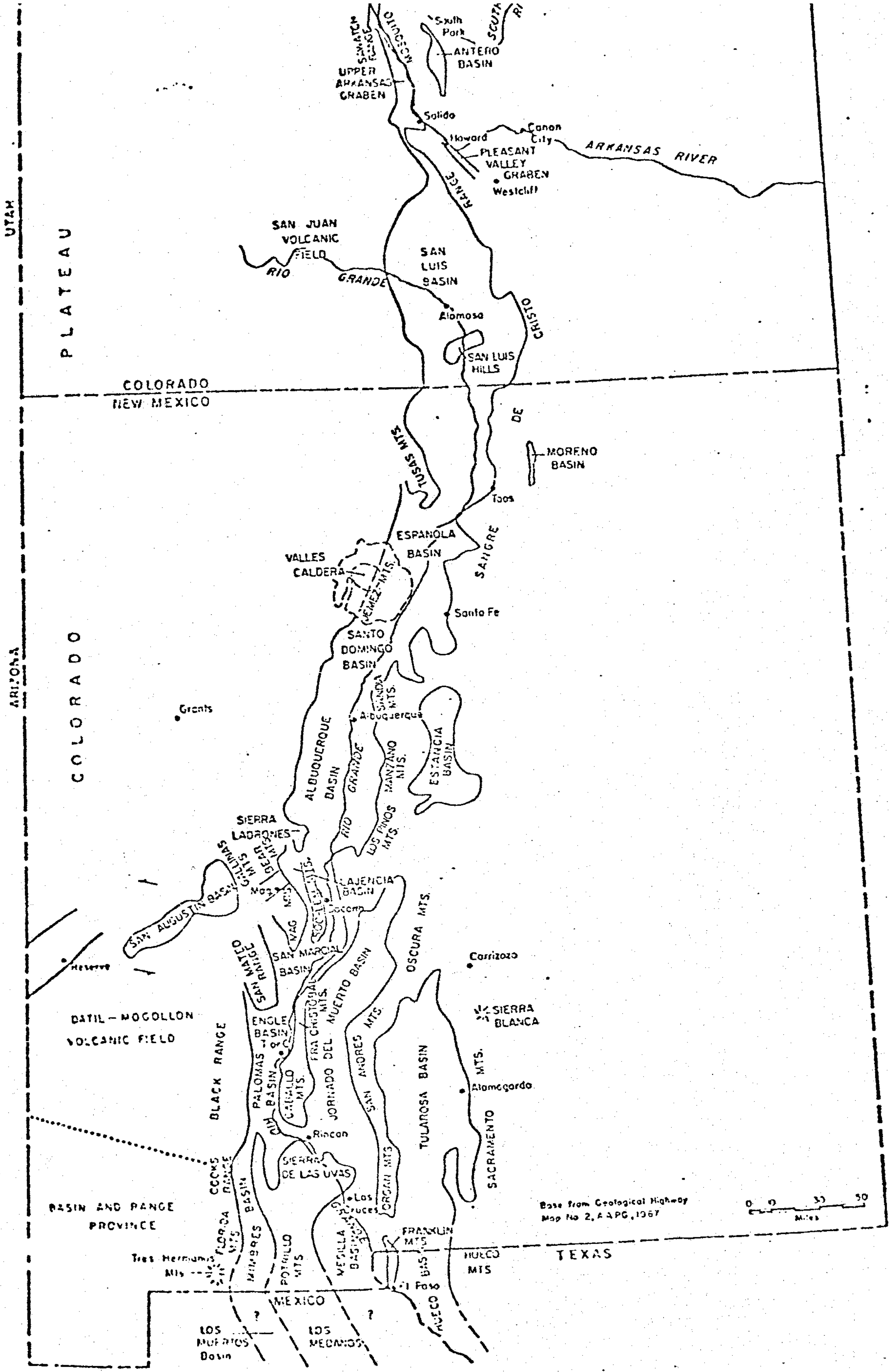


Figure 2. Generalized map of the Rio Grande rift (from Chapin, 1971).

Shuleski (1976) has proposed five shallow magma bodies above the extensive magma layer to explain the screening of SV-waves observed in the Socorro area (see Figure 3).

Sanford (1968) conducted a detailed gravity survey covering parts of the Rio Grande rift and adjacent areas near Socorro, New Mexico. A series of regional and residual Bouguer anomaly maps showed that the Rio Grande valley is a series of linked structural depressions, that are asymmetrical in cross-section.

A crustal study using seismic energy from large daily explosions at Santa Rita and Tyrone, New Mexico, and Morenci, Arizona open pit copper mines was made by Mark Dee (1973). The P-wave velocities found in this study were 6.2 km/sec for the Pg phase and 8.1 km/sec for the P_n phase

A detailed study of the crustal structure in central New Mexico, using arrival times from the Gasbuggy nuclear explosion of 1967, was made by Toppozada and Sanford (1976). At the critical distance 100 km north of Socorro a total crustal thickness of 39.9±1 km was found, which is near the average Moho depth obtained by Phinney (1964) using spectra of long-period body waves recorded at Albuquerque. Toppozada (1974) found that the Moho dips about 2 degrees northward from Las Cruces to Albuquerque. Using this dip, and going southward 100 km along the Gasbuggy profile, a depth of 36.4±1 km was found beneath the SNM station at Socorro (see Figure 4). Other geophysical data suggest that the crustal thickness obtained in this way is a reasonable estimate for the Socorro area.

