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Vol. 3

Geophysical Investigations of the Western Ohio-Indiana Region

Annual Report
October 1983 - September 1984

Prepared by H. N. Pollack, D. H. Christensen, J. Welc

Department of Geological Sciences
The University of Michigan

Prepared for
U.S. Nuclear Regulatory
Commission

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Abstract

Earthquake activity in the Western Ohio - Indiana region has been monitored with a precision seismograph network consisting of nine stations located in west-central Ohio and four stations sited in Indiana. Twelve local and near-regional earthquakes have been recorded and located during this report period, ranging in magnitude from 0.3 to 4.0 m_{blg}. An event which occurred on January 14, 1984 in Toledo, Ohio and two events on July 28 and August 29, 1984 near Terre Haute, Indiana were felt. Only minor damage was reported from these events. Of the twelve events, four occurred in the center of the Ohio array, three occurred near the city of Toledo, Ohio, four occurred in Indiana (including one on the Indiana-Illinois border), and one was located near Chicago, Illinois.

Teleseismic P-wave residuals have been updated and evaluated by back projection to various depths in the lower crust. The residuals are found to correspond roughly to magnetic anomalies in the lower crust of Ohio. It is thought that these magnetic anomalies may represent the remains of an ancient rift zone, or perhaps they are the signature of the Grenville Front complex which may cross through this area.

Summary

During the period from October, 1983 through Septempber, 1984 the Western Ohio-Indiana network has been operational a total of 85% of the time. No major changes were made in the array during this period.

Twelve local and near regional earthquakes have been recorded during the fiscal year. These events ranged in magnitude from 0.3 to 4.0 m_{blg}. Three of these events occurred near Toledo, Ohio. The Toledo, Ohio event on January 14, 1984 was felt in many parts of the city. To our knowledge no damage was reported. Four events were located in Indiana (including one on the Indiana-Illinois state line), three of which were about 35 km south to southeast of Terre Haute, Indiana. The events which occurred on July 28, 1984 and August 29, 1984 with magnitudes of 4.0 m_{blg} and 3.2 m_{blg}, respectively, were both felt as far away as Terre Haute, but only minor damage was reported. These events represent the first events to be recorded in Indiana by the array. One event was located north of Chicago, Illinois while the remaining four events occurred in the center of the Ohio array, in the same small area where now a total of twelve events have been located since 1980.

The Celina, Ohio event of June 17, 1977 was relocated using S-P travel times from four local stations. The new location of this event is 40.57 ^{o}N x 84.67 ^{o}W.

The teleseismic P-wave residual tables have been updated to include newly acquired data and residuals from the Indiana array. We have attempted to relate these residuals to lower crustal structures as seen on the most recent aeromagnetic anomaly map of Ohio (Hildenbrand and Kucks, 1984). The relative residuals have been back projected to various depths in the crust using the back azimuth and angle of incidence of each ray and the appropriate locations plotted. The results show that there is a good correlation between the relatively slow arrivals recorded on the easternmost stations and a strong band of north-south magnetic anomalies, just east of the array. This magnetic feature may represent a possible ancient rift zone, or perhaps it is a signature of the Grenville Front which may also run through this region.

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PREFACE

This is the third annual report under the three year contract NRC-04-81-195-04, a continuation of effort funded under contract NRC-04-76-192: The contract includes maintenance and systematic processing of a 9-station seismic array in western Ohio initiated in 1976, and the subsequent expansion in 1981 to include a 4-station array in Indiana, in addition to concurrent regional investigations. The final report for this project which would normally be due at this time will be delayed until the end of the contract extension period, currently set for September 1985.

We wish to express our appreciation to Scott Baird for keeping a wide range of instruments and computer peripherals in constant working condition, and to Sandy Wirick, Tiberiu Sipos, and James Mullany for their help in successfully operating the seismic network.

Previous Reports

Four major reports concerning this investigation were published under the previous contract no. NRC 04-76-192:

Mauk, F. J., D. Coupland, D. Christensen, J. Kimball, P. Ford, 1979, Geophysical Investigations of the Anna, Ohio, Earthquake Zone: Annual Progress Report for the Nuclear Regulatory Commission, July 1978-July 1979, NUREG/CR-1065.

Mauk, F. J., S. G. Henry, D. H. Christensen, J. Sauber, C. Lanford, W. Meerschaert, J. K. Kimball, 1980, Geophysical Investigations of the Anna, Ohio, Earthquake Zone: Annual Progress Report for the Nuclear Regulatory Commission, July 1979-1980, NUREG/CR-1649.

Mauk, F. J., D. H. Christensen, 1980, A Probabilistic Evaluation of Earthquake Detection and Location Capability for Illinois, Indiana, Kentucky, Ohio and West Virginia: Report for the Nuclear Regulatory Commission. September, 1980, NUREG/CR-1648.

Jackson, P. L., D. H. Christensen, F. J. Mauk, 1981, Geophysical Investigations of the Western Ohio - Indiana Region: Final Report for the Nuclear Regulatory Commission, November, 1975 - September, 1981, NUREG/CR-2484.

Christensen, D. H., M. G. Wiedenbeck, P. L. Jackson, 1983, Geophysical Investigations of the Western Ohio - Indiana Region: Annual Report for the U. S. Nuclear Regulatory Commission, October 1981 - September 1982, NUREG/CR-3145, Vol. 1.

Pollack, H. N., D. H. Christensen, 1984, Geophysical Investigations of the Western Ohio - Indiana Region: Annual Report for the U. S. Nuclear Regulatory Commission, October 1982 - September 1983, NUREG/CR-3145, Vol. 2.

The Western Ohio - Indiana Seismic Array

The Western Ohio - Indiana seismic network consists of thirteen local and two regional (ACM, AAM) short period vertical stations. The thirteen local stations are formed by the original nine stations of the Anna, Ohio network, fully operational since June 1978, and a subnetwork of four stations located in Indiana which were installed in Feburary 1981. Locations, elevations, magnifications and other information about the stations are listed in Table 1. Station locations are shown in Figure 1.

The nine west-central Ohio stations are designed as schematically illustrated in Figure 2a. The data from these stations are transmitted by radio to a central tower at Wapakoneta, Ohio. The four Indiana stations are designed as schematically shown in Figure 2b and the data transmitted by telephone link to the receiving facility at Wapakoneta, Ohio. The receiving facility at Wapakoneta, Ohio is schematically shown in Figure 2c. At this facility signals from the thirteen Ohio and Indiana stations are multiplexed onto three trunk lines and transmitted to the recording facility at the University of Michigan in Ann Arbor, Michigan. The recording facility is schematically illustrated in Figure 2d. Individual station data is discriminated from the multiplexed signal and recorded at the University of Michigan.

Full system response curves have been experimentally produced for the Ohio network using the calibration coils in the HS-10, 1 Hz geophones through in-field studies. The calculated response is shown in the unity gain curves in Figure 3a. The response curves for the Indiana stations, which were calculated through a combination of experimental and published response characteristics are shown in Figure 3b. The curves in Figure 3 represent the response of the system using 2 Hz, 5 Hz, and 12.5 Hz low pass filters. Although any of the three responses are possible in playback mode from the analog tape, only one can be used for the directly recorded visual records. Currently we are using the 12.5 Hz low pass filter for this purpose.

During the last fiscal year (October 1983 - September 1984) the stations have been operational approximately 85% of the time. Station failures were usually caused by battery failures, phone line problems, and lightning strikes. However, many problems were caused by equipment failures which can be related to the aging of several electronic components. During the early months of the coming fiscal year we will be replacing some of the older components in the field installations, including the VCO-amplifier packages and the geophones. This upgrade should increase our operating time and improve the quality of the data. These improvements will be decussed in future reports. Individual station reliability data averaged for each month are gived in Table 2. Detailed daily station uptimes are listed in Appendix A. The downtime reflected in the above mentioned reliability data includes both periods of instrumental failures and periods in which the records were not interpretable due to other factors (i.e. weather, cultural noise, etc.).

Further descriptions of the Anna array instrumentation can be found in previous annual progress reports by Mauk et al. (1979, 1980), Jackson et al. (1982) and Christensen et al. (1983).

TABLE 1

STATION CHARACTERISTICS OF THE OHIO-INDIANA SEISMIC ARRAY

Station Code	Latitude °N	Longitude °W	Elevation (Feet)	Displacement Gain (2 Hz) (x1000)	Carrier (MHz)	Subcarrier (Hz)
AN1	40.4792	84.1309	1003.	246.7	164.0093	1700
AN3	40.5489	83.8121	1070.	246.7	165.8093	1400
AN4	40.2222	83.8978	1134.	246.7	173.1940	1400
AN7	40.8235	83.8602	922.	493.4	171.4060	1700
AN8	40.2441	84.2860	992.	246.7	166.4218	680
AN9	40.7118	84.4967	835.	246.7	167.8090	2040
AN10	40.4729	84.4700	901.	246.7	167.1937	1020
AN11	40.5638	84.6804	895.	246.7	166.6565	1020
AN12	40.9217	84.1823	741.	493.4	163.7937	2040
IN1	40.542	85.894	837.	84.7		680
IN2	39.939	86.783	872.	84.7		1020
IN3	39.265	85.785	722.	84.7		1400
IN4	39.570	84.903	1025.	84.7		1700
ACM	42.6475	85.8517	880.	42.3		1700
AAM	42.2997	83.6561	817.	12.5		

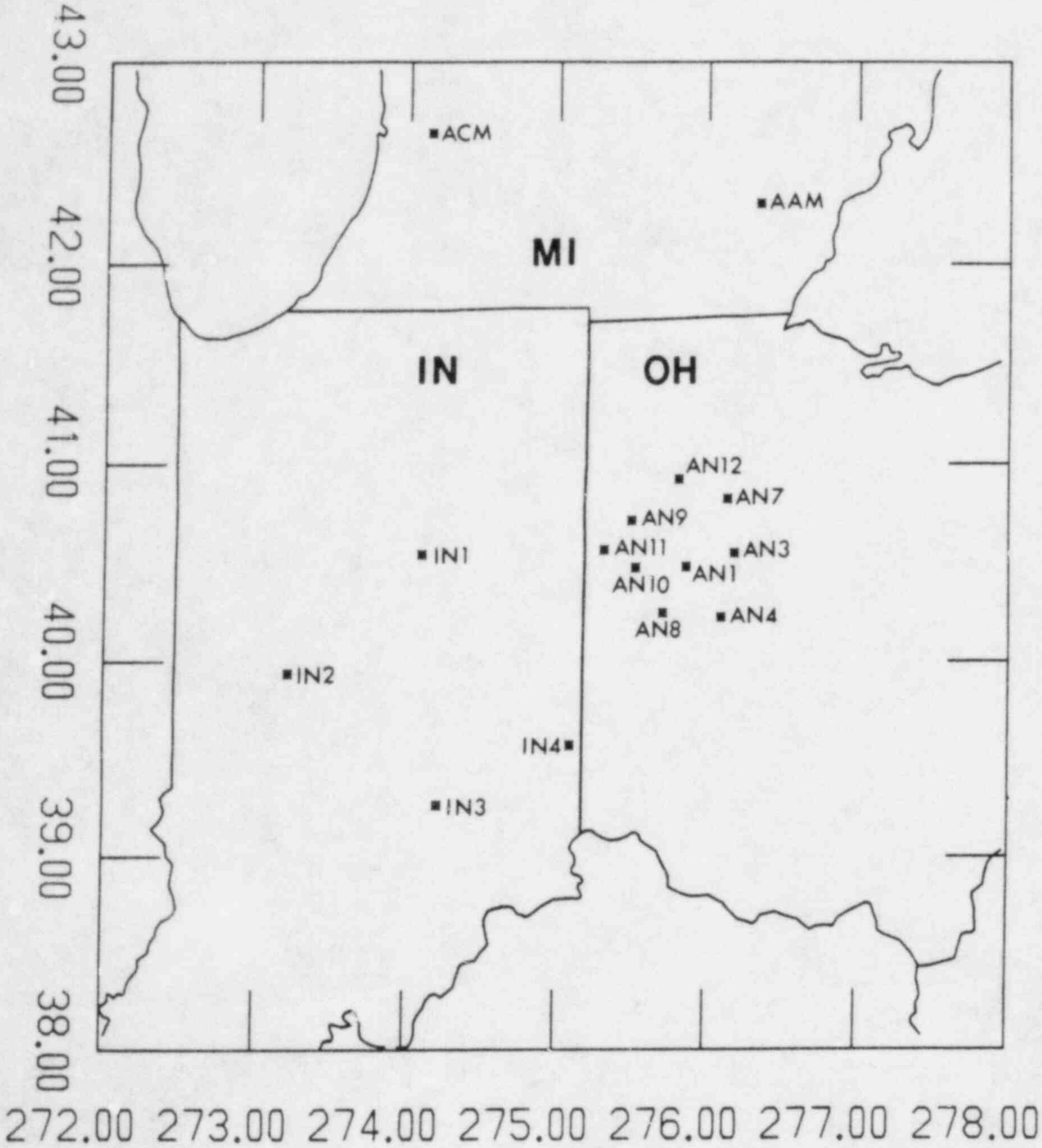


Figure 1. Station Locations for the Ohio-Indiana Seismic Array

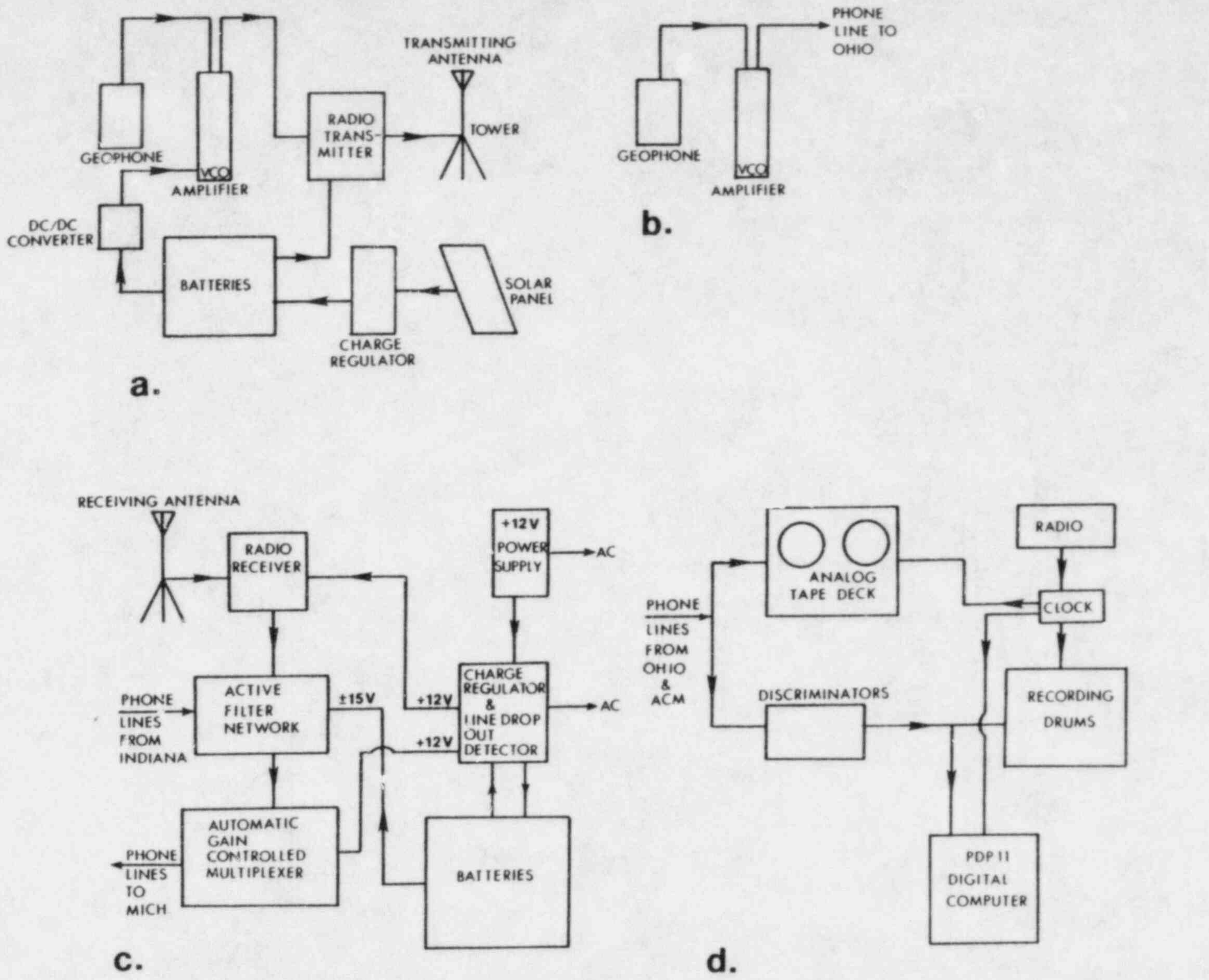


Figure 2. Schematics of Field Installations, Multiplexing and Recording Facilities (see legend, following page).

