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An Integrated Geophysical and Geological Study of the Tectonic Framework of the 38th Parallel Lineament in the Vicinity of its Intersection with the Extension of the New Madrid Fault Zone

Annual Progress Report for Fiscal Year 1980

Prepared by L. W. Braile, W. J. Hinze, J. L. Sexton
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ABSTRACT

Gravity, magnetic, seismic refraction and reflection, and basement geology are being used to investigate the northeastern extension of the New Madrid Fault Zone. Parallel, linear trends of correlative gravity and magnetic anomalies, previously related to the New Madrid Fault Zone and its associated structure, extend to the northeast into Indiana to approximately 39.5°N latitude. This feature also is suggested in the historical seismicity pattern and perhaps the basement geology and the crustal seismic model. The crustal seismic model is somewhat anomalous in comparison to the "normal" crust adjacent to the Mississippi Embayment. An additional pair of parallel trends of geophysical anomalies has been identified extending from New Madrid to St. Louis on either side of the Mississippi River. One possible origin for the basement structures is a Precambrian triple junction associated with continental rifting during break-up of the continents.

TECHNICAL SUMMARY

A variety of geologic and geophysical data are being assembled, analyzed, and interpreted to trace the northern extension of the New Madrid Fault Zone in the vicinity of its intersection with the 38th Parallel Lineament, to determine the tectonic and geologic history of the area, and to relate the structural features to the regional contemporary geodynamics. This tectonic approach to earthquake hazards evaluation is designed to supplement the more common approach based on historical seismicity because of deficiencies in the historical seismic record and insufficient knowledge of neotectonic structures in the midcontinent. The viability of the tectonic approach is well exemplified by the progress that has been made in recent years to evaluate the earthquake hazards of the greater New Madrid region.

Gravity anomaly data have been observed, assembled, reduced, and compiled between 35°-39°N latitude and 82°-92°W longitude. The resulting Bouguer gravity anomaly maps and data set are extremely important to the crustal studies investigation. In addition, the Bouguer gravity anomaly map of southern Indiana to 40°N latitude has been prepared based upon approximately 7200 gravity observations spaced at 2 to 3 km. A total magnetic intensity anomaly map and associated 2 km grid has been prepared for the area between 35°-39°N latitude and approximately 82°-91°W longitude based upon 28 individual magnetic surveys. In addition, a digital data set has been prepared of Missouri from the ground-based vertical magnetic intensity anomaly map. Improved computer codes for processing these large gravity and magnetic anomaly data sets with a variety of frequency domain operators have been prepared. The interpretation of these data are being facilitated by geologic studies of the basement rocks, pre-Mt. Simon sedimentary rocks, and mafic and ultramafic rocks that have intruded the Paleozoic sedimentary rocks. Additional constraints upon interpretation are imposed by measurements of the natural remanent magnetization and density of approximately 100 basement rock samples. The magnetic expression of an ultramafic intrusive which was observed in the southeastern Illinois magnetic survey has been mapped on the ground and modeled utilizing available geologic data.

High-resolution seismic reflection profiling in the Ohio River appears to be a feasible method of mapping bedrock faults extending from the New Madrid Fault Zone into southern Illinois. However, a definitive answer to the question of mapping faults in the bedrock with seismic profiling in the rivers and particularly identification of faults in the sediments overlying the bedrock awaits further processing of the data.

Nine seismic profiles, which have particularly strong shear wave components, have been recorded from coal mine blasts in the Wabash River Valley. Interpretation of the seismic record sections of these profiles by modeling suggests a crustal model which is somewhat anomalous to the "normal" crust adjacent to the Mississippi Embayment. The "average" Wabash River Valley model has a 39 km thick crust consisting of 2.5 km of sedimentary rocks (V_p = 4.59 km/sec, V_s = 2.64 km/sec), basement rocks (V_p = 6.14 km/sec, V_s = 3.57 km/sec) extending to a depth of 15 km, and a lower crust with a compressional velocity of 6.85 km/sec and a shear velocity of 4.00 km/sec. The lower crust in this model brings a relatively high velocity layer to a shallower depth than found in the Mississippi Embayment or adjacent so-called normal areas.