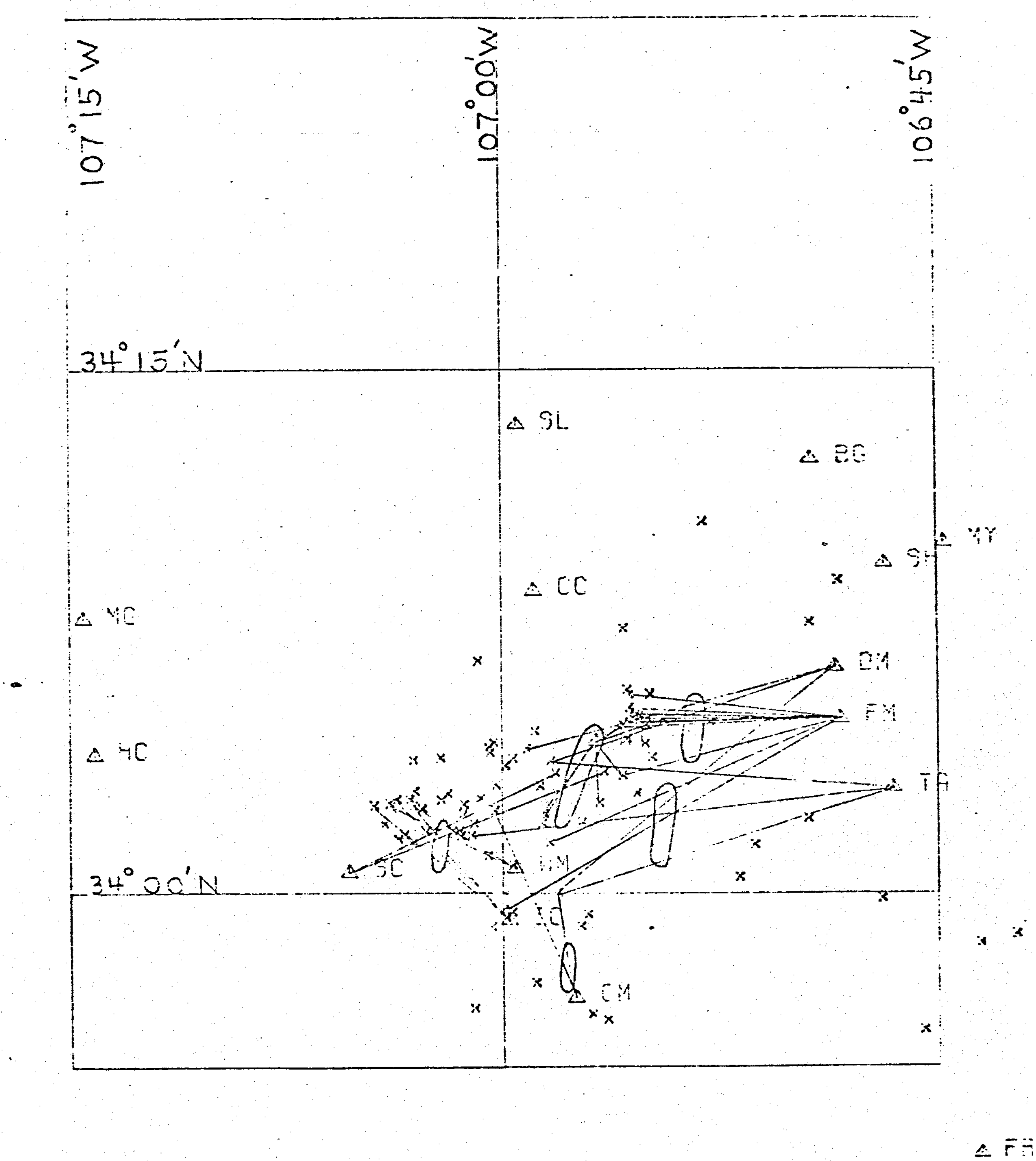


Figure 3. Map showing the locations of five shallow magma bodies in the Socorro area. The locations are based on observed SV-wave Screening (from Shuleski, 1976).

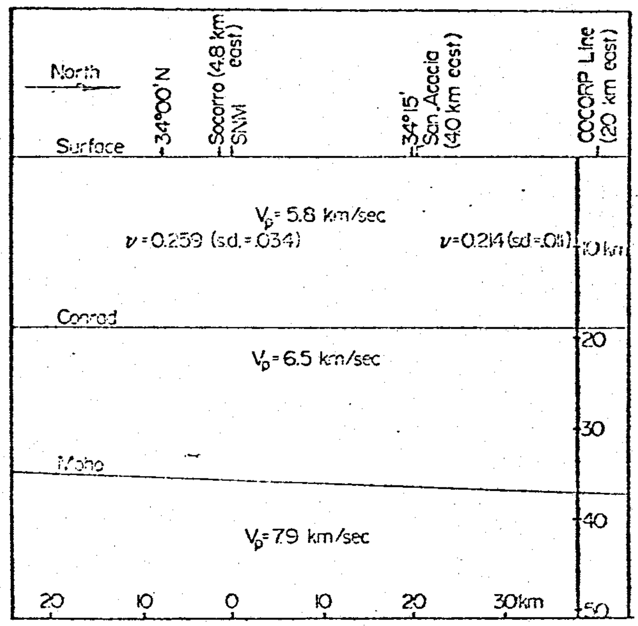


Figure 4. North-south crustal profile of the Rio Grande rift through the Socorro region (from Sanford et al., 1977).

INSTRUMENTATION

The basic recording technique employed throughout this study was to deploy a movable array of four to six portable Sprengnether MEQ-800 Seismographs. In all, 21 different stations were occupied by the movable array (see Figure 1). For reference purposes, WT was a station for all arrays used.

The Sprengnether MEQ-800 Seismographs consisted of either a Mark Products L4-C (1.0 Hz) or a Willmore (1.5 Hz) vertical seismometer, a gain-stable amplifier, a quartz-crystal timing system, and a smoked-paper recorder which operated at a recording rate of 120 mm/minute. Gain settings varied from 78 to 120 db in 6 db increments depending on the background noise conditions. Filtering of high frequency signals above 30 Hz was used to reduce noise generated by wind.

Clocks for timing seismic arrivals were synchronized to WWV-UST at the beginning of each recording week (Monday through Friday). The timing system was checked for drift at the end of each recording period. Drifts ranged from 0.0 to 0.3 seconds during the 96 hour period and were assumed to occur linearly when timing corrections were calculated.

DATA ANALYSIS

Arrival times for three open pit mining explosions were gathered from eleven stations in the vicinity of Socorro, New Mexico. Locations and elevations for the recording stations and mining explosions are listed in Tables 1 and 2.

The basic measurement in this study was the difference in arrival times of P_n phases between the ten stations and WT for the three mining explosions. In order to obtain accurate time differences, 5 to 6 samples of each explosion were measured for each station. The results are listed in Table 3. Note that the standard deviations of the time differences are quite small which indicates that the measurements are quite reliable.

Time differences between the ten stations and WT were converted to time residuals (relative to WT) by applying three corrections: (1) a correction for differences in distance to the mining explosions, (2) a correction for differences in elevation of the stations, and (3) a correction for differences in the geologic section beneath each station. The three corrections are described below.

The equation for the distance correction, which is subtracted from the time difference is

$$\frac{\Delta\ (\text{Station} - \text{WT})}{V_{P_n}},$$

where Δ (Station - WT) is the difference in distance to the mining explosion, and V_{P_n} is the velocity of the P_n phase. The P_n velocity

Table 1. Locations and Elevations of Recording Stations.

Recording Station	Location		Elevation (in km)	Distance to Explosions (in km)		
	Latitude	Longitude		SR	TR	MR
CC	33.144	106.981	1.649	180.11	210.93	248.93
CM	33.950	106.958	1.640	164.00	195.87	241.45
DM	34.107	106.808	1.536	186.31	218.12	261.31
FM	34.083	106.805	1.576	184.37	216.30	260.40
FR	33.875	106.727	1.558	172.26	205.25	258.19
GM	34.145	107.234	1.945	168.33	197.52	228.74
HC	34.066	107.236	2.207	160.44	190.04	224.16
IC	33.987	106.997	1.731	165.04	196.54	239.86
NG	33.965	106.993	1.737	163.27	194.89	239.12
SC	34.010	107.089	2.085	162.17	193.05	233.24
WT	34.072	106.946	1.564	175.44	206.79	248.16

Table 2. Locations and Elevations of Mining Explosions.