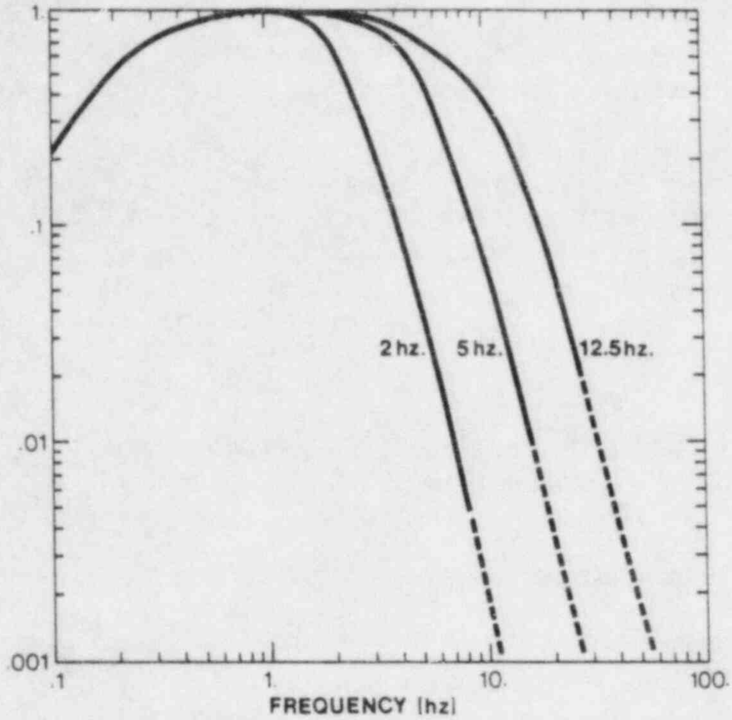
a. GEOPHONE - Geospace HS-10-1, 1 Hz, .7 critical damping
AMPLIFIER VCO - Interproducts
RADIO TRANSMITTER - Delco Radio Transmitter
TRANSMITTING ANTENNA - Db Products, 7db gain antenna
TOWER - TRI-X radio tower
BATTERIES - Delco 1150
DC/DC CONVERTER - constructed inhouse
CHARGE REGULATOR - Solarex SR012075AF, 75 watts
SOLAR PANEL - Solarex 6600/12 H. Solar cell system with 66 watts DC peak power output

b. GEOPHONE - Mark Products L-4C, 1 Hz, .7 critical damping
AMPLIFIER VCO - Interproducts

c. RECEIVING ANTENNAS - Db Products, 7db gain antennas, mounted on a 300 foot tower
RADIO RECEIVERS - Repco Radio Receiver
ACTIVE FILTER NETWORK
AUTOMATIC GAIN CONTROLLED (AGC) MULTIPLEXER
POWER SUPPLY - Power Mate PT 15 C.
CHARGE REGULATOR
BATTERIES - MDP5 NICAD

d. ANALOG TAPE DECK - Hewlett-Packard 3964A
DISCRIMINATORS - Teledyne Geotech 46.12
RADIO - Kinemetrics Model WVTR Mark IV
CLOCK - Teledyne Geotech TG-120
RECORDING DRUMS - Sprengnether, VR-65-3 (3) and VR-55-3 (2)
PDP 11 DIGITAL COMPUTER - DEC PDP-11 Model 23 Minclab digital computer

Figure 2 (Legend)



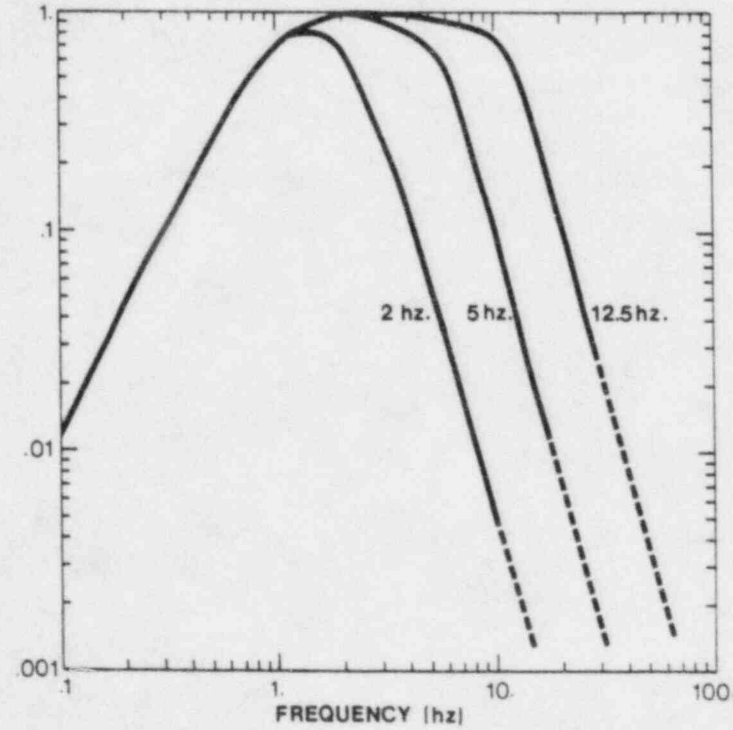


Figure 3. Unity Gain Frequency Responses for the Seismic Network (upper, Ohio stations - lower, Indiana stations)

TABLE 2

STATION RELIABILITY DATA (%)

Month	AN1	AN3	AN4	AN7	AN8	AN9	AN10	AN11	AN12	IN1	IN2	IN3	IN4	ACM	Monthly Total
OCT 1983	100	100	100	98	99	99	96	99	99	96	0	0	100	97	85
NOV 1983	100	72	91	97	99	98	74	98	71	91	95	37	45	86	82
DEC 1983	98	33	88	98	98	97	80	97	86	93	92	70	0	98	81
JAN 1984	99	70	99	98	99	99	67	99	99	97	99	51	0	98	84
FEB 1984	100	86	93	99	99	97	12	98	78	97	98	3	0	100	76
MAR 1984	96	98	97	98	87	100	4	100	0	94	97	97	71	100	81
APR 1984	100	100	99	99	98	99	93	99	56	95	100	96	100	100	95
MAY 1984	100	100	32	100	100	100	100	100	100	100	100	100	96	100	95
JUN 1984	100	100	10	100	100	100	100	100	70	99	93	83	79	66	86
JUL 1984	100	100	100	100	100	100	100	100	9	99	56	53	89	0	79
AUG 1984	100	96	100	100	100	100	66	100	0	100	100	100	100	32	85
SEP 1984	100	100	100	56	100	100	100	100	0	100	100	100	100	100	90
Station Total	99	88	84	95	98	99	74	99	56	97	86	66	65	81	Total 85

Local and Near-Regional Events
(September 1983 - September 1984)

During the report period (September 1983 - September 1984) twelve earthquakes were recorded in the region. The location of these events are shown in Figure 4, and their origin times, epicenters, and estimated magnitudes listed in Table 3. The magnitudes of these events range from 0.3 to 4.0 m_{blg}. Events which occurred on January 14, 1984 in Toledo, Ohio (magnitude = 2.6 m_b) and on July 28 and August 29, 1984 south to southeast of Terre Haute, Indiana (magnitude = 4.0 and 3.2 m_{blg}, respectively) were felt; however, no major damage was reported.

The event of January 14, 1984 that occurred near Toledo, Ohio had a magnitude of approximately 2.6 m_b and was felt by many Toledo residents. Two additional events were recorded in the Toledo area during the fiscal year. The event on December 7, 1983 is located very close to the January 14, 1984 event. However, its location is not well constrained due to a temporary timing problem (clock failure) with the array. The second event occurred about 70 kilometers west of Toledo on September 30, 1983.

Four earthquakes were located in central and western Indiana, including one on the Indiana-Illinois border. These events are of particular interest because they are the first to be recorded in Indiana since the installation of the Indiana array in 1981. In addition, the epicentral locations are near the extreme northeastern extension of the Wabash valley fault system. Three of these events, including the two felt events on July 28, 1984 and August 29, 1984 occurred about 35 kilometers south-southeast of Terre Haute, Indiana (one on the Indiana-Illinois border). The fourth event occurred approximately 30 kilometers southeast of Indianapolis, Indiana. The event on July 28, 1984 with a magnitude of 4.0 m_{blg} is the largest regional event recorded during the report period. Reports indicate that it was felt up to a radius of about 40 kilometers with a maximum intensity of V near the epicenter in Clay City, Indiana. A digital blow-up of this event is plotted in Figure 5. The event on August 29, 1984 with a magnitude of 3.2 m_{blg} was felt in a much smaller region but with a similar maximum intensity of V near Clay City, even though the epicentral location is about 20 kilometers to the west. (Intensity information was taken from the PDE bulletin, published by the National Earthquake Information Service).

An event on December 3, 1983 which occurred north of Chicago, Illinois near the Illinois-Wisconsin border was well outside the array and was recorded at only three stations. The location of this event is very poor and could be in error by up to 50 kilometers.

The four remaining events occurred in the central portion of the array near Anna, Ohio, all with magnitudes of less than one. This makes a total of twelve events which have occurred in that small region since recording began in 1976.

There have now been a total of 28 local and near regional events recorded by the Ohio-Indiana array since its initiation in 1976, five of which have been felt. This does not include the July 27, 1980 Sharpsburg, Kentucky event (m_b = 5.1) which was well outside the array. The only felt event that has occurred in the historic Anna Seismic Zone since the inception of the array was on June 17, 1977. At the time of this event only two of the local Ohio stations had been installed, making the event

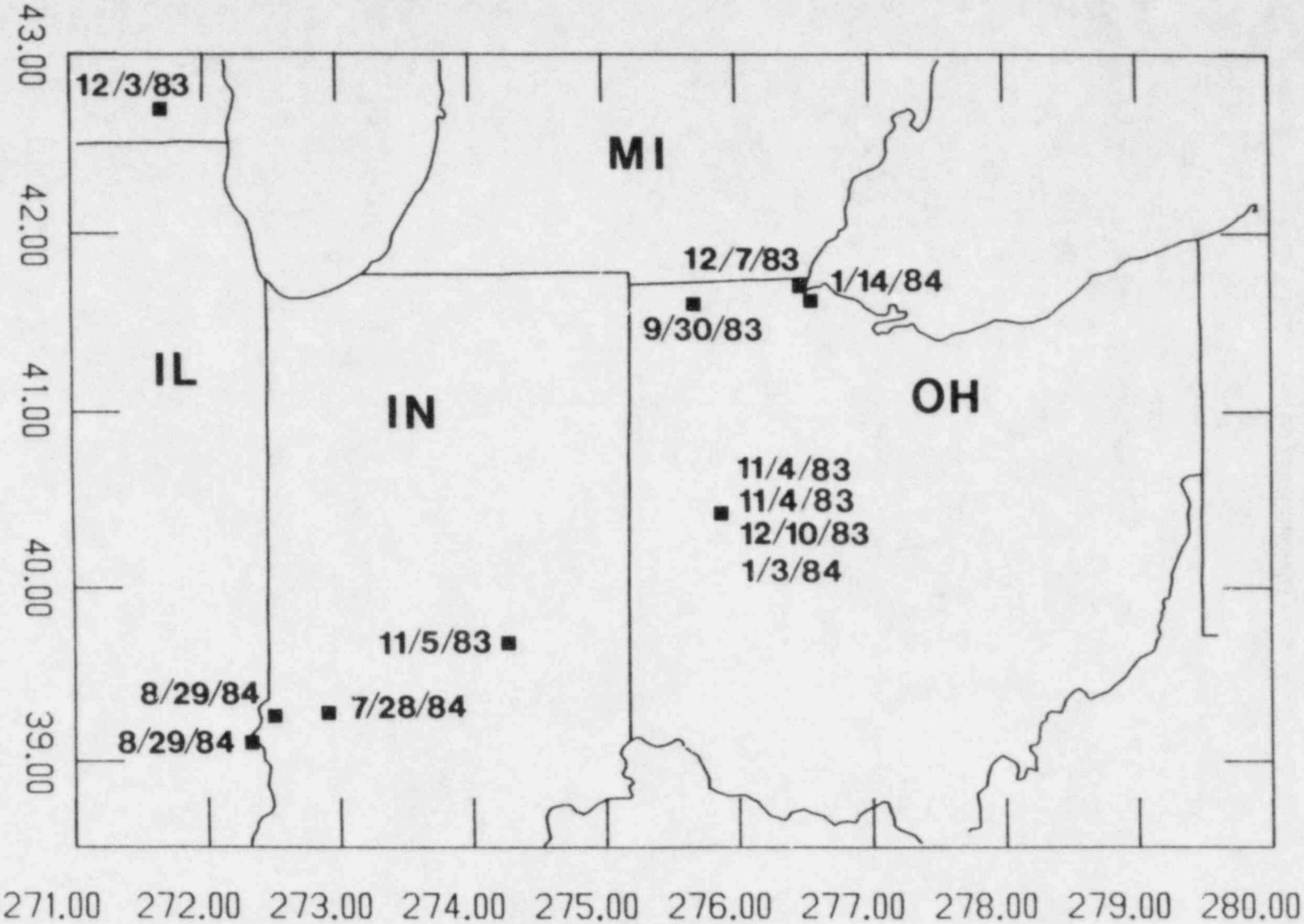


Figure 4. Local and Near-Regional Earthquake Locations from September, 1983 through September, 1984.