The gravity and magnetic anomaly signatures of a three-dimensional crustal structure model of the Mississippi Embayment derived from surface wave dispersion and seismic refraction studies have been computed at satellite elevations using spherical-earth considerations. These signatures compare well with observed magnetic anomaly and upward continued gravity data. The major positive gravity anomaly is derived from the crust and the magnetic anomaly minimum is caused by a decrease in the magnetization of the thickened lower crust.

Parallel, linear trends of correlative gravity and magnetic anomalies which previously have been related to the New Madrid Fault Zone are found to extend northeast into Indiana to 39.5°N latitude. An additional pair of parallel trends of anomalies is identified extending from New Madrid to St. Louis. These anomalies are under continuing investigation to determine their origin and relate their source to a model which will explain the occurrence of earthquakes in the midcontinent. One possible origin for the basement structures is a Precambrian triple junction associated with continental rifting during a period of continental break-up.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

The studies presented in this report are the result of the combined effort of a large group of undergraduate and graduate students as well as faculty of Purdue University, University of Texas at El Paso, and the University of Pittsburgh. The authors of this report acknowledge the conscientious, dedicated effort of the students, the cooperation of Neil Steuer and Thomas Buschbach, and the contribution of Ralph von Frese to the satellite gravity and magnetic paper.

The following students have been involved in this program during the contract year:

University of Texas at El Paso

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Purdue University

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John McGinnis
Keith Peregrine
Jon Reed
Mark Sparlin

University of Pittsburgh

Mark Dadosky
Jeff Kersting
Ding-wen Yuan

INTRODUCTION

The midcontinent region of the United States has long been regarded as part of the stable craton. Geological evidence has led to the assumption that this area has undergone only minor tectonism during the past several hundred million years and that this tectonism has largely taken the form of broad, slow, vertical movements. However, during the past decade there has been accumulating evidence that the midcontinent region has been and is presently tectonically active. Seismicity studies and improved geophysical discrimination of lateral crustal variations have triggered this change in geologic thought.

As a result, increasing attention is being devoted to the seismicity, geologic structures associated with earthquake activity, and understanding the origin and mode of the tectonic processes in the midcontinent. A major seismo-tectonic investigation is centered upon the New Madrid Seismic Zone and its possible extensions. Thus, the intersection of the extension of the New Madrid Seismic Zone and the 38th Parallel Lineament has been the focus of intensive study (Heyl, 1972; Buschbach, 1980; Hildenbrand and others, 1978 and 1979; Hinze and others, 1977 and 1980).

The 38th Parallel Lineament is a band of geologic features extending across eastern U.S. along the 38th parallel of latitude. It is manifested in many ways, but primarily by a series of east-west trending fault zones which were active at least through the Paleozoic era. It may represent a Precambrian fracture zone or crustal boundary extending deeply into the crust and possibly the mantle. The northeasterly-trending New Madrid Seismic Zone has been the site of several intermediate and major earthquakes in historic time and is the most seismically active area in eastern North America. The trend of the New Madrid Seismic Zone extends into southern Illinois and Indiana and the Wabash River Valley Fault System. This trend intersects the 38th Parallel Lineament in the vicinity of the confluence of the Wabash and Ohio Rivers. Additional details of these tectonic features are discussed by Hinze and others (1977). Fundamental questions of the New Madrid Seismic Zone are its northerly extensions and the nature of its intersection with the 38th Parallel Lineament. These questions are particularly significant to the evaluation of the earthquake risk in the region.