Mining Explosion	Location		Elevation (in km)	Distance to Explosions (in km)		
	Latitude	Longitude		SR	TR	MR
Santa Rita (SR)	32.797	108.058	2.100	0.00	33.92	122.77
Tyrone (TR)	32.645	108.373	1.925	33.92	0.00	101.17
Morenci (MR)	33.063	109.335	1.350	122.77	101.17	0.00

Table 3. Arrival Times Between Stations and WT from Mining Explosions.

Time Differences

CC-WT	CM-WT	DM-WT	FM-WT	FR-WT	GM-WT	HC-WT	IC-WT	NG-WT	SC-WT	
.53	-1.36	1.34	1.03		- .75	-1.85	-1.27	-1.58	-1.64	
.59	-1.38	1.33	1.09		- .79	-1.86	-1.31	-1.56	-1.66	
.58	-1.35	1.33	1.08		- .77	-1.87	-1.29	-1.57	-1.63	Santa Rita
.59	-1.35	1.36	1.06		- .79	-1.86	-1.30	-1.55	-1.65	
.61	-1.35	1.32	1.06		- .78	-1.84	-1.29	-1.56	-1.66	
	-1.36						-1.31			
.58	-1.36	1.34	1.06		- .78	-1.86	-1.30	-1.56	-1.65	Average
.03	.01	.02	.02		.02	.01	.02	.01	.01	Standard Deviation
.59	-1.37	1.37	1.20	-.15	-1.09	-1.93	-1.23	-1.42	-1.63	
.56	-1.39	1.37	1.19	-.14	-1.08	-1.96	-1.22	-1.42	-1.64	
.55	-1.40	1.42	1.21	-.25	-1.05	-1.95	-1.20	-1.41	-1.61	Tyrone
.56	-1.38	1.39	1.19	-.29	-1.09	-1.93	-1.21	-1.44	-1.62	
.54	-1.38	1.41	1.18	-.17	-1.06	-1.95	-1.22	-1.43	-1.59	
.55		1.38					-1.22			
.56	-1.38	1.39	1.19	-.20	-1.07	-1.94	-1.22	-1.42	-1.62	Average
.02	.01	.02	.01	.07	.02	.01	.01		.02	Standard Deviation
.14	- .82	1.68	1.54		-2.37	-2.94	-1.06	-1.10	-1.80	
.14	- .89	1.66	1.50		-2.35	-2.95	-1.00	-1.07	-1.81	
.13	- .86	1.66	1.52		-2.35	-2.92	-1.00	-1.06	-1.79	Morenci
.15	- .85	1.65	1.53		-2.32	-2.94	-1.05	-1.08	-1.78	
.12	- .83	1.65	1.54		-2.38	-2.94	-1.04	-1.06	-1.79	
.13			1.53				-1.07	-1.08		
.13	- .85	1.66	1.53		-2.35	-2.94	-1.03	-1.08	-1.79	Average
.01	.03	.01	.02		.02	.01	.03	.02	.01	Standard Deviation

for each mining explosion was obtained by plotting observed time differences versus distance differences as shown in Figures 5 through 7. Results of a linear regression analysis of the data for each explosion are given in these figures. Distance corrections are listed in Table 4.

The correction for differences in elevation is illustrated in Figure 8. The equation for the elevation correction is

$$\frac{h_{WT} - h_s}{V_1} \cos i_1 ,$$

where h_{WT} is the elevation of station WT, h_s is the elevation of each individual station and i_1 is the angle of the P_n raypath from the Conrad discontinuity. The elevation correction is added to the observed time differences. Table 4 lists the time residuals after distance and elevation corrections have been applied.

The final correction for geologic conditions beneath each station is more subjective than the other two corrections. The geologic section beneath each station east of the Rio Grande valley were obtained from the data presented by Sanford (1968, p. 10), which in turn is based on geologic mapping by Wilpolt and Wanek (1951). The densities for 305 meters (1000 feet) thick segments of these sections were taken from the study by Sanford (1968). Velocities were found from these densities by using the observational relation between density and velocity obtained by C. Drake (Grant and West, 1965), p. 200) (see Figure 9). The correction for each 305 meters of the geologic section beneath the station was obtained

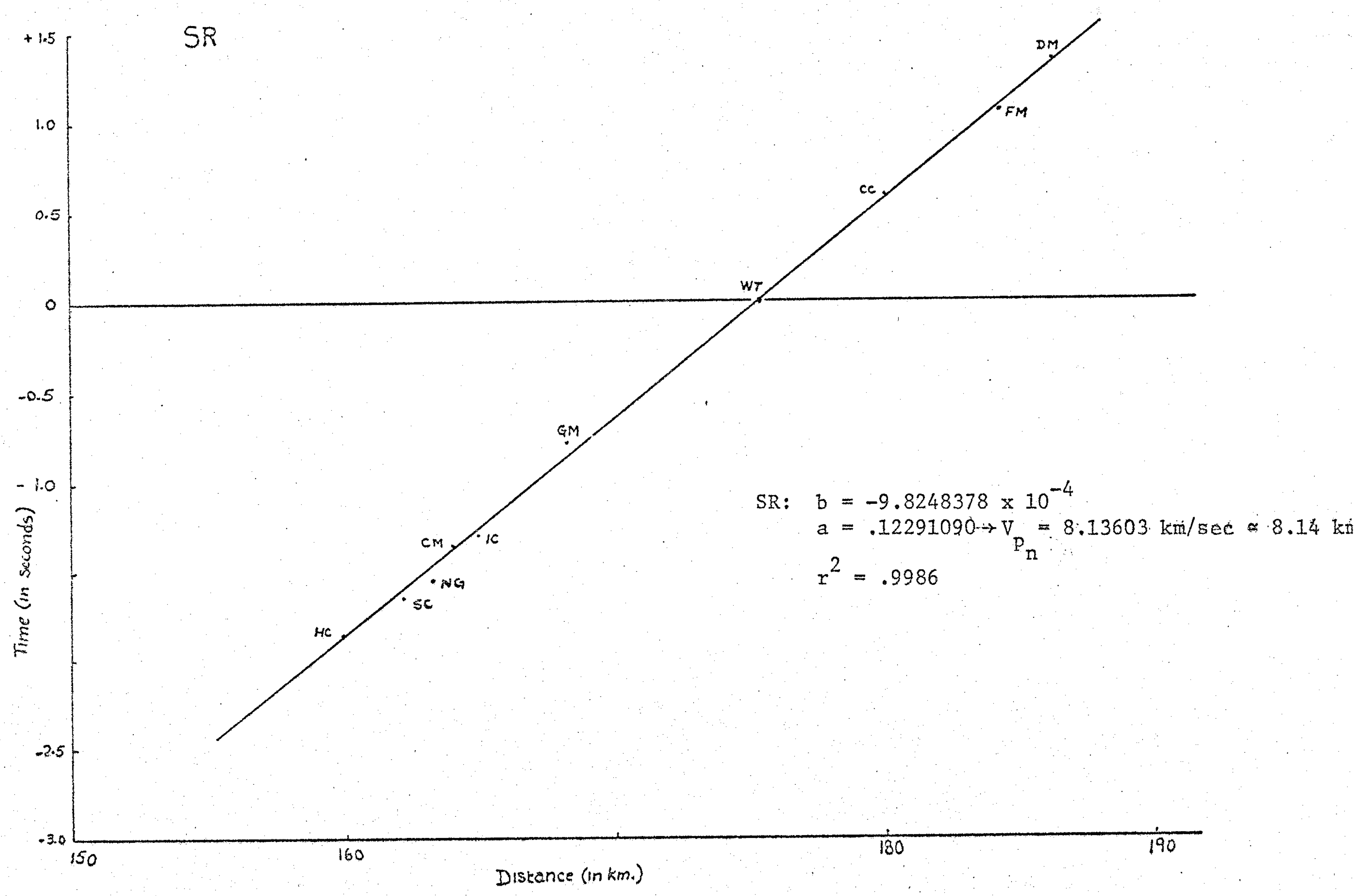


Figure 5. Time-distance curve for P_n arrivals from Santa Rita mining explosions.