TABLE 3

LOCAL AND NEAR-REGIONAL EVENTS FROM
SEPTEMBER 1983 THROUGH SEPTEMBER 1984

Date Year Mo Da	Origin Time Hr Mi Sec (GMT)	Location Latitude °N	Longitude °W	Magnitude (duration)	Depth (km)
1983 09 30	02:33:44.8	41.59	84.33	1.2-1.4	--
1983 11 04	21:00:59.8	40.43	84.10	0.3-0.5	--
1983 11 04	22:50:00.5	40.43	84.10	0.8-1.0	--
1983 11 05	02:36:35.8	39.68	85.73	0.9-1.2	--
1983 12 03	21:29:41.0	42.7	88.3	1.3-1.5	--
1983 12 07	22:57:01.6	41.7	83.5	1.0-1.2	--
1983 12 10	19:01:55.2	40.43	84.11	0.6-0.8	--
1984 01 03	07:57:58.6	40.42	84.11	0.3-0.5	--
1984 01 14	20:14:32.1	41.63	83.44	2.6 m_b	--
1984 07 28	23:39:27.3	39.27	87.09	4.0 m_{blg}	--
1984 08 29	06:50:59.0	39.25	87.50	3.2 m_{blg}	--
1984 08 29	18:56:27.2	39.09	87.69	2.7 m_{blg}	--

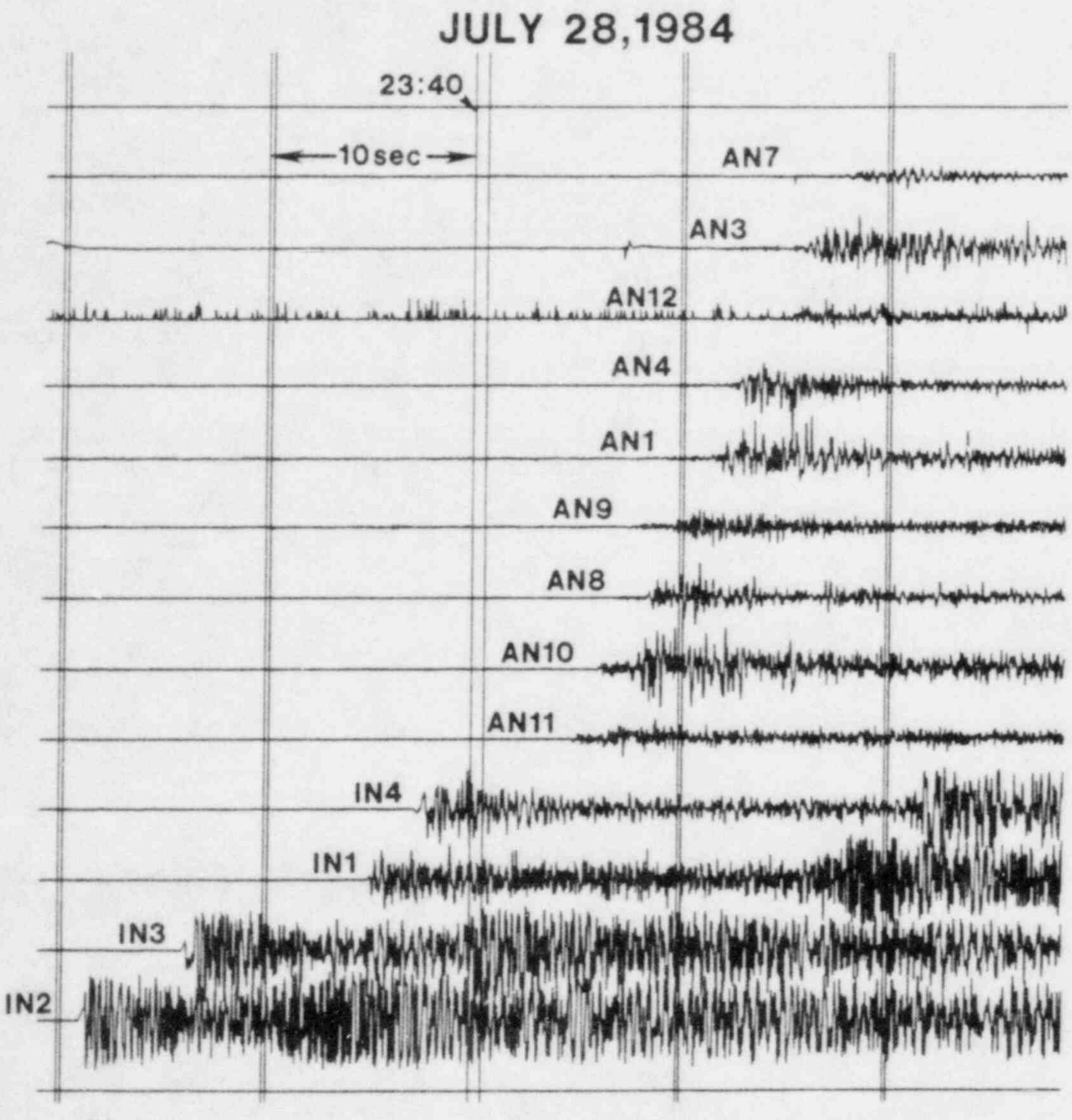


Figure 5. Digitized Event Recorded by the Ohio-Indiana Array, July 28, 1984. Stations AN3, AN9, AN11, and IN3 are plotted with reversed polarity.

difficult to locate. Although there were several reported arrivals from stations at distances greater than 200 kilometers, the final location as reported by NEIS and ISC is not well constrained. The NEIS location of 40.7 °N x 84.6 °W (origin time 15:39:47.3) requires a residual at the closest station (AN1) of -4.0 seconds, a value that is an order of magnitude larger than residual values found at similar distances for recent array locations. Arrival times at regional stations for an event of this size are often complicated by the misinterpretation of P_n and P_g arrivals. In several of our previous reports we show a location for this event in Grand Lake, based partially on felt reports.

We have relocated the June 17, 1977 event using just the local P and S arrivals. In lieu of a good S wave velocity structure, we have plotted the S-P travel time curve shown in Figure 6 from P and S arrivals of well-located local and near-regional events. The best fit line in Figure 6 has a slope of .119 sec/km and a y-intercept of .191 seconds with a .99 correlation coefficient. Four stations were used to relocate the 1977 event. The S-P times and corresponding distances are listed in Table 4. The distance ranges shown were calculated using an error of ±.5 seconds for each S-P time. The location of the 1977 event was graphically determined to be at 40.57 °N x 84.67 °W by the very tight intersection of arcs from the four stations with a possible error of about 5 kilometers. This locates the epicenter of the June 17, 1977 event about 9 kilometers west of Grand Lake and about 17 kilometers southwest of the NEIS location.

A complete listing of all local and near-regional events located by the University of Michigan since 1977 can be found in Table 5 and are displayed in Figure 7. A detailed plot of the events in the west-central Ohio region are illustrated in Figure 8.

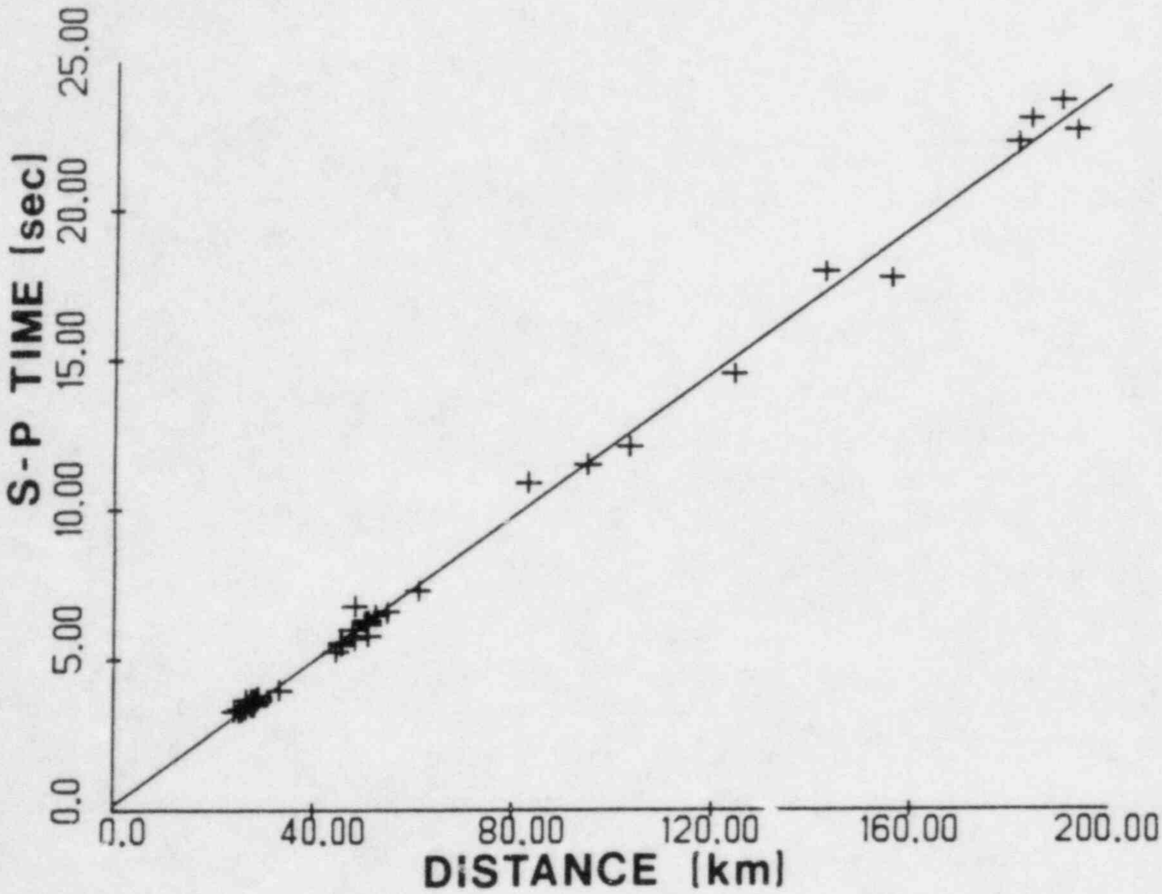


Figure 6. S-P Times versus Distance Plot for Local and Near-Regional Events.

TABLE 4

S-P TIMES AND CORRESPONDING DISTANCES
FOR THE JUNE 17,1977 CELINA EARTHQUAKE

Station	S-P Time (sec)	Distance (km)
AN1a*	6.0 ± .5	48.6 ± 4.2
AN3	8.8 ± .5	72.1 ± 4.2
BGO	15.0 ± .5	124.0 ± 4.2
AAM	25.5 ± .5	212.0 ± 4.2

* Station AN1a was a predecessor of the current station AN1 and has a slightly different location.
The location of AN1a is 40.4310 °N. x 84.1240 °W.

TABLE 5

LOCAL AND NEAR-REGIONAL EVENTS FROM
JUNE 1977 THROUGH SEPTEMBER 1984

Date Year Mo Da	Origin Time Hr Mi Sec (GMT)	Location Latitude °N	Longitude °W	Magnitude (duration)	Depth (km)
1977 06 17	15:39:47.3	40.57	84.67	3.3 m_b	--
1980 07 10	11:40:53.3	40.415	84.111	0.9	--
1980 08 20	09:34:53.4	41.87	82.99	3.2 m_{blg}	--
1980 09 26	12:27:25.6	40.430	84.085	0.5	--
1980 10 04	11:46:58.0	39.80	83.75	2.0	--
1980 12 10	02:30:54.3	40.43	84.11	1.2	--
1981 01 04	17:17:37.1	40.418	84.087	1.8	5-7
1981 02 07	05:45:43.0	40.417	84.087	1.8	5-7
1981 03 15	03:46:30.3	41.10	84.35	1.2	--
1981 05 15	23:15:14.0	40.88	84.34	0.8	--
1981 05 19	05:56:11.7	40.407	84.085	1.2	2-8
1982 11 26	08:25:04.9	42.17	85.48	2.0-2.5	--
1983 01 12	02:49:41.1	39.28	84.60	1.8-2.0	--
1983 01 22	07:46:59.3	41.86	81.16	2.7 m_{blg}	--
1983 07 05	02:58:52.9	40.43	84.10	2.0-2.2	5-7
1983 07 13	01:17:34.8	40.43	84.10	1.2-1.5	--
1983 09 30	02:33:44.8	41.59	84.33	1.2-1.4	--
1983 11 04	21:00:59.8	40.43	84.10	0.3-0.5	--
1983 11 04	22:50:00.5	40.43	84.10	0.8-1.0	--
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1983 12 07	22:57:01.6	41.7	83.5	1.0-1.2	--
1983 12 10	19:01:55.2	40.43	84.11	0.6-0.8	--
1984 01 03	07:57:58.6	40.42	84.11	0.3-0.5	--
1984 01 14	20:14:32.1	41.63	83.44	2.6 m_b	--
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1984 08 29	18:56:27.2	39.09	87.69	2.7 m_{blg}	--

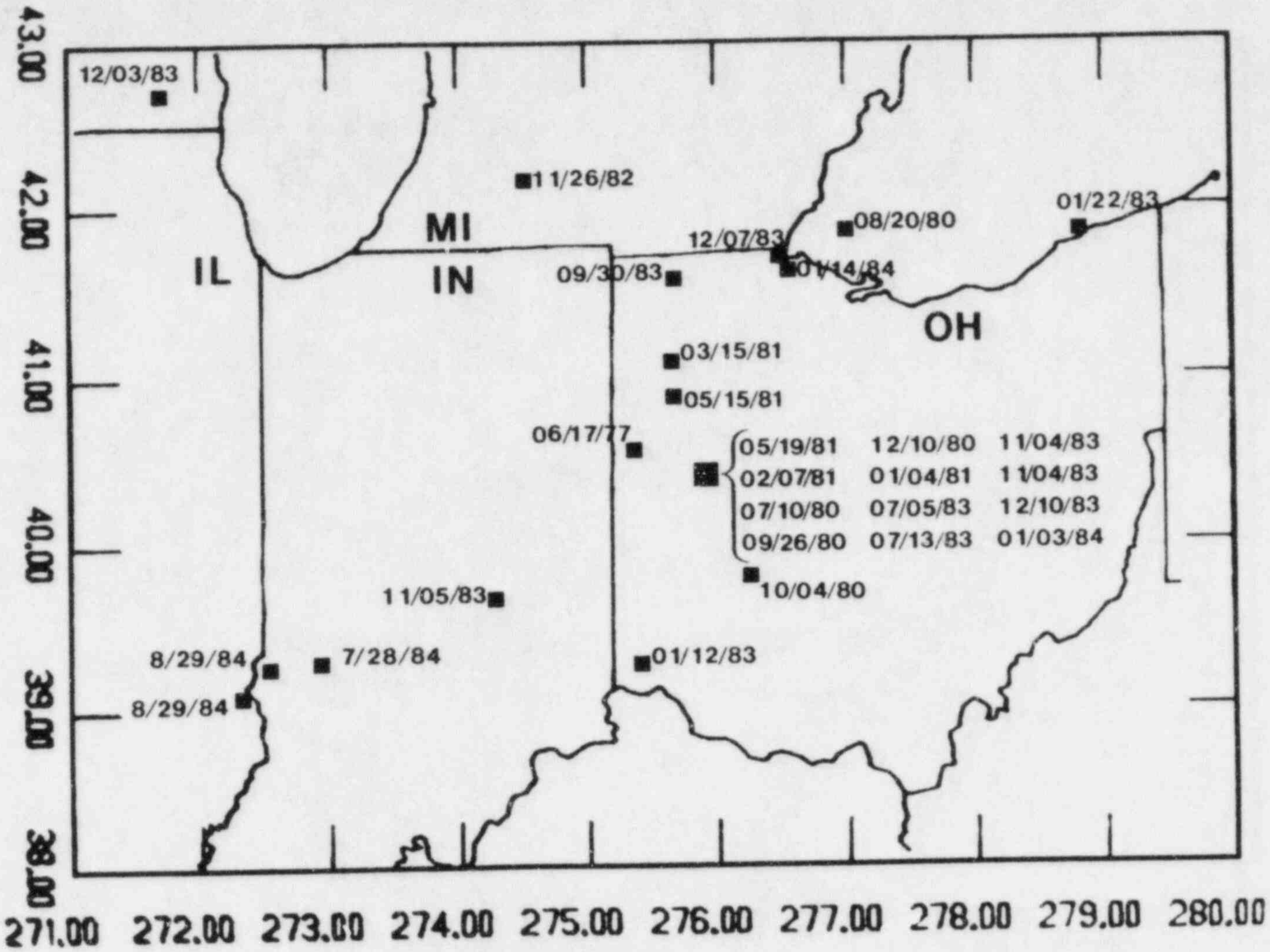

Figure 7. Local and Near-Regional Earthquake Locations from July, 1977 through September, 1984.