In 1976, L.W. Braile and W.J. Hinze of Purdue University, G.R. Keller of the University of Texas at El Paso, and E.G. Lidiak of the University of Pittsburgh initiated an integrated geological/geophysical study of the tectonic framework of the 38th Parallel Lineament in the vicinity of its intersection with the extension of the New Madrid Seismic Zone. The objectives of this study are to investigate the tectonic and geologic history of the 38th Parallel Lineament and the extension of the New Madrid Seismic Zone and associated features, and to determine the variations in structure and properties of the crust and their relationship to the regional contemporary geodynamics. To accomplish these goals several hypotheses have been considered as the source of the contemporary tectonism. These hypotheses which include crustal rifting, regional thermal expansion and contraction, crustal boundaries and zones of weakness, local basement inhomogenities, and isostatic warping are reviewed by Hinze and others (1980). Consideration of them has led to the design of a comprehensive, integrated data collection, synthesis and interpretation program involving geologic, gravity, magnetic, crustal seismic refraction, and reflection seismic studies. The original area of interest was bounded by 85^{o}W and 90^{o}W longitude and $36^{o}30'$N and 39^{o}N latitude, but preliminary interpretation of the data, the suggested tectonic hypotheses, and realization of the importance of regional data to the solution of the seismo-tectonic problem of the intersection zone has caused the study area to be extended at least locally to 84^{o}W and 92^{o}W longitude and 35^{o}N and 40^{o}N latitude.

During the 1979-80 contract year, considerable progress has been made in acquiring and synthesizing critical gravity, seismic refraction and reflection, and geologic data. Furthermore, these data together with previously acquired information have been compiled into highly useful data sets and significant progress has been made in interpreting the data, developing hypotheses, and designing experiments to test the hypotheses.

REPORTS, PAPERS, AND PRESENTATIONS

Oral presentations on the progress and results of the integrated investigation were made to the New Madrid Seismo-Tectonic Study group at Columbus, Ohio on 14 September, 1979 and at Bloomington, Indiana on 9 April, 1980.

In addition to University seminars by the principal investigators, a total of ten technical papers on this study have been presented at scientific meetings. Five technical papers were presented at the 1979 American Geophysical Union Midwest Meeting in Columbus, Ohio on 13-14 September, 1979. The abstracts of these papers entitled Seismicity, Stresses, and Structures; Basement Rocks In The New Madrid Region; A Model For Intraplate Seismicity Of Eastern North America; Magnetic Anomaly Map Of The Greater New Madrid Seismic Zone; and A Bouguer Gravity Map Of A Portion Of The Central Midcontinent are presented in Appendix I. Five additional papers were presented at the North-Central Section Meetings of the Geological Society of America on 10 April, 1980 in Bloomington, Indiana. The abstracts of these papers entitled Seismo-Tectonics Of The New Madrid Seismic Zone And Its Extension-An Overview; The Magnetic Anomaly Associated With The Structure Of The Omaha Oil Field, Illinois; Enhanced Gravity And Magnetic Anomaly Maps Of The East-Central Midcontinent; A New Gravity Anomaly Map Of Southern Indiana; and Crustal Seismic Studies Of The New Madrid Seismic Zone also are presented in Appendix I.

Two reports have been submitted for publication as Nuclear Regulatory Commission Reports. They are entitled Bouguer Gravity Anomaly Map Of The East-Central Midcontinent Of The United States and Aeromagnetic Map Of The East-Central Midcontinent Of The United States. In addition, one Nuclear Regulatory Commission Report on the results of the 1979 fiscal year study of intersection of the extension of the New Madrid Seismic Zone and the 38th Parallel Lineament was published (Braile and others, 1979).

The paper Models For Midcontinent Tectonism (Hinze and others, 1980) was one of four papers dealing with intraplate tectonics published in the volume "Continental Tectonics", one of the National Research Council's series on Studies in Geophysics. Three manuscripts by the principals of this study program which were previously accepted for publication in the forthcoming U.S. Geological Survey Professional Paper on the New Madrid Seismic Zone underwent final revision for publication. They are "High Resolution Seismic Reflection Surveying on Reelfoot Scarp, Northwestern Tennessee" by J.L. Sexton, E.P. Frey, and D. Malicki; "A Crustal Structure Study of the Mississippi Embayment" by C.B. Austin and G.R. Keller; and