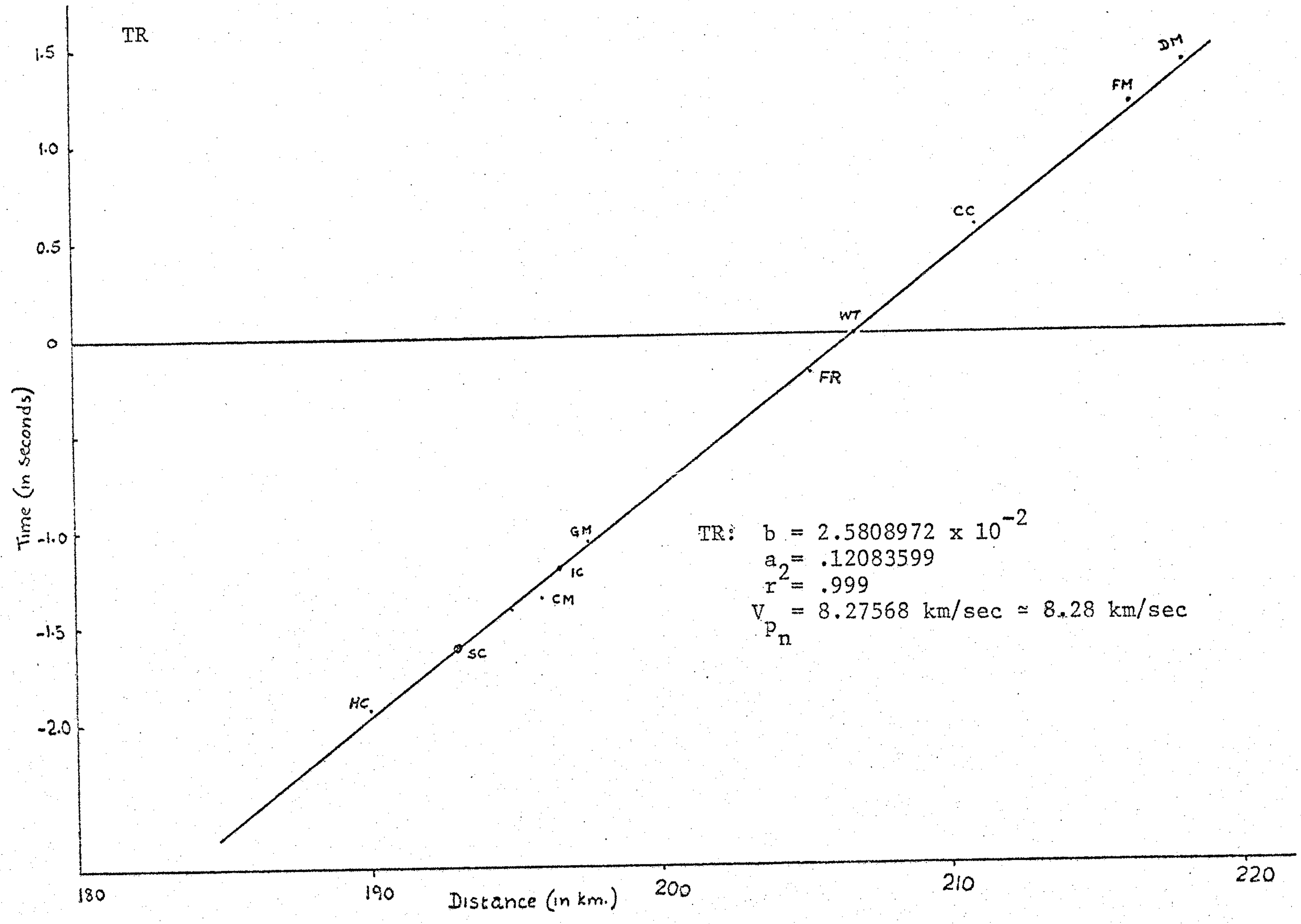


Figure 6. Time-distance curve for P_n arrivals from Tyrone mining explosions.