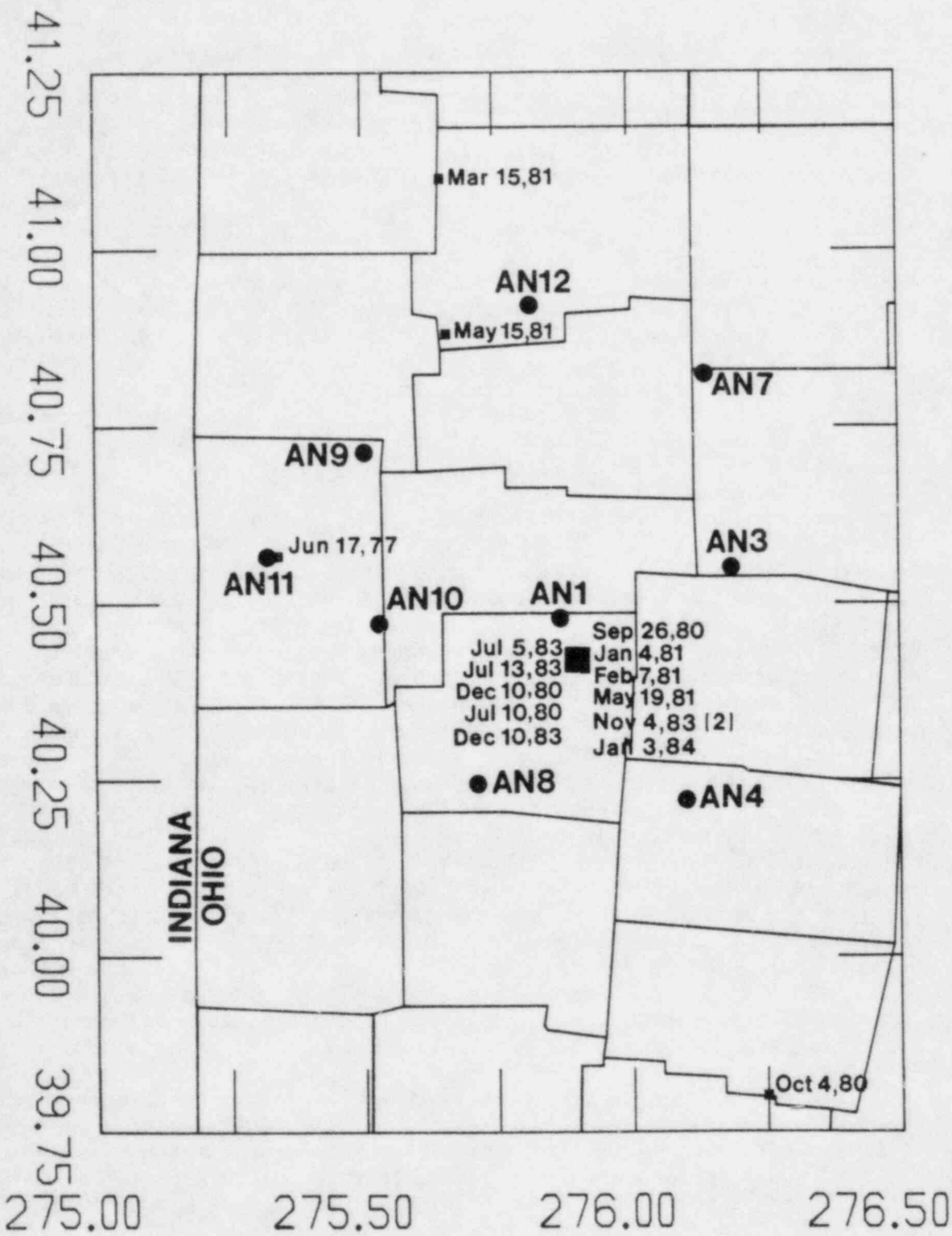

Figure 8. Local Earthquake Locations in the Anna, Ohio Region since 1977.

Teleseismic Events and P-wave Residuals

Teleseismic phase arrivals have been tabulated for almost 700 events since June 1978. The phase arrivals for each event recorded by the array between June 1978 and March 1983 are listed in Jackson et al. (1982, Appendix B), Christensen et al. (1983, Appendix A), and Pollack and Christensen (1984, Appendix B). The teleseismic phase arrivals for the period April 1983 through March 1984 are listed in Appendix B of this report.

Teleseismic P-wave residuals (observed minus J-B) have been calculated for the above events (with epicentral distance $\leq$ 102°). The calculated residual, back azimuth, distance and return angle are listed for each event in Jackson et al. (1982, Appendix C), Christensen (1983, Appendix B and C) and in Pollack and Christensen (1984, Appendix C and D) for the time period between June 1978 through March 1983. P-wave residuals calculated from events which occurred between April 1983 and March 1984 are listed in Appendix C for the nine Ohio stations (including ACM and AAM) and Appendix D for the four Indiana stations.

Average P-wave residuals have been calculated for each station using a hand-picked subset of the events. The events considered had epicentral distances between 20° and 102°. Events with residuals greater than ± 4.0 seconds or which had emergent arrivals were not used in the calculations. The residuals are listed in Table 6 for each station along with the number of values used in the average. The average residuals range from -.49 seconds at station AAM to -1.03 seconds at station IN1. Positive residuals reflect slower than average paths and negative residuals reflect faster than average paths. The average teleseismic P-wave residuals are strongly biased by the azimuthal concentrations of arrivals from the south (South America, Mexico, Caribbean) and from the northwest (Alaska, Japan) because of the large number of earthquakes at those azimuths.

The residuals were sorted by azimuth of arrival in ten degree intervals for each of the stations. The average residual at each azimuth is plotted in the histograms in Figures 9a-c. The histograms for the nine Ohio stations are very similar in appearance, with relatively small positive residuals at azimuths from 30 to 140 degrees and larger negative residuals at azimuths of 150 to 330 degrees. The histograms for the Indiana stations (IN1, IN2, IN3, IN4) are based on a much smaller data set and are therefore incomplete at many azimuths. The most consistent feature in these histograms are large negative residuals in the northern and southern azimuths.

In order to correct for the azimuthal bias in the averaged P-wave residual we have also averaged the residuals azimuthally giving equal weight to arrivals in each 10° azimuth interval. These results are also shown in Table 6. This procedure must be carefully interpreted because of the high weight which is now given to those azimuth intervals with few arrivals. It must be remembered that source effects (ie. location, origin time and source structure) have not been removed or taken into account in either of the above averaging schemes. The average P-wave residuals for each station that were calculated by averaging over all arrivals are plotted in Figure 10 and the azimuthally averaged P-wave residuals for each station are plotted in Figure 11. Both figures show the same basic pattern with the largest

TABLE 6

AVERAGE TELESEISMIC P-WAVE RESIDUALS FOR THE OHIO-INDIANA NETWORK (WITH RESPECT TO THE J-B TABLES)

Station	Average P-Wave Residual (observed minus J-B in seconds)	[equal azimuthal weighting]	Number of Observations
AN1	-.57	[-.33]	245
AN3	-.54	[-.32]	241
AN4	-.55	[-.36]	242
AN7	-.53	[-.35]	223
AN8	-.55	[-.36]	210
AN9	-.53	[-.33]	242
AN10	-.59	[-.44]	243
AN11	-.71	[-.50]	273
AN12	-.51	[-.28]	260
IN1	-1.03	[-.80]	69
IN2	-.62	[-.31]	63
IN3	-.69	[-.40]	69
IN4	-.86	[-.75]	63
ACM	-.78	[-.48]	81
AAM	-.49	[-.16]	180

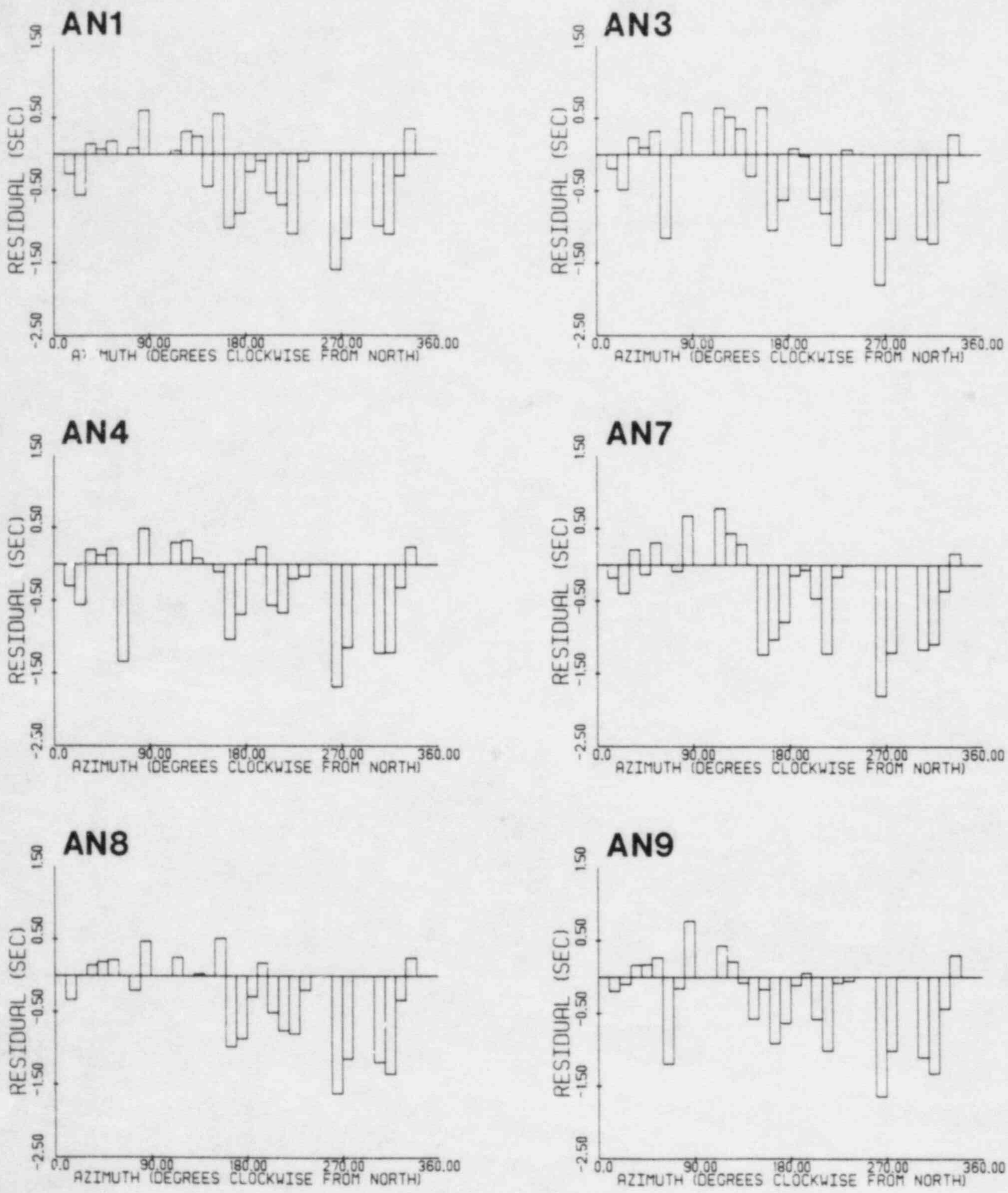

Figure 9a. Average Teleseismic P-Wave Residuals vs. Azimuth for the Ohio-Indiana Network. Stations AN1, AN3, AN4, AN7, AN8 and AN9.

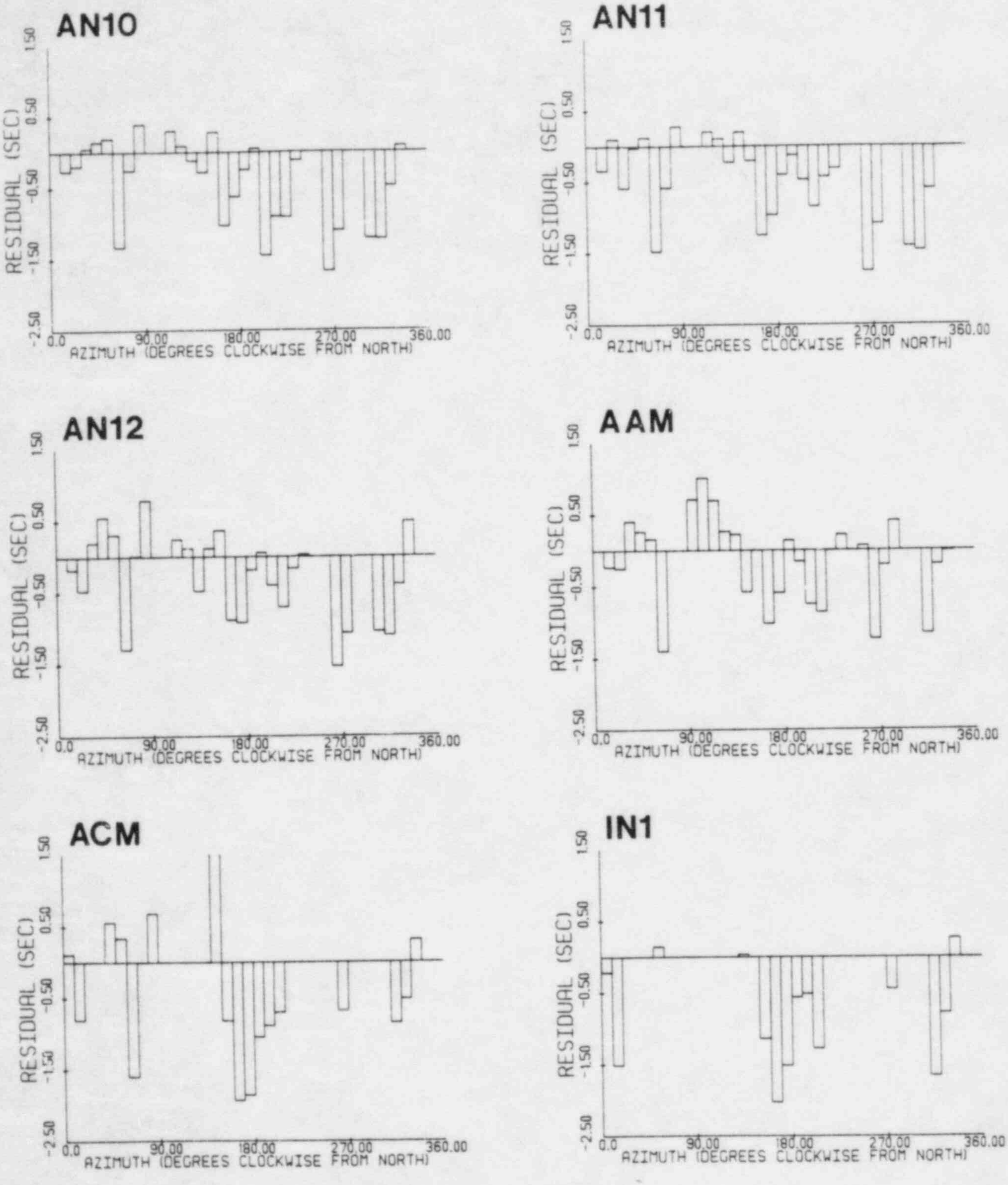

Figure 9b. Average Teleseismic P-Wave Residuals vs. Azimuth for the Ohio-Indiana Network. Stations AN10, AN11, AN12, AAM, ACM and IN1.