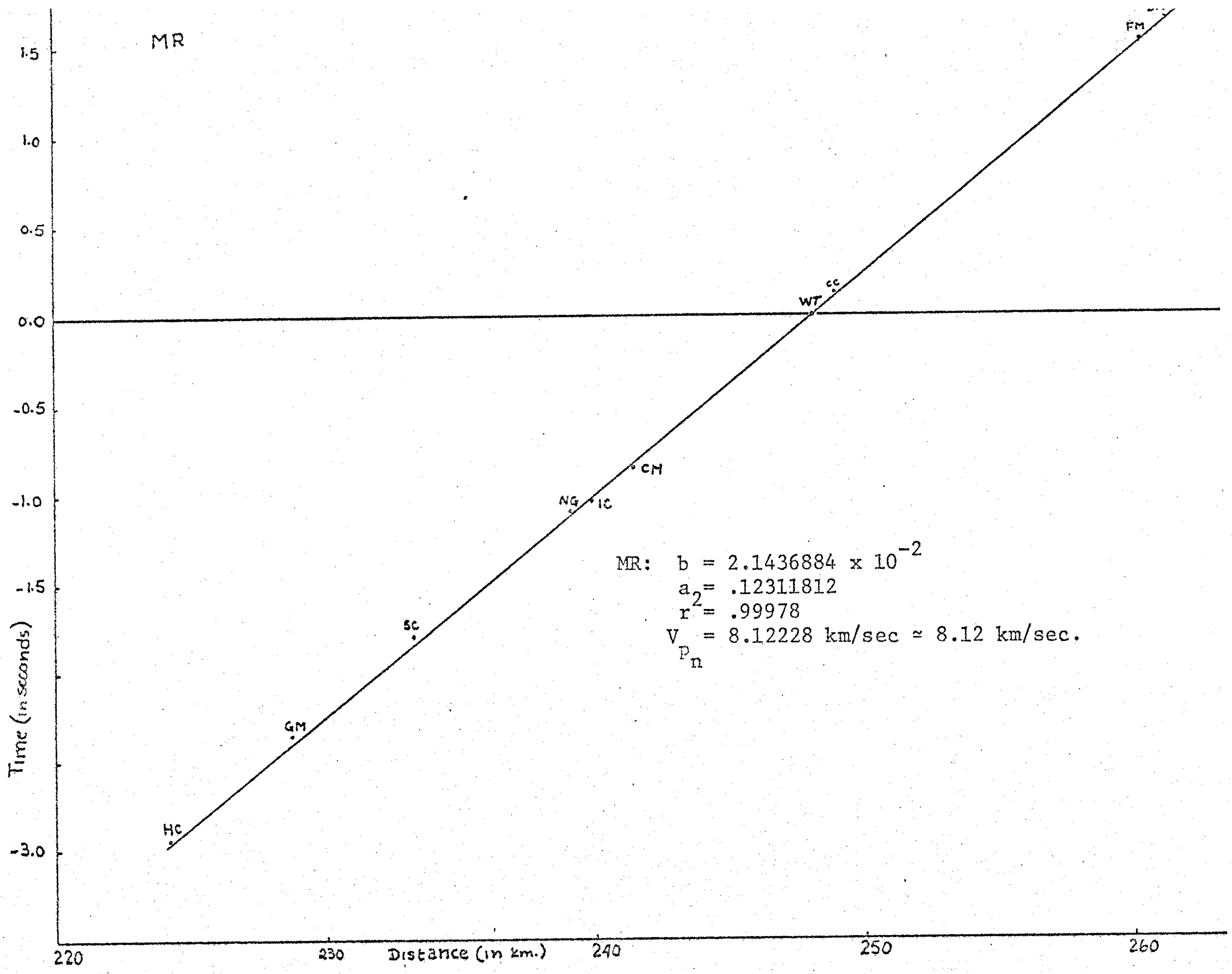
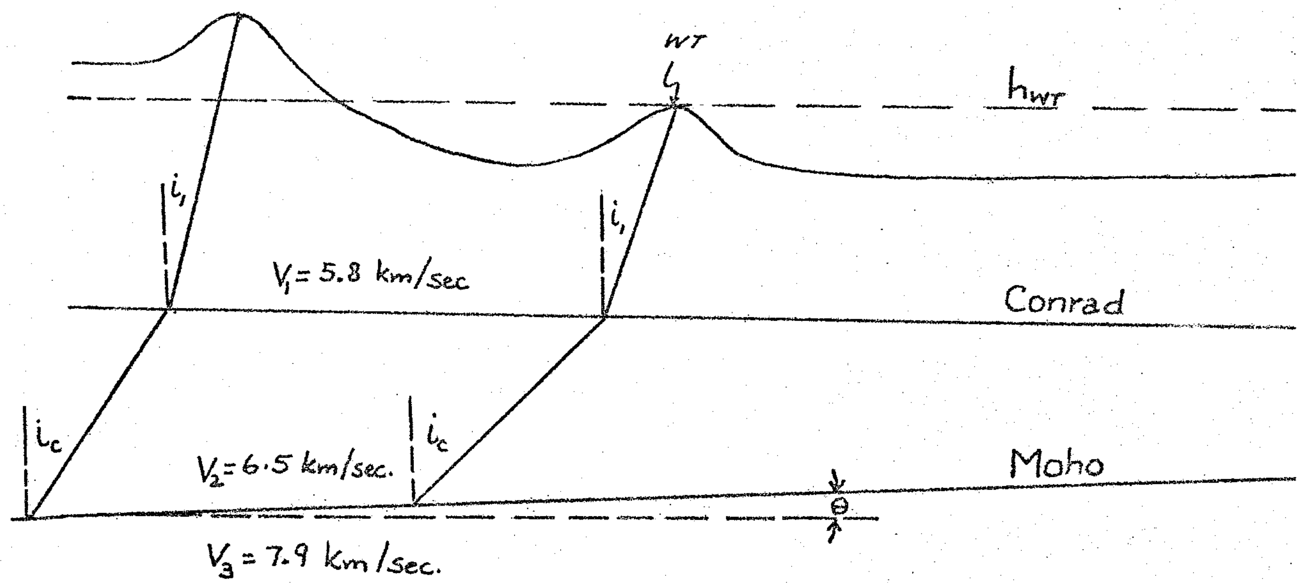


Figure 7. Time-distance curve for P_n arrivals from Morenci mining explosions.

Table 4. Summary of Time Differences, Corrections, and Residuals.

Stations	Explosions	Time Differences (Sta.-WT)	Distance Correction in Sec.	Elevation Correction in Sec.	Residuals After Distance and Elevation Corrections (in Sec.)	Geologic Correction (in Sec.)	Residuals After All Corrections (in Sec.)
CC	SR	.58	.57	-.01	.00	-	.00
	TR	.56	.50		.05	-	.05
	MR	.13	.09		.03	-	.03
CM	SR	-1.36	-1.41	-.01	.04	.09	-.05
	TR	-1.38	-1.32		-.06	.09	-.15
	MR	- .85	- .83		-.03	.09	-.12
DM	SR	1.34	1.34	.00	.00	.01	-.01
	TR	1.39	1.37		.01	.01	.00
	MR	1.66	1.62		.03	.01	.02
FM	SR	1.06	1.10	.00	-.04	-	-.04
	TR	1.19	1.15		.03	-	.03
	MR	1.53	1.51		.02	-	.02
FR	SR			.00			
	TR	- .20	- .19		-.01	.06	-.07
	MR						
GM	SR	- .78	- .87	-.04	.04	-	.04
	TR	-1.07	-1.12		.02	-	.02
	MR	-2.35	-2.39		-.01	-	-.01
HC	SR	-1.86	-1.84	-.08	-.10	.06	-.16
	TR	-1.94	-2.02		-.02	.06	-.08
	MR	-2.94	-2.96		-.06	.06	-.12
IC	SR	-1.30	-1.28	-.02	-.04	.09	-.13
	TR	-1.22	-1.24		.01	.09	-.08
	MR	-1.03	-1.02		-.03	.09	-.12
NG	SR	-1.56	-1.50	-.02	-.08	.09	-.17
	TR	-1.42	-1.44		.01	.09	-.08
	MR	-1.08	-1.11		.01	.09	-.08
SC	SR	-1.65	-1.63	-.06	-.08	.08	-.16
	TR	-1.62	-1.66		-.01	.08	-.09
	MR	-1.79	-1.84		-.01	.08	-.09



$$\text{Elevation Correction} = \frac{h_{WT} - h_S}{V_1} \cos i_1$$

Where:

h_S = Station Elevation

h_{WT} = WT station Elevation

$$i_c = \sin^{-1} \frac{6.5}{7.9}$$

$$\frac{\sin i_1}{\sin i_c} = \frac{5.8}{6.5}$$

$$\sin i_1 = \frac{5.8}{7.9}$$

$$\therefore\ i_1 = \sin^{-1} \frac{5.8}{7.9}$$

Figure 8. Diagram illustrating correction for differences in elevation.