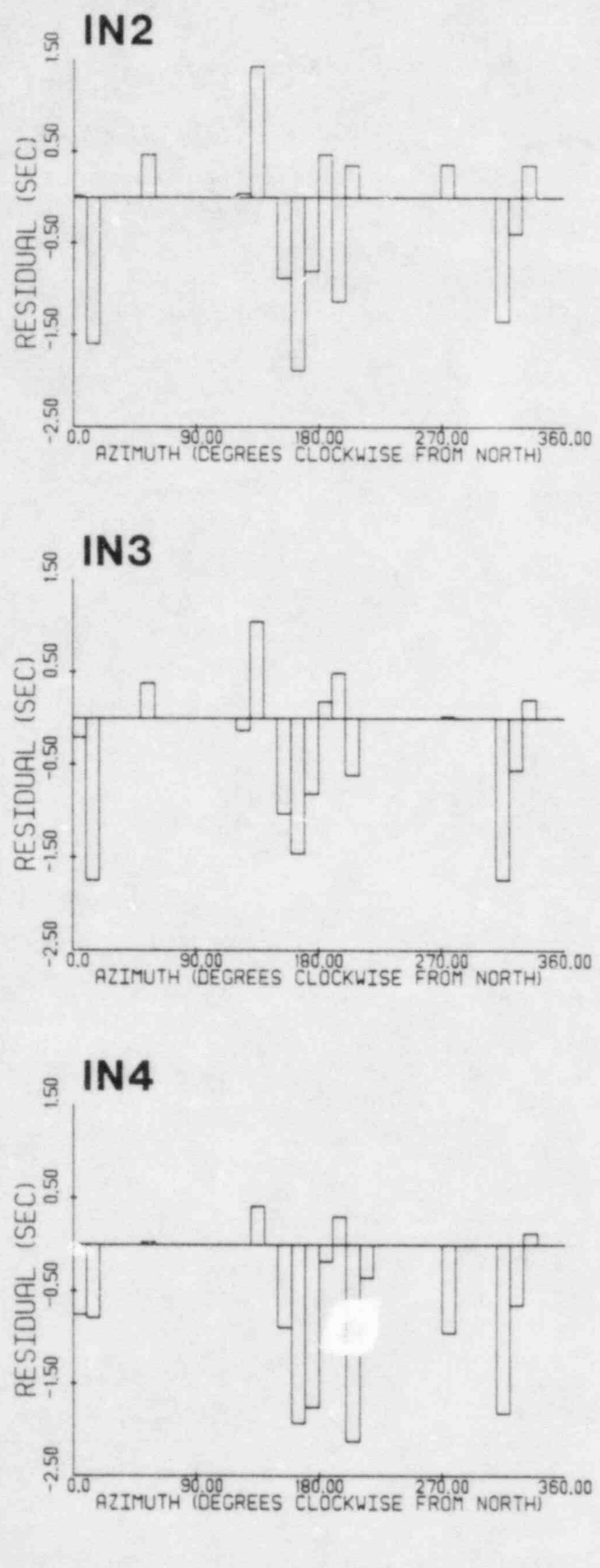

Figure 9c. Average Teleseismic P-Wave Residuals vs. Azimuth for the Ohio-Indiana Network. Stations IN2, IN3 and IN4.

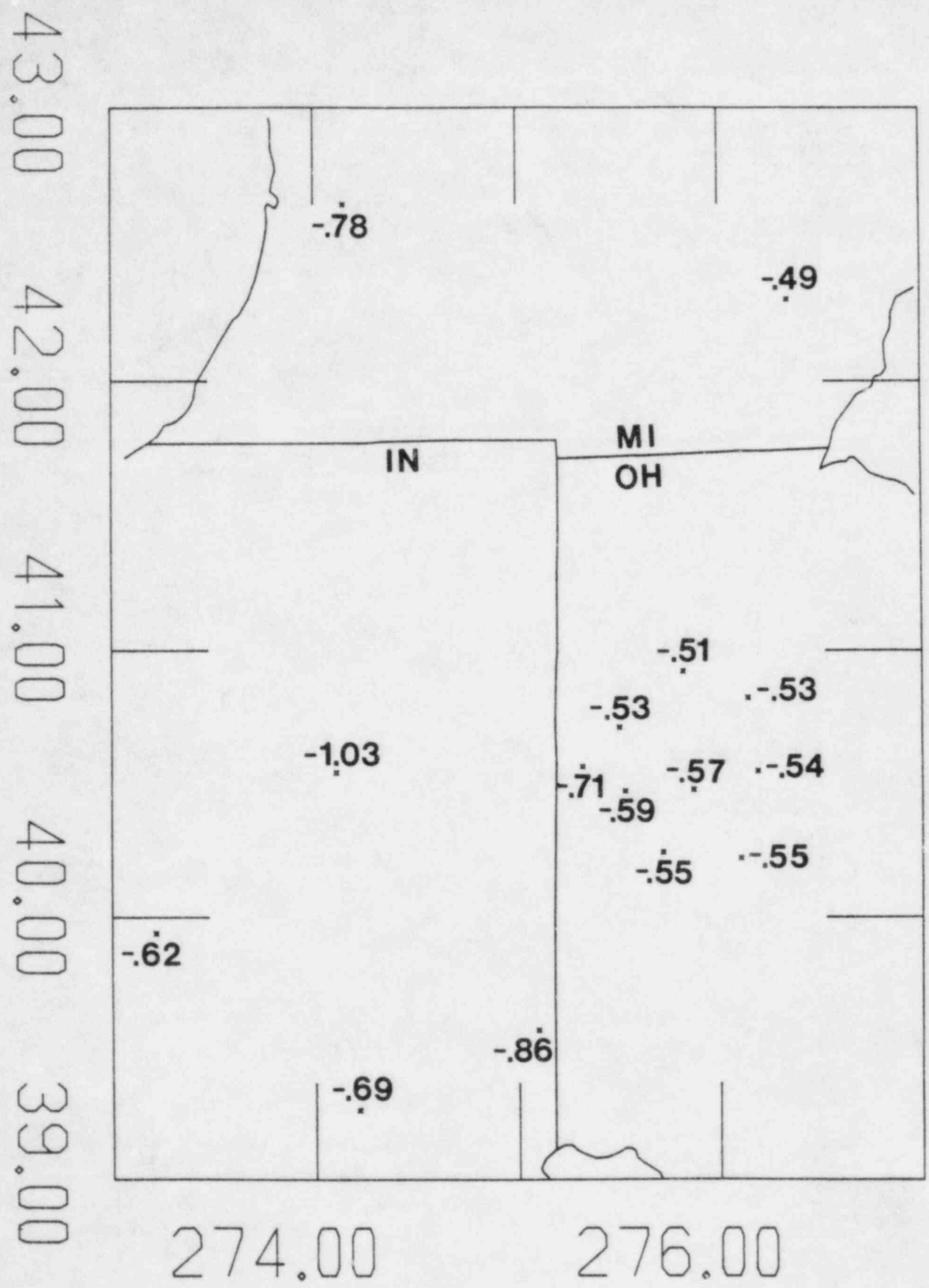

Figure 10. Average P-Wave Residuals for the Ohio-Indiana Network (with respect to the J-B tables). The residuals are averaged over all arrivals at each station.

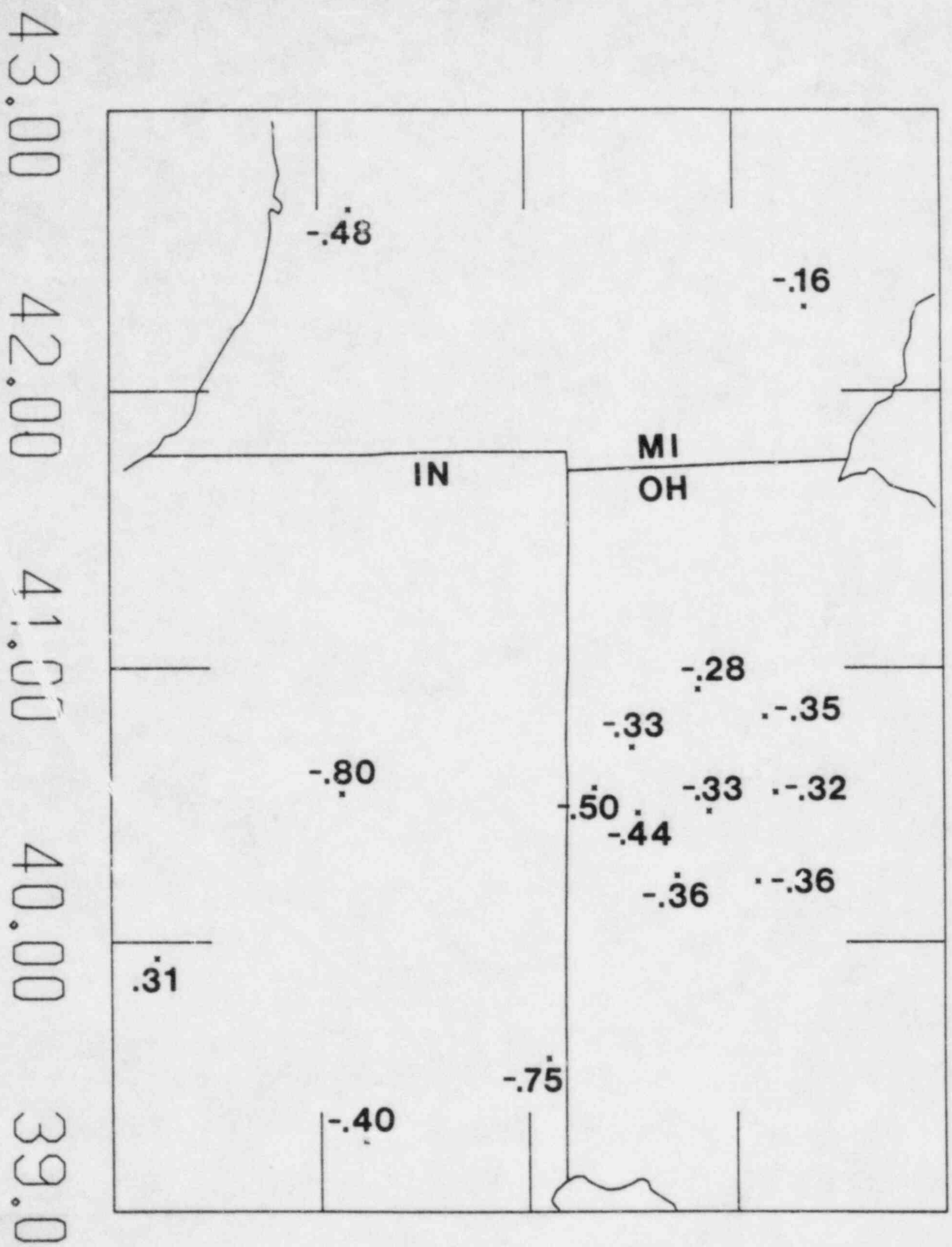

Figure 11. Average P-Wave Residuals for the Ohio-Indiana Network (with respect to the J-B tables). The residuals are azimuthally averaged over ten degree intervals at each station.

negative (fastest) values occurring in the center of the arch structure and the smallest negative (slowest) values occurring toward the basins (see Figure 12). The only major difference in the two sets of residuals is a consistent difference of about .20 seconds.

In order to remove source effects from the P wave residuals, it is convenient to look at differences in residuals between stations instead of the absolute residual values. This effectively eliminates travel time anomalies resulting from hypocentral mislocation, structure at the source, and mantle path structure since all of the rays travel essentially the same path to the stations. This leaves only the shallow heterogeneous structure beneath the stations to account for the differences. In earlier reports we arbitrarily chose the westernmost Ohio station (AN11) as the standard by which to measure the residual differences. For each station, residual differences were calculated (observed residual - AN11 observed residual). These differences were averaged over ten degree azimuth intervals for each station and are plotted in Figures 13a-c. There are several observations that can be made from these histograms. Nearly all of the values for the Ohio stations are positive, becoming larger toward the northeast. This means that the shallow velocity structure across the array changes from fastest in the western part of Ohio to slowest in the northeast. The residual differences for the Indiana stations are mostly negative, indicating faster average velocities relative to the Ohio portion of the array.

If possible, it would be desirable to invert this data set for the heterogeneous regional crustal structure using a block inversion technique (see Aki et al., 1977); however, the number of stations and their spacing do not provide adequate overlap of rays. It is still informative to look at the residuals in greater detail. To do this we have back projected each of the rays to a common depth using the appropriate back azimuth, angle of incidence and a simple velocity structure and plotted the residuals where each ray intersect the given depth in much the same manner as Haddon and Husebye (1978). The goal is to determine whether the patterns from the various stations will merge into a smooth, coherent spatial pattern at a particular depth and to see if the anomalous regions can be correlated to other geophysical measurements. We will compare our results to magnetic anomaly data. A recently published aeromagnetic map (Hildenbrand and Kucks, 1984) is shown in Figure 14 along with the locations of the Ohio seismic stations for scale. The north-south trend of magnetic highs on the eastern margin of this map are part of a larger band of magnetic highs which run north-south the entire length of Ohio. This anomaly has been suggested to be the remains of an ancient rift zone or perhaps the signature of the Grenville Front, which may run through the region (see Keller et al., 1982 and Keller et al., 1983).

In Figure 15 we have plotted the back projected relative residuals for the Ohio portion of the array (station residual - AN11 residual) to a depth of 50 kilometers. Positive residuals represent relatively late arrivals and are plotted as plus signs. Negative residuals are plotted as diamonds and represent relatively early arrivals. The size of the symbols are directly proportional to the size of the residual. Because of the large number of rays plotted on Figure 15 it is very hard to see trends in the fast and

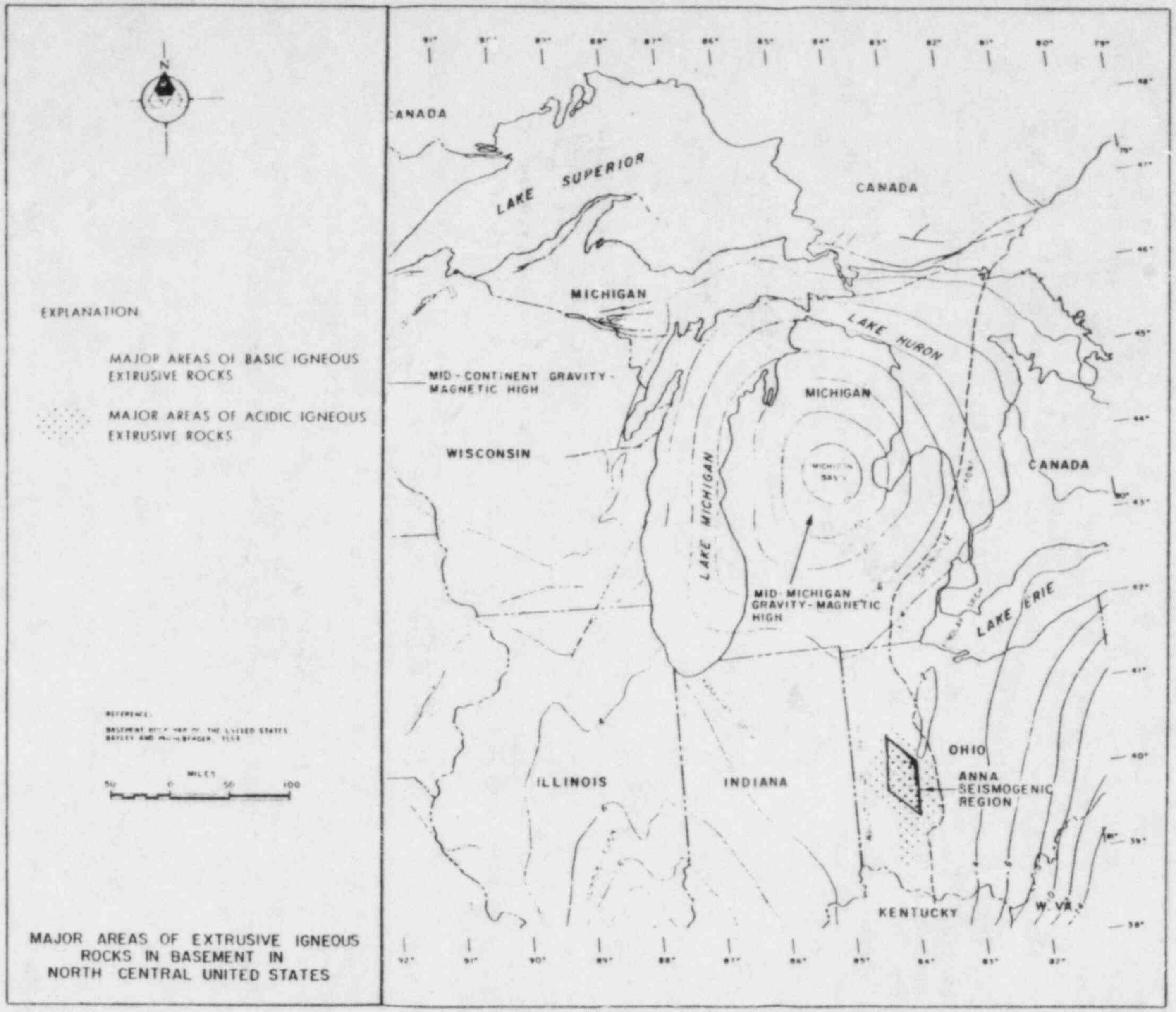

Figure 12. Basement Rock Map of North Central United States (from Bayley and Muehlberger, 1968).