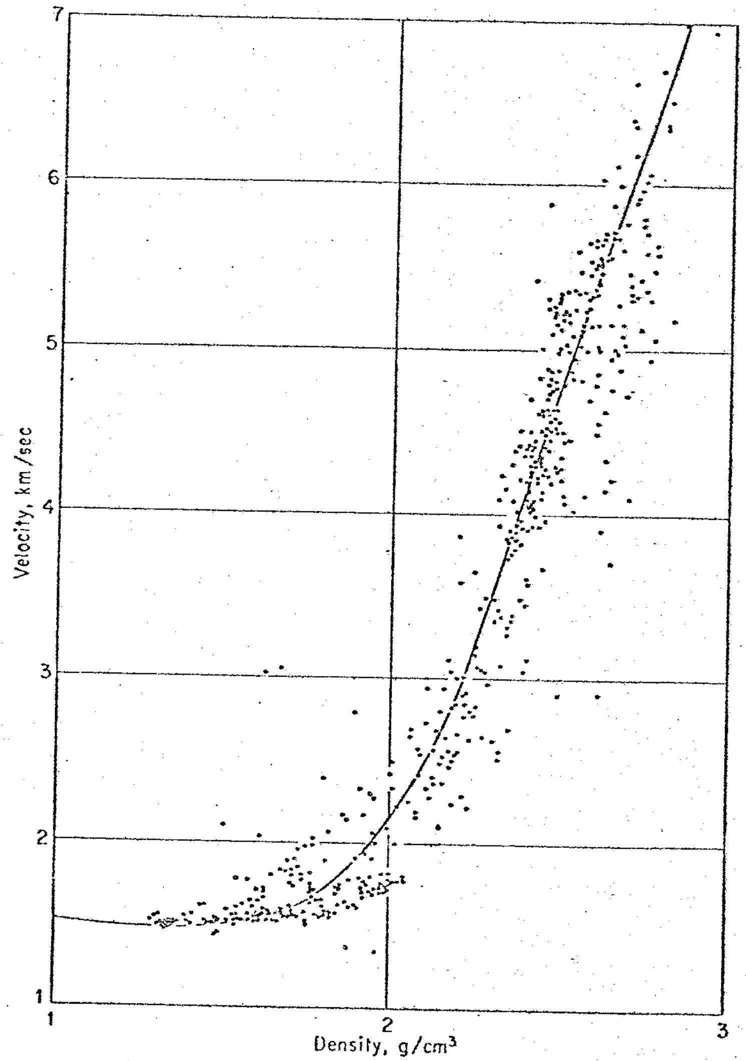


Figure 9. A plot of seismic P-wave velocity vs. bulk density (from Grant and West, 1965).

from the equation,

$$.305 \text{ km} \left(\frac{1}{V_r} - \frac{1}{5.8 \text{ km/sec}}\right),$$

where V_r is the average velocity of the 305 meter segment of the geologic section. Geologic corrections for stations east of the Rio Grande valley are listed in Table 4.

From unpublished studies (Chapin and others, personal communication, 1977), geologic sections beneath each station west of the Rio Grande valley were obtained. These sections are mostly composed of volcanic tuff which for purposes of estimating velocity were subdivided into aggregate thicknesses of densely, moderately, and poorly welded types. From unpublished seismic measurements of tuff velocities along the northern margin of the Socorro caldera (Sanford, 1977, personal communication), the velocities of the three types of tuffs were estimated to be 4.27 km/sec, 3.66 km/sec, and 2.74 km/sec, respectively.

The correction for each geologic section beneath each station was obtained from the general equation:

$$\frac{L}{V_r} - \frac{L}{5.8 \text{ km/sec}},$$

where L is the thickness of the columnar section beneath each station having a velocity of V_r.

DISCUSSION OF RESULTS

The residuals after distance, elevation, and geologic corrections are plotted and contoured in Figures 10, 11, and 12. The contour maps based on data from the Tyrone (TR) and Morenci (MR) mining explosions are similar in appearance. The contours have a NW-SE orientation and the residuals become more negative to the southwest. The contour map based on the Santa Rita (SR) mining explosions has a more complex configuration than the other two maps. A possible explanation for this difference is that the stations for the Santa Rita explosions are near the cross-over distance.

The increasing negative residuals to the southwest in Figures 10, 11, and 12, cannot be readily explained by a thinning of the crust in that direction. The apparent P_n velocities for the mining explosions, which range from 8.12 km/sec to 8.28 km/sec, are substantially higher than the true P_n velocity of 7.9 km/sec obtained by Toppozada (1974). The relations between these observed velocities would indicate that thickening of the crust to the southwest is more probable than thinning.

The more positive residuals at stations CC, DM, FM, and WT than at stations SC, NG, IC, and CM could be explained by passage of seismic energy through (1) an extensive magma layer at a depth of about 18 km or (2) small isolated magma bodies located at a depth of less than 18 km. The southern margin of the magma body has been determined by Rinehart (1976) and is shown in Figure 13.