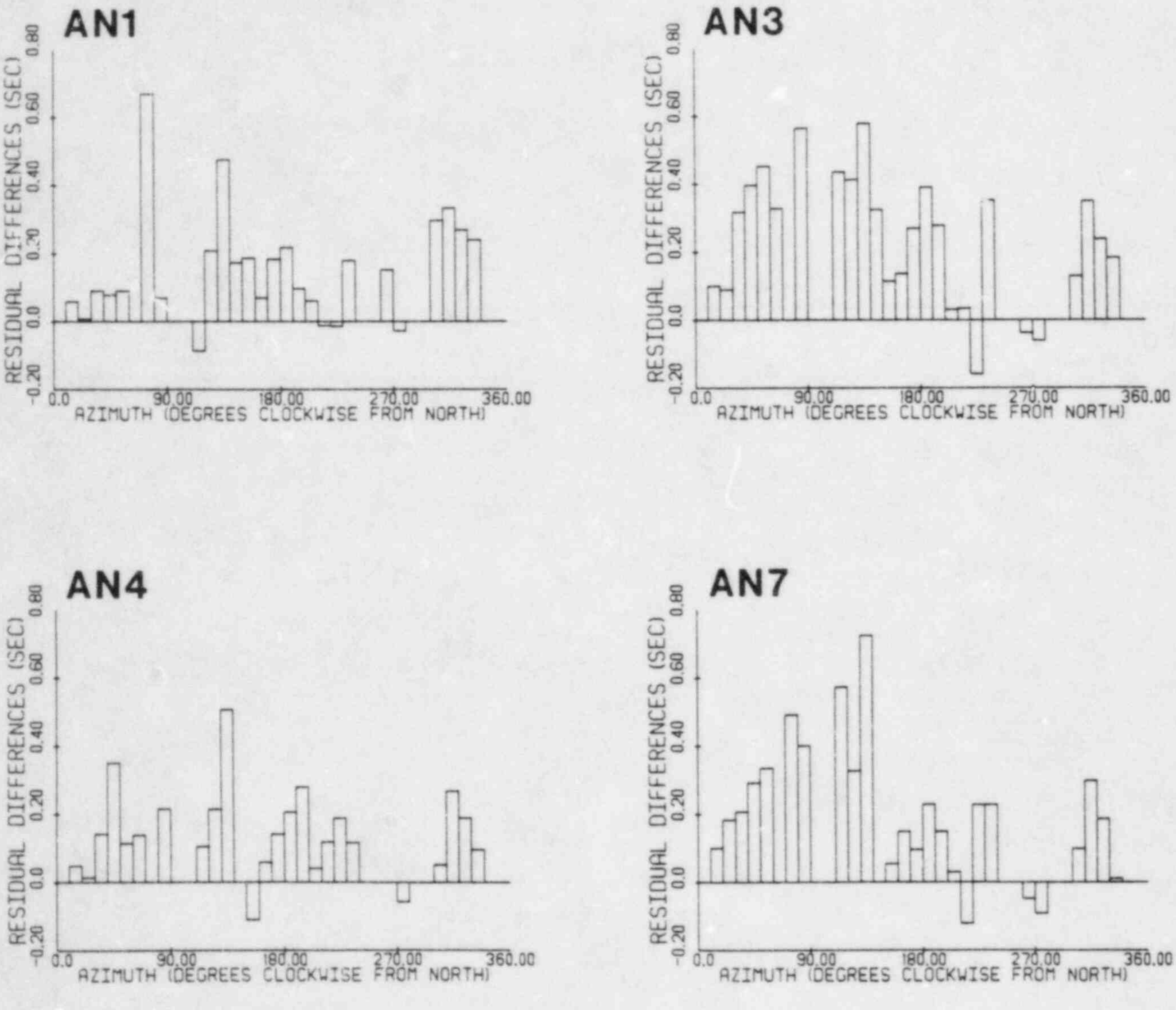

Figure 13a. Differences in P-Wave Residuals Between Stations Relative to AN11 vs. Azimuth (Station Residual - AN11 Residual). Stations AN1, AN3, AN4 and AN7.

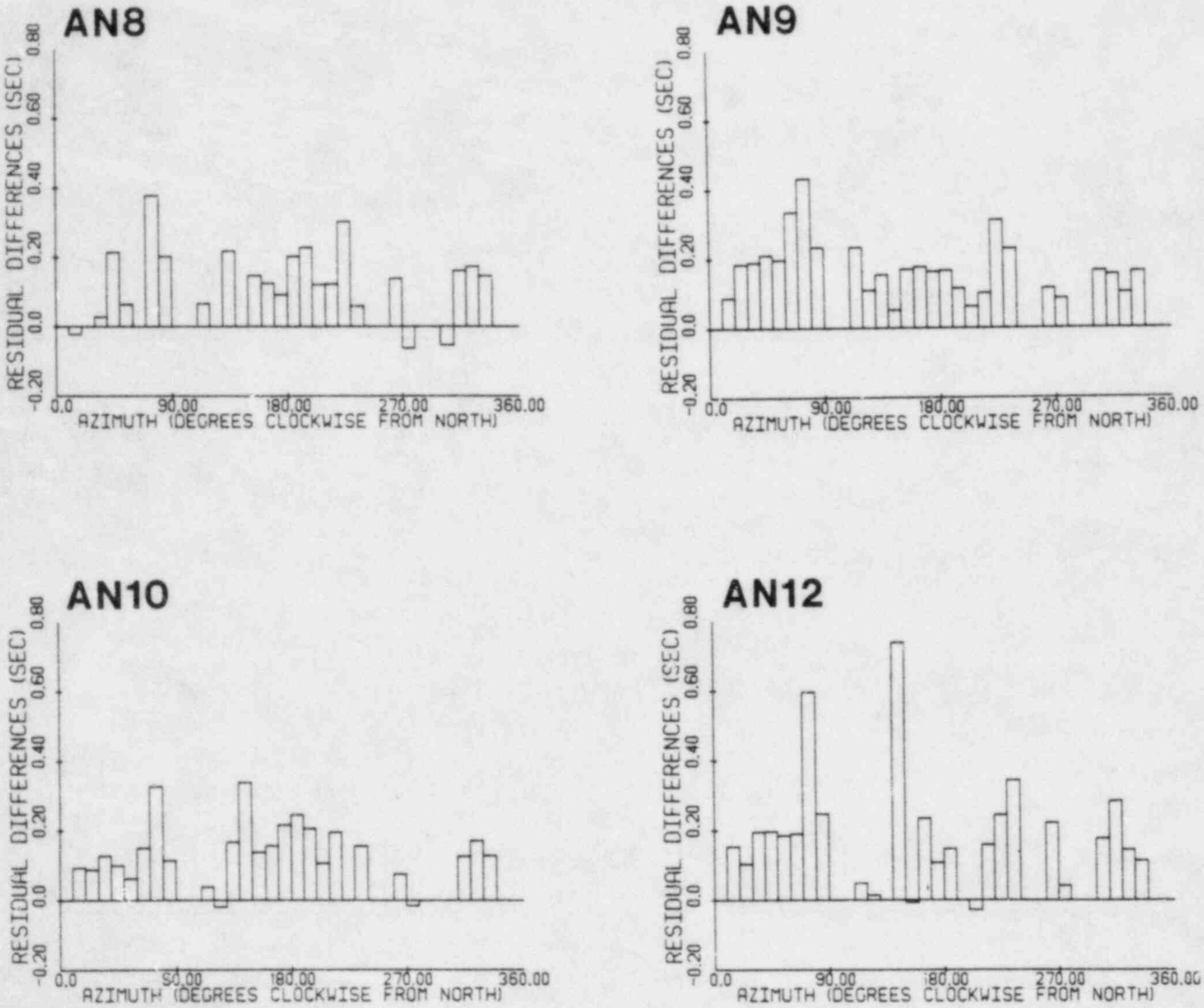

Figure 13b. Differences in P-Wave Residuals Between Stations Relative to AN11 vs. Azimuth (Station Residual - AN11 Residual). Stations AN8, AN9, AN10 and AN12.

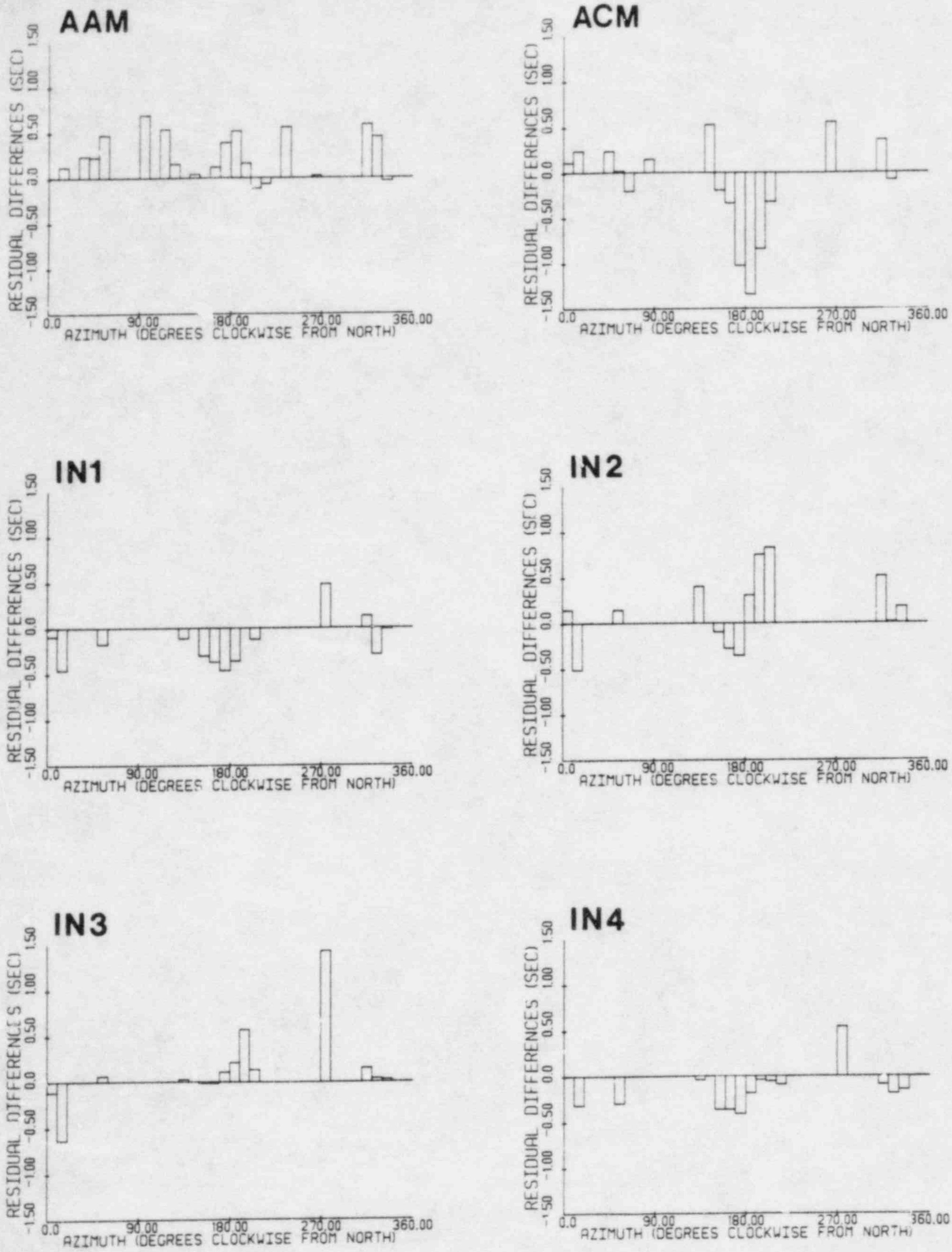

Figure 13c. Differences in P-Wave Residuals Between Stations Relative to AN11 vs. Azimuth (Station Residual - AN11 Residual). Stations AAM, ACM, IN1, IN2, IN3 and IN4.

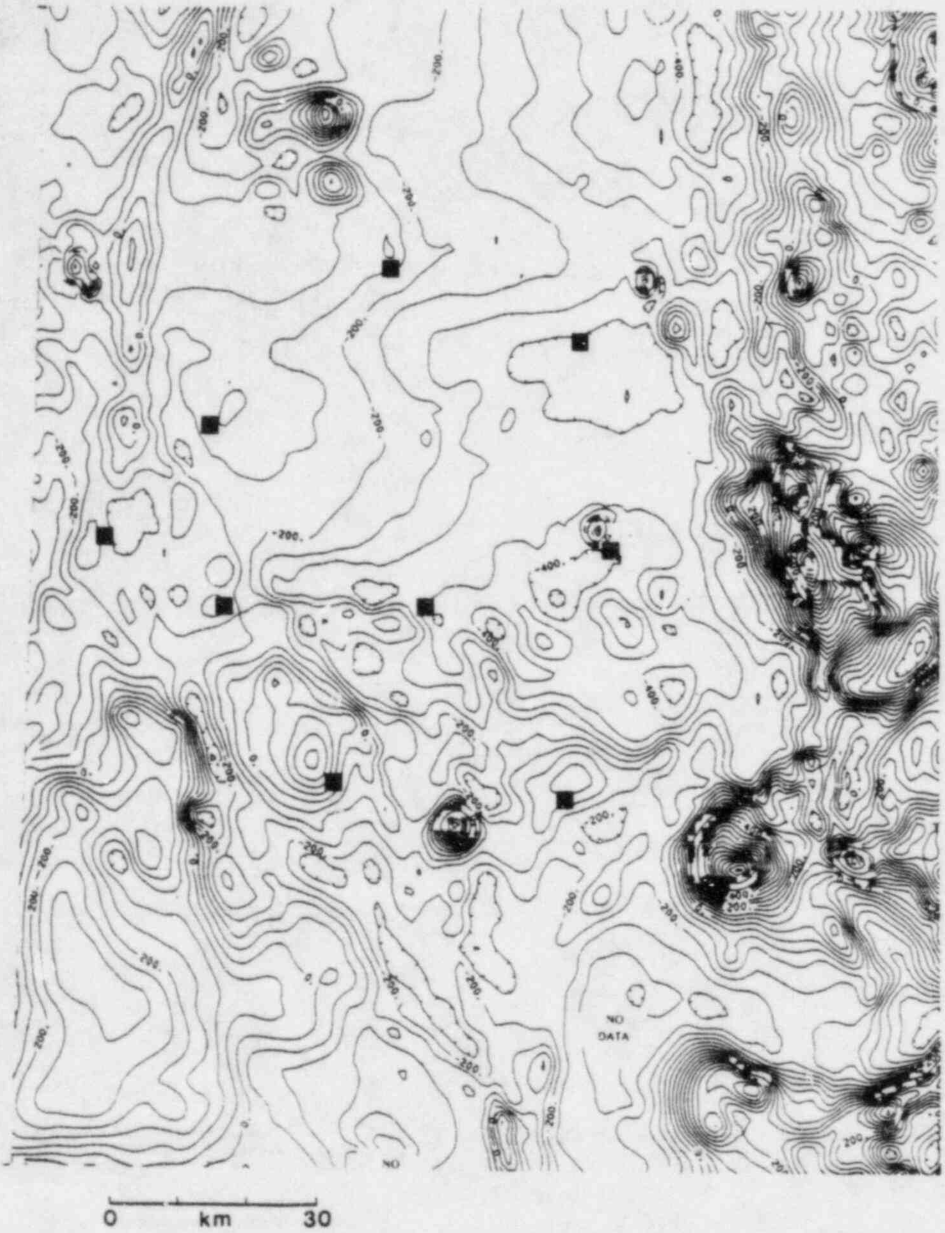

Figure 14. Aeromagnetic Map of Ohio, Residual Total Intensity Magnetic Map (from Hildenbrand and Kucks). The Ohio seismic stations are shown as solid squares. Contour interval is 50 Gammas.

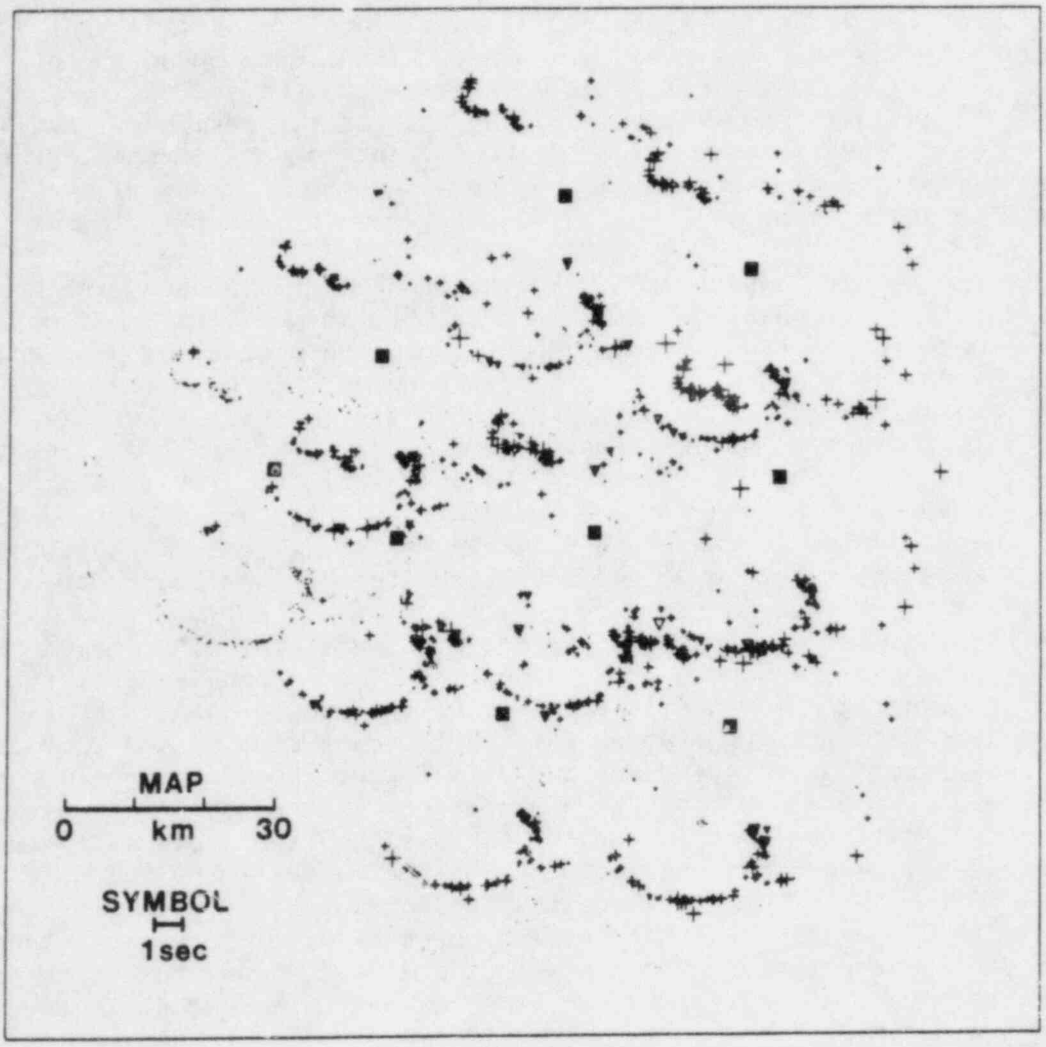

Figure 15. Back Projected Residual Differences to a Depth of 50 kilometers for the Anna, Ohio Region. The residuals are calculated using station AN11 as the base station. Positive residual differences are plotted as plus signs and negative residual differences are plotted as triangles. The size of the residuals are directly proportional to the size of the symbols. Station locations are shown as the solid squares.

slow regions. In Figure 16 we have reduced the number of points plotted in Figure 15 by averaging the relative residuals over a five by five kilometer grid and plotting the mean value in each grid element as a single symbol. The same symbol convention as in Figure 15 is used for all the following residual plots. Figure 16 is plotted at the same scale as the magnetic map (see Figure 14) so that the residuals can be visually compared to the magnetic anomaly map. The residuals in Figure 16 clearly show the gradual increase in residual from west to east, as well as the region of large positive residual differences in the extreme eastern part of the figure. In addition there is a good correlation between the very large positive residuals in the extreme eastern section of the array and the line of magnetic highs.

Thus far we have always used the station AN11 as the base line to which the residuals are calculated. As stated before, the residual differences tend to remove the source and path effects from the residuals; however, the differences do not correct for the structure around the base station. In order to see if our choice of base station biases our results we have also plotted back projected residual maps to depths of 50 kilometers using two different base stations. Residual differences were calculated using AN1 and AN10 as the base stations and these residuals are plotted in Figures 17 and 18, respectively. It can be seen in Figures 16, 17, and 18 that the general trends which have been previously pointed out are common to each of the residual difference maps.

We have pointed out that the regions of slowest velocity imaged by projecting the anomalies to 50 kilometers depth correspond well to the regions of high magnetic anomalies in Figure 14. Back projected maps of the residual differences using station AN10 as the base station and projection depths of 25 and 75 kilometers are shown in Figure 19 and Figure 20, respectively. We can see from these plots that if the source of the large positive residual anomalies is located at 25 kilometers depth in the crust, then these residuals cannot be explained by the same feature which is responsible for the high magnetic anomalies. However, if we allow the residuals to be generated at depths of 50 or more kilometers, then there is a good spatial correlation with the magnetic anomalies and thus both seismic and magnetic observations can be explained by the same feature in the lower crust and upper mantle.

It is also interesting to look at the back projected relative residuals for the complete array. These residuals have been calculated and averaged over a five by five kilometer grid using station AN10 as the base station and plotted in Figure 21. Once again the array stations have been plotted as the solid squares for orientation. The main features of the projections at this scale is the change from positive residuals around the edge of arch structure (in Ohio, Michigan, and western Indiana) to large negative residuals in the center of the platform (in central Indiana). This trend reflects the relatively fast velocities at the crest of the arch as compared to the slower velocities toward the adjacent basins.

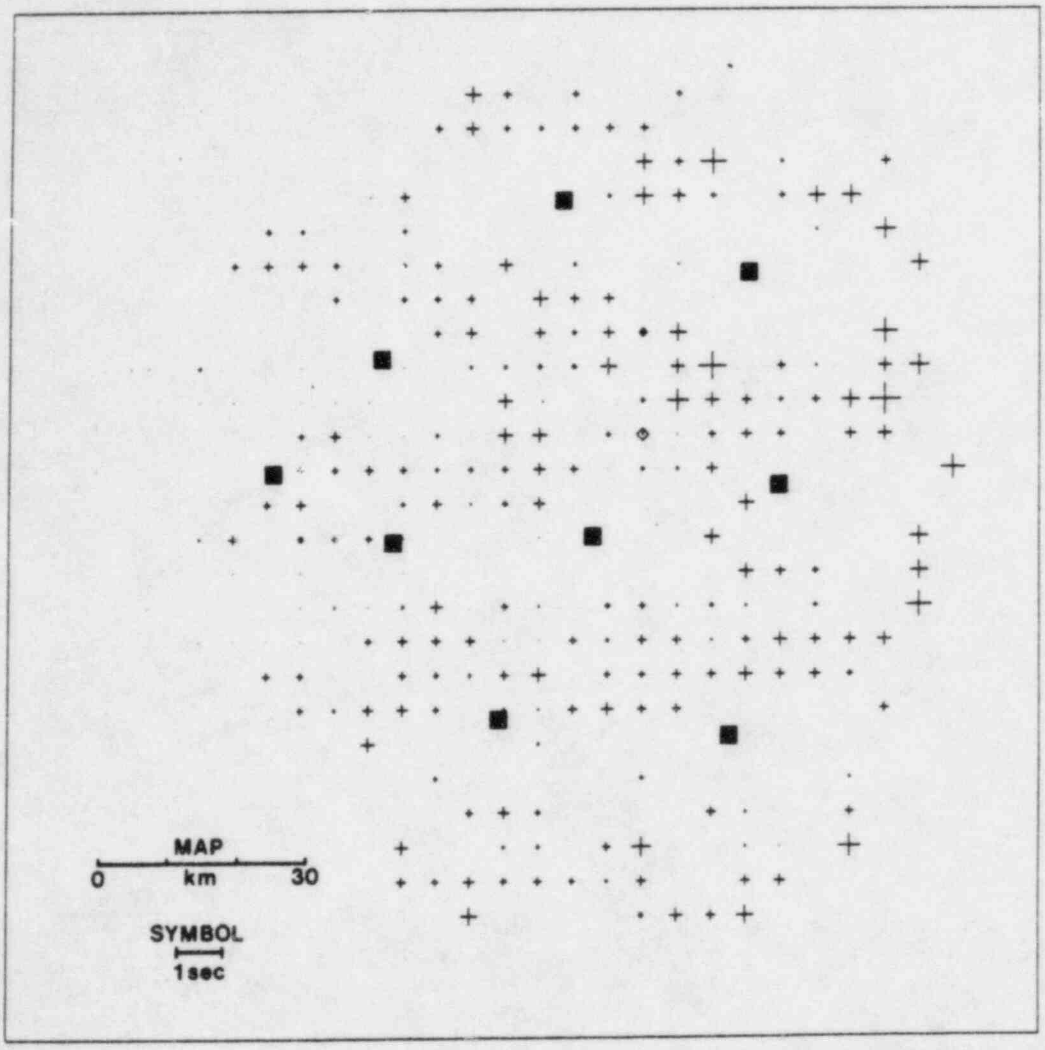

Figure 16. Back Projected Residual Differences to a Depth of 50 kilometers for the Anna, Ohio Region. The residuals are calculated using station AN11 as the base station and are averaged over a 5 X 5 kilometer grid. Positive residual differences are plotted as plus signs and negative residual differences are plotted as diamonds. The size of the residuals are directly proportional to the size of the symbols. Station locations are shown as the solid squares.

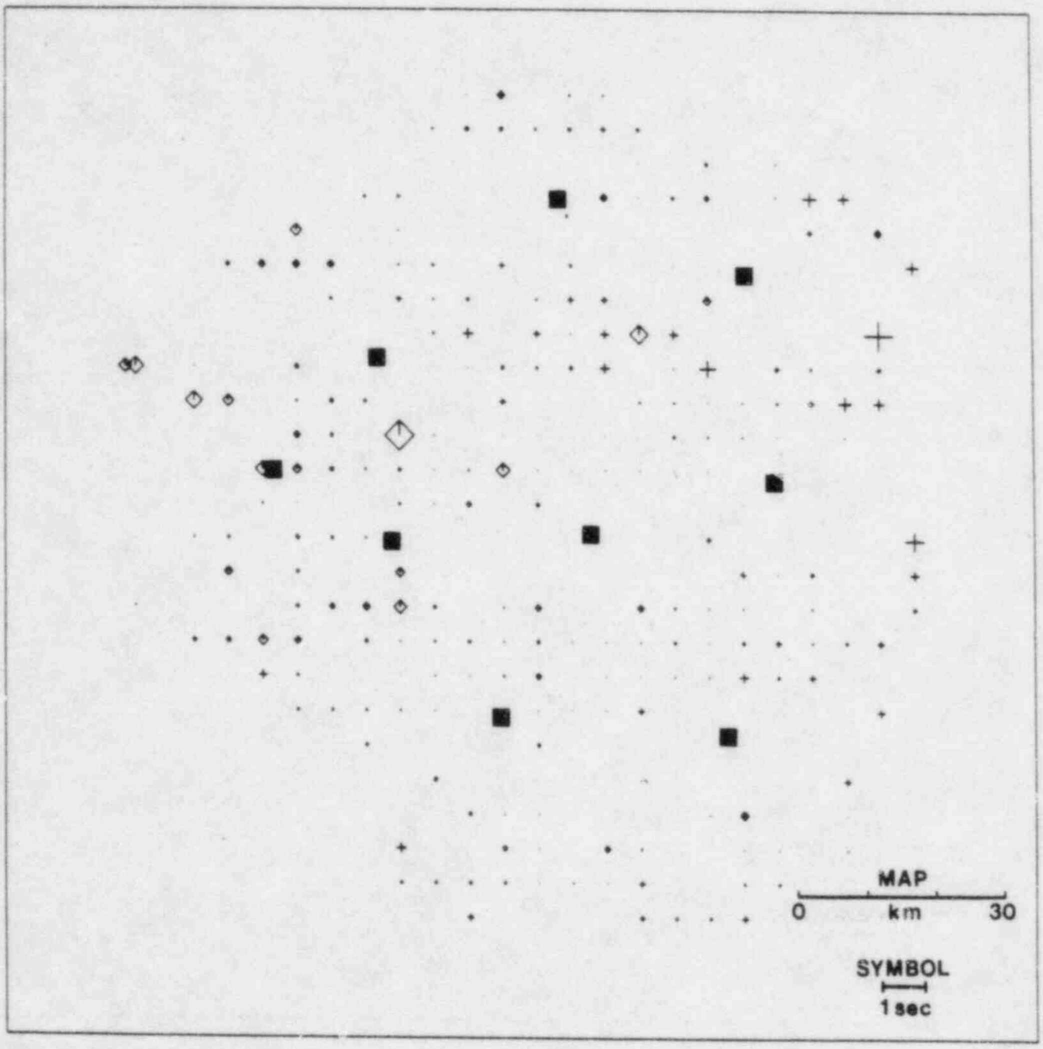

Figure 17. Back Projected Residual Differences to a Depth of 50 kilometers for the Anna, Ohio Region. The residuals are calculated using station AN1 as the base station and are averaged over a 5 X 5 kilometer grid. Positive residual differences are plotted as plus signs and negative residual differences are plotted as diamonds. The size of the residuals are directly proportional to the size of the symbols. Station locations are shown as the solid squares.