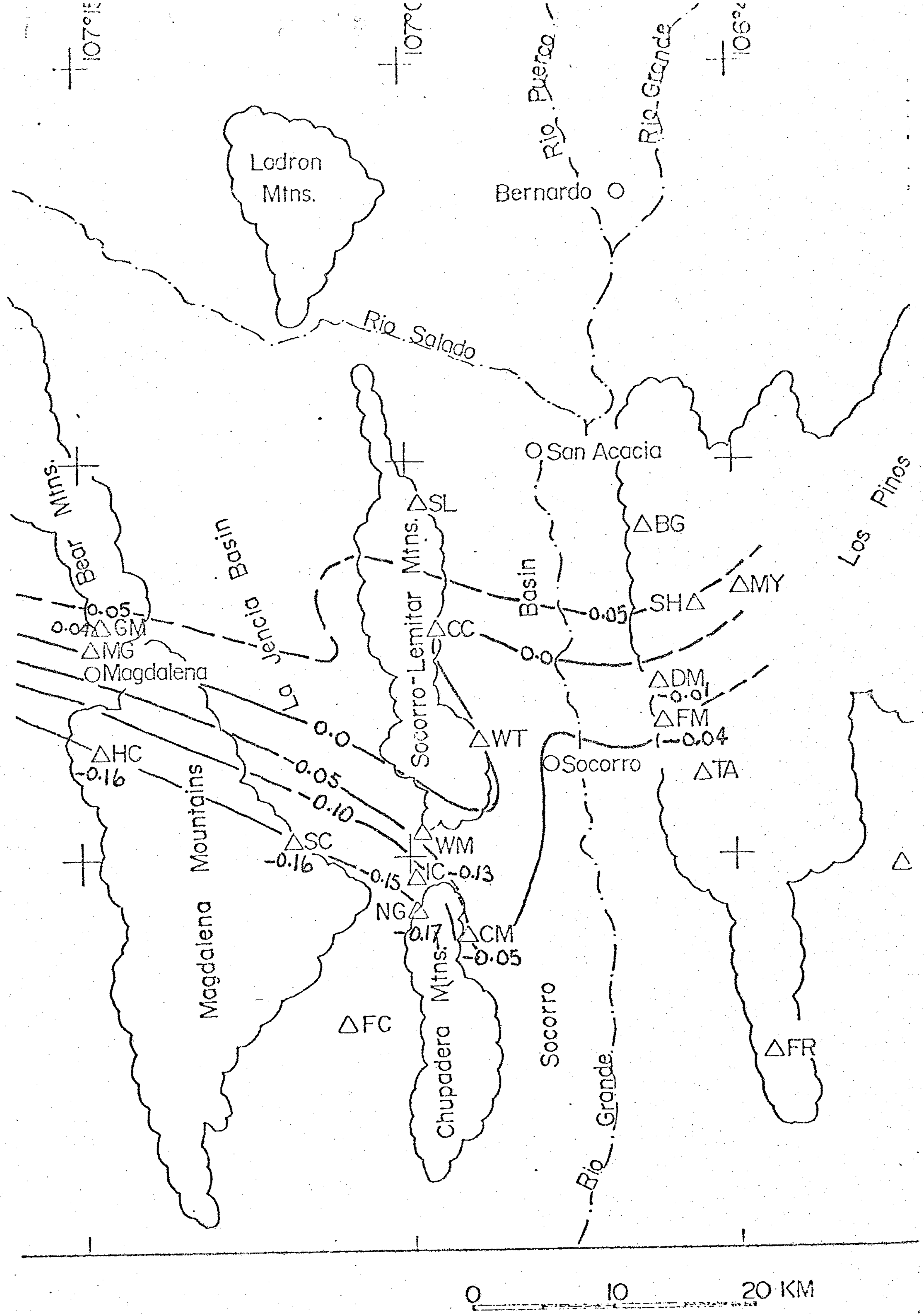


Figure 10. Map of the residuals for SR data after distance elevation, and geologic corrections.

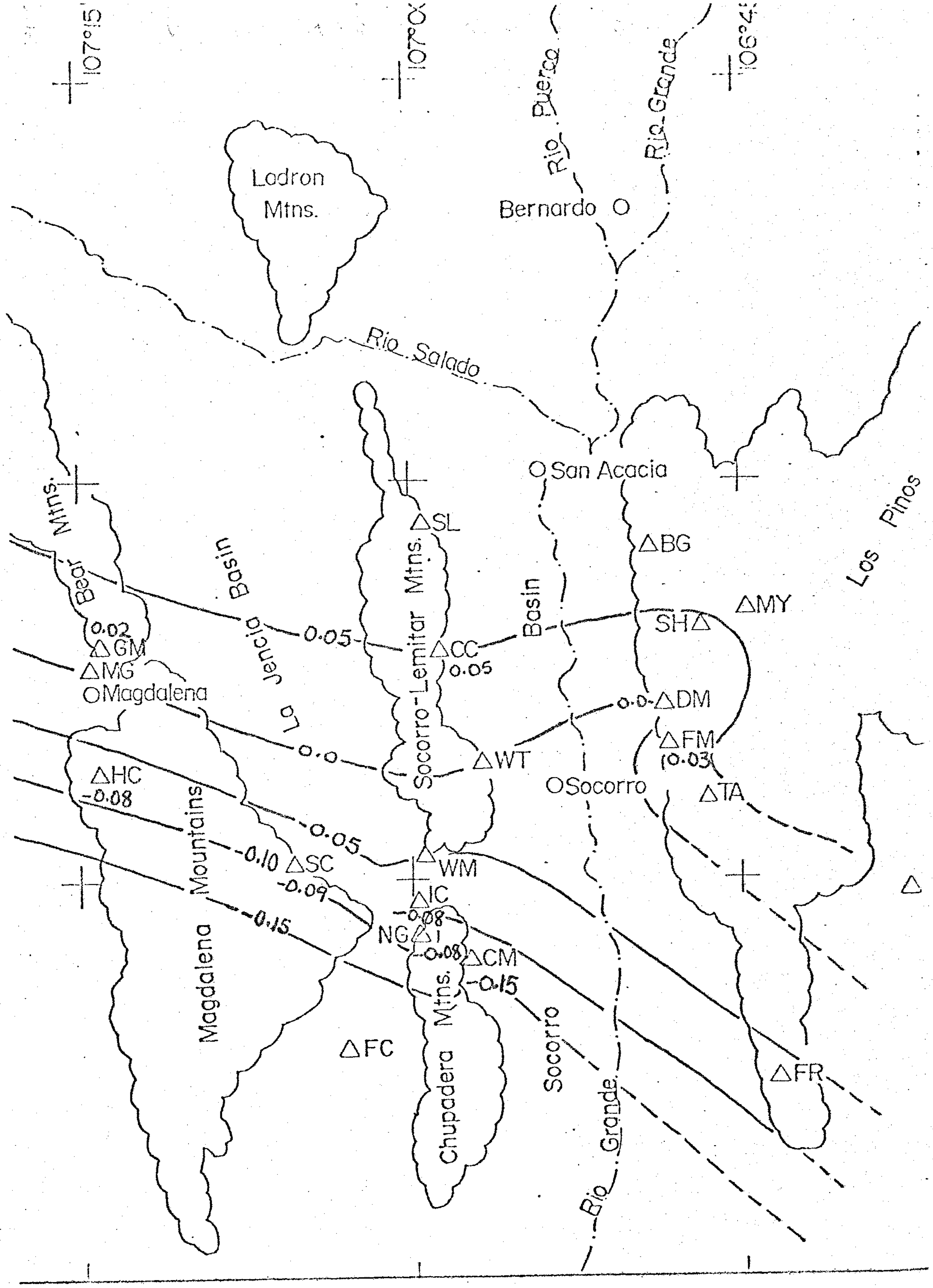


Figure 11. Map of the residuals for Tyrone (TR) data after distance, elevation, and geologic conditions.