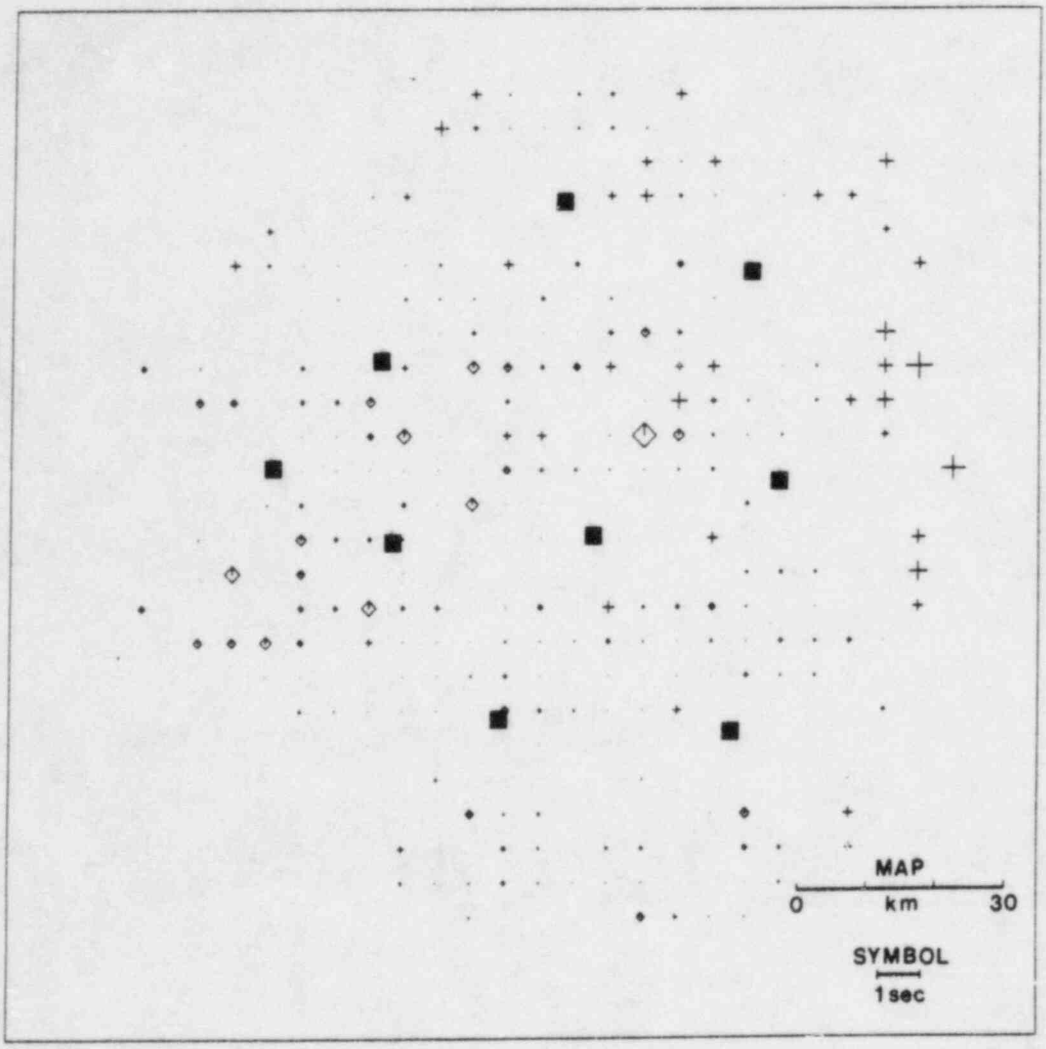

Figure 18. Back Projected Residual Differences to a Depth of 50 kilometers for the Anna, Ohio Region. The residuals are calculated using station AN10 as the base station and are averaged over a 5 X 5 kilometer grid. Positive residual differences are plotted as plus signs and negative residual differences are plotted as diamonds. The size of the residuals are directly proportional to the size of the symbols. Station locations are shown as the solid squares.

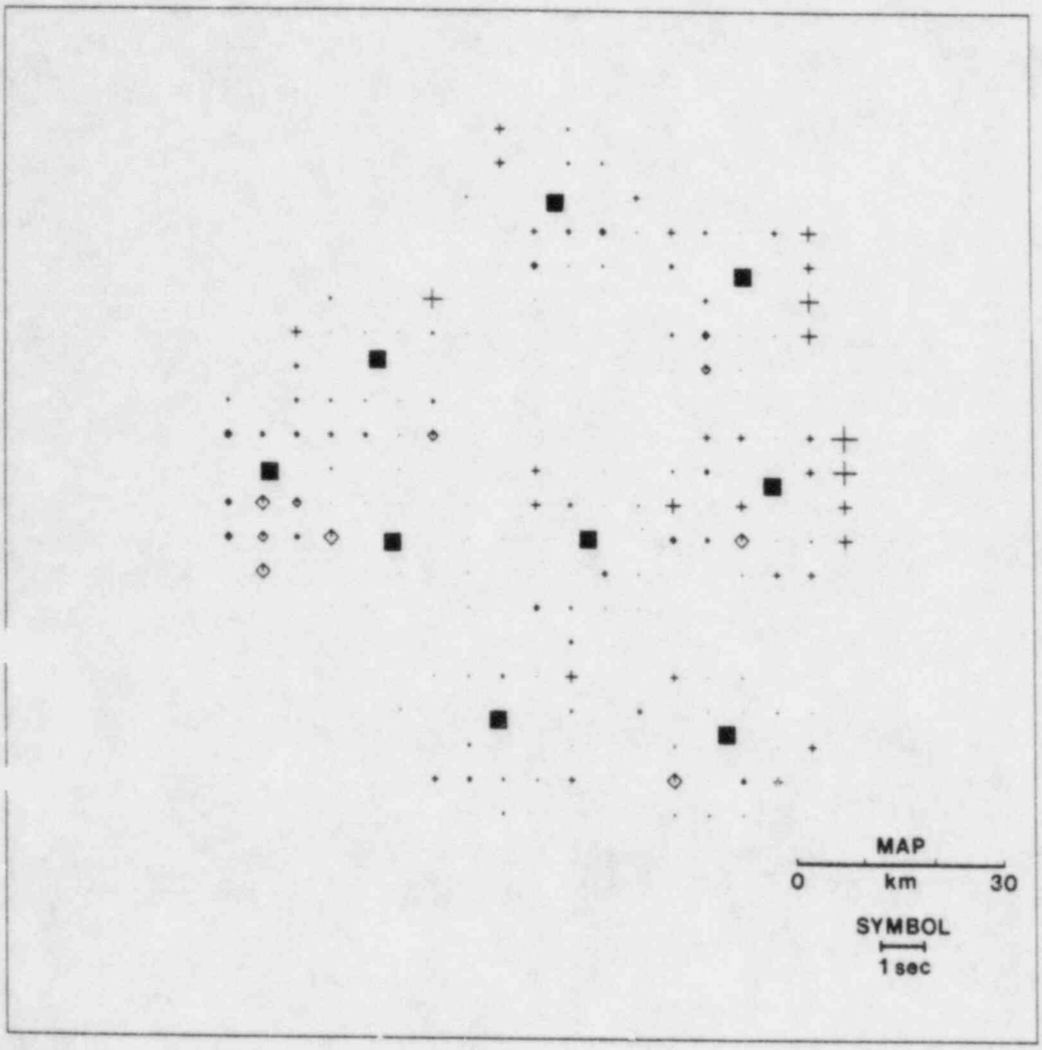

Figure 19. Back Projected Residual Differences to a Depth of 25 kilometers for the Anna, Ohio Region. The residuals are calculated using station AN10 as the base station and are averaged over a 5 X 5 kilometer grid. Positive residual differences are plotted as plus signs and negative residual differences are plotted as diamonds. The size of the residuals are directly proportional to the size of the symbols. Station locations are shown as the solid squares.

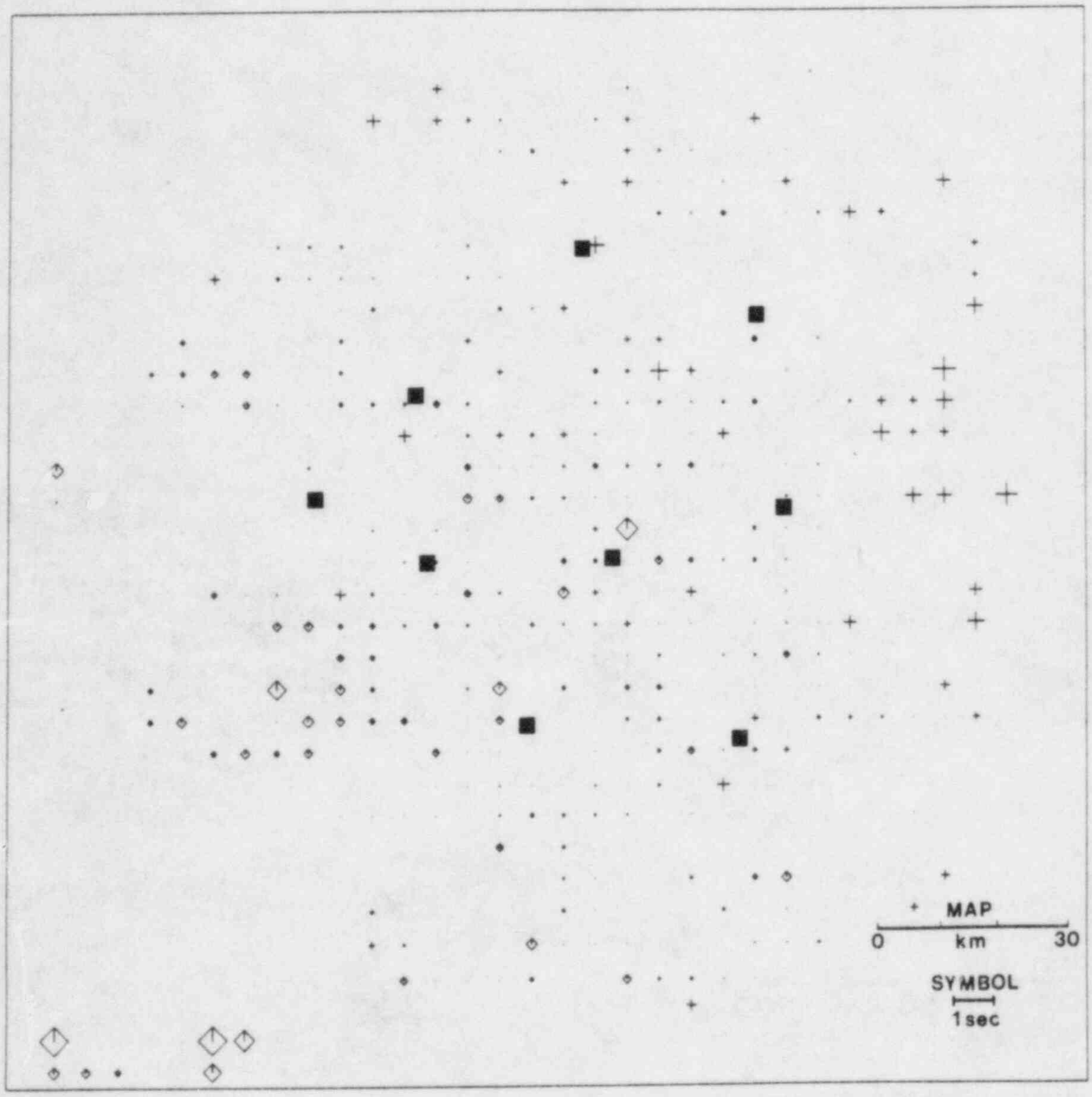

Figure 20. Back Projected Residual Differences to a Depth of 75 kilometers for the Anna, Ohio Region. The residuals are calculated using station AN10 as the base station and are averaged over a 5 X 5 kilometer grid. Positive residual differences are plotted as plus signs and negative residual differences are plotted as diamonds. The size of the residuals are directly proportional to the size of the symbols. Station locations are shown as the solid squares.

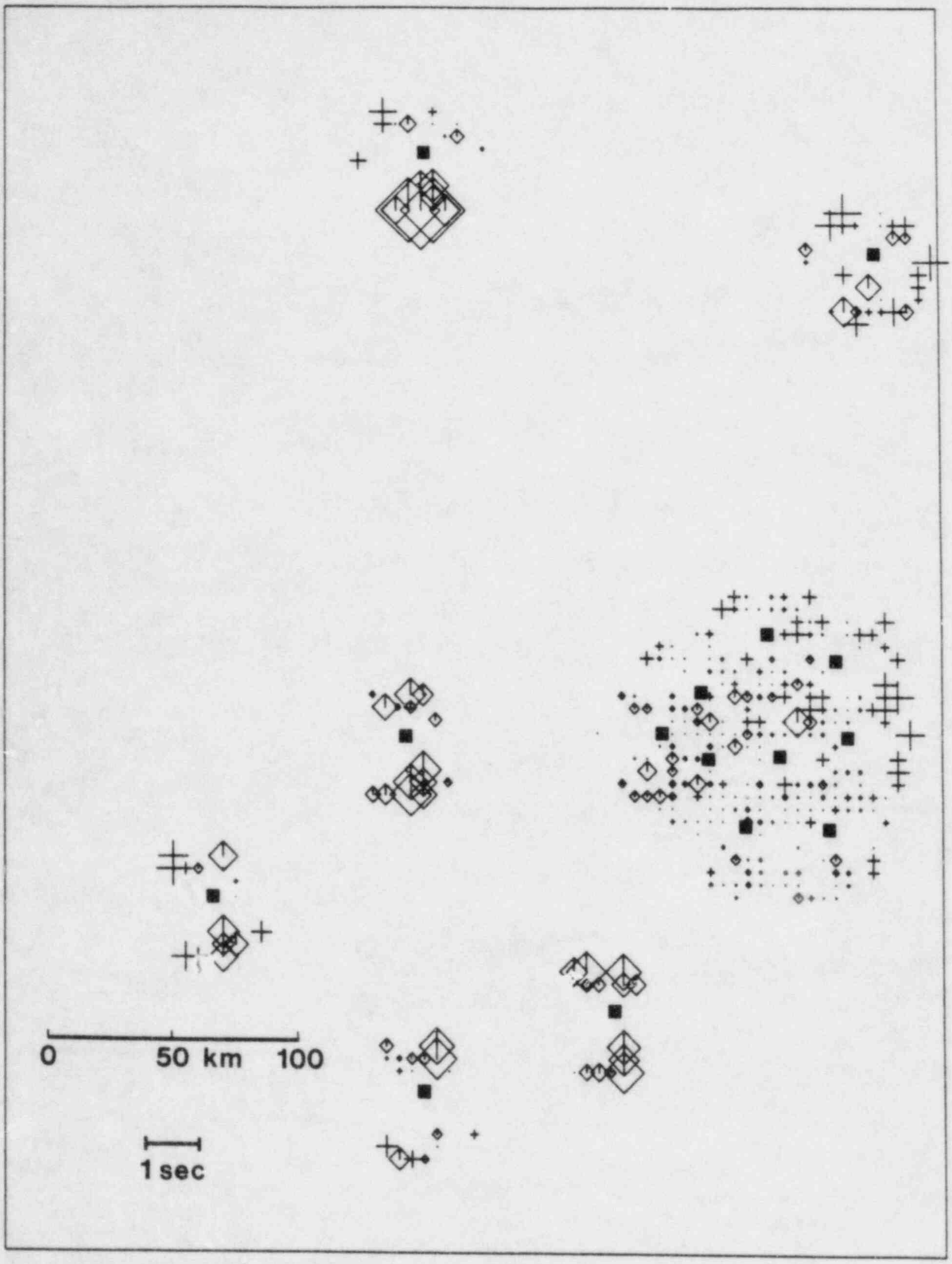

Figure 21. Back Projected Residual Differences to a Depth of 50 kilometers for the Ohio-Indiana Network. The residuals are calculated using station AN10 as the base station and are averaged over a 5 X 5 kilometer grid. Positive residual differences are plotted as plus signs and negative residual differences are plotted as diamonds. The size of the residuals are directly proportional to the size of the symbols. Station locations are shown as the solid squares.

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APPENDICES

A. Station Reliabilit, Tables

B. Teleseismic Phase Arrivals

C. P-Wave Residuals from Teleseismic Events with Respect to J-B Tables for Ohio Stations plus ACM and AAM

D. P-Wave Residuals from Teleseismic Events with Respect to J-B Tables for Indiana Stations

These appendices may be found in the form of microfiche in the back pocket of this report.

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16. ABSTRACT *(200 words or less)*

Earthquake activity in the Western Ohio - Indiana region has been monitored with a precision seismograph network consisting of nine stations located in west-central Ohio and four stations sited in Indiana. Twelve local and near-regional earthquakes have been recorded and located during this report period, ranging in magnitude from 0.3 to 4.0 m_{blg}. An event which occurred on January 14,, 1984, in Toledo, Ohio, and two events on July 2[illegible]ugust 29, 1984, near Terre Haute, Indiana, were felt. Only minor damage was [illegible]ted from these events. Of the twelve events, four occurred in the center of the Ohio array, three occurred near the city of Toledo, Ohio, four occurred in the center of the Ohio array, three occurred near the city of Toledo, Ohio, four occurred in Indiana (including one on the Indiana-Illinois border), and one was located near Chicago, Illinois.

Teleseismic P-wave residuals have been updated and evaluated by back projection to various depths in the lower crust. The residuals are found to correspond roughly to magnetic anomalies in the lower crust of Ohio. It is thought that these magnetic anomalies may represent the remains of an ancient rift zone, or perhaps they are the signature of the Grenville Front complex which may cross through this area.

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