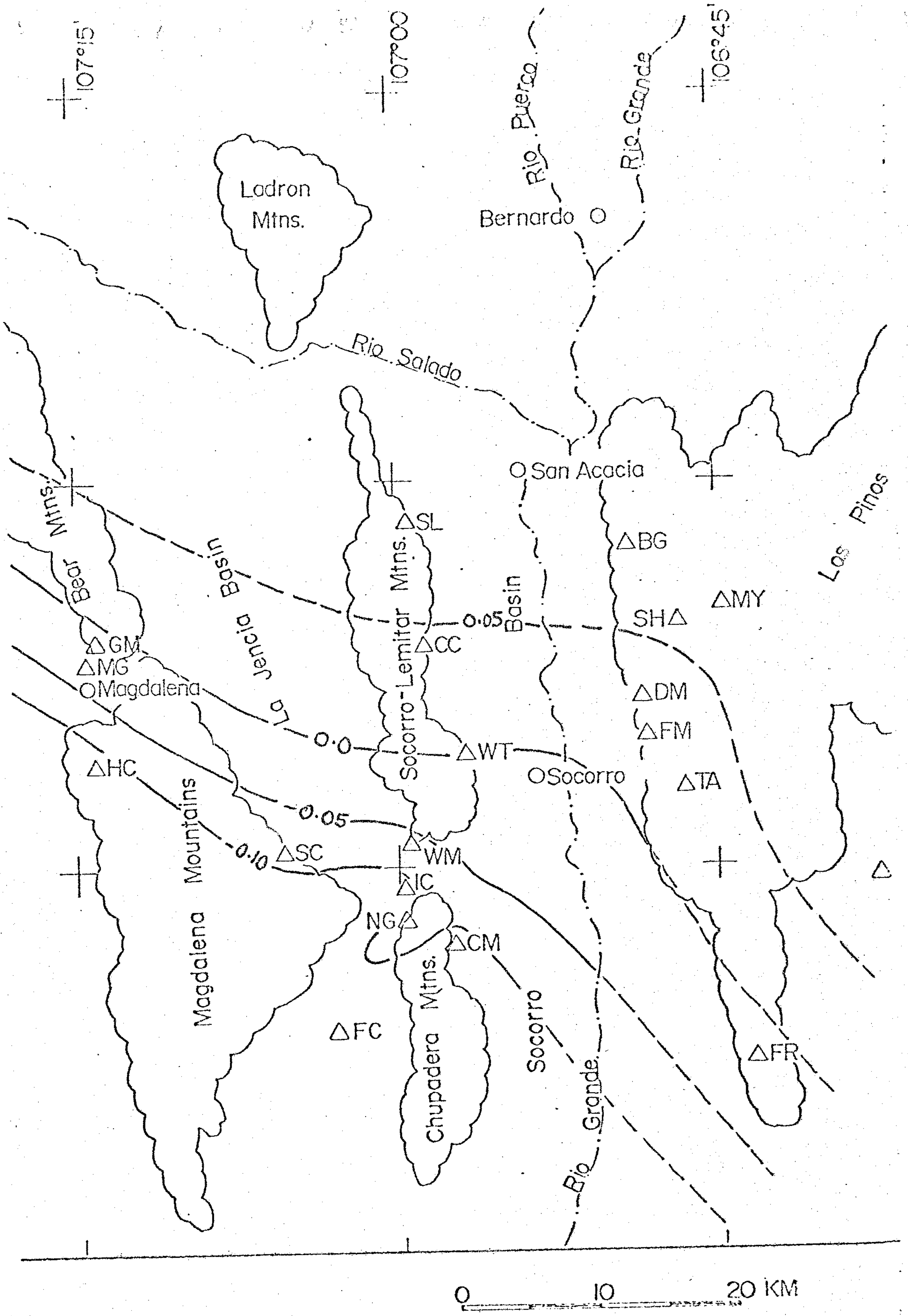


Figure 12. Map of the residuals for Morenci (MR) data after distance, elevation, and geologic corrections.

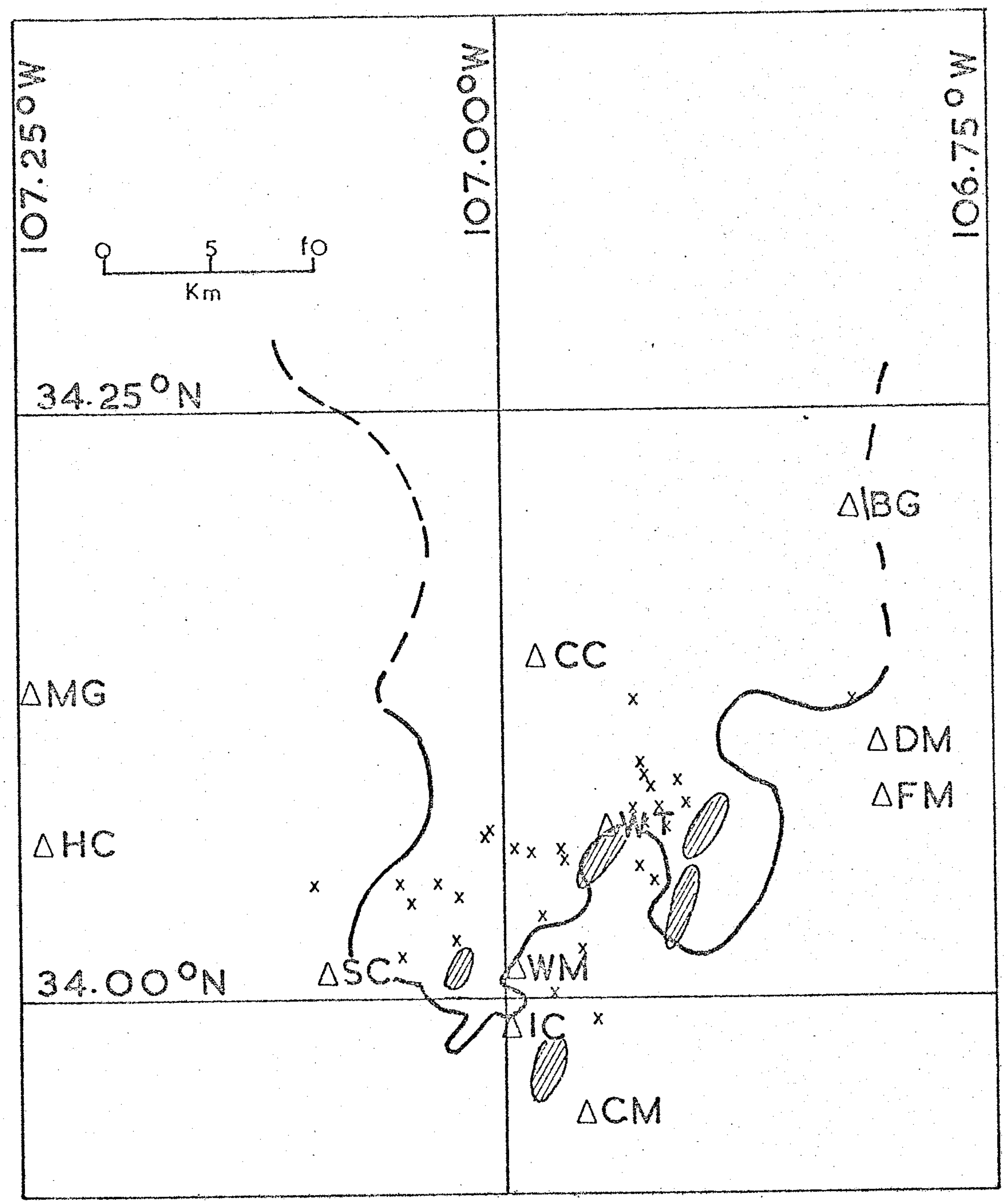


Figure 13. Boundary of extensive magma layer at depths of 18 to 20 km and location of shallow magma bodies with respect to location of earthquake swarms (from Rinehart, 1976).

The positions of shallow magma bodies, as defined by SV phase screening (Shuleski, 1976) are also shown in Figure 13. Further evidence for the existence of the shallow magma bodies is anomalously high values of Poisson's ratio in segments of the crust south and southwest of station WT (Caravella, 1976).

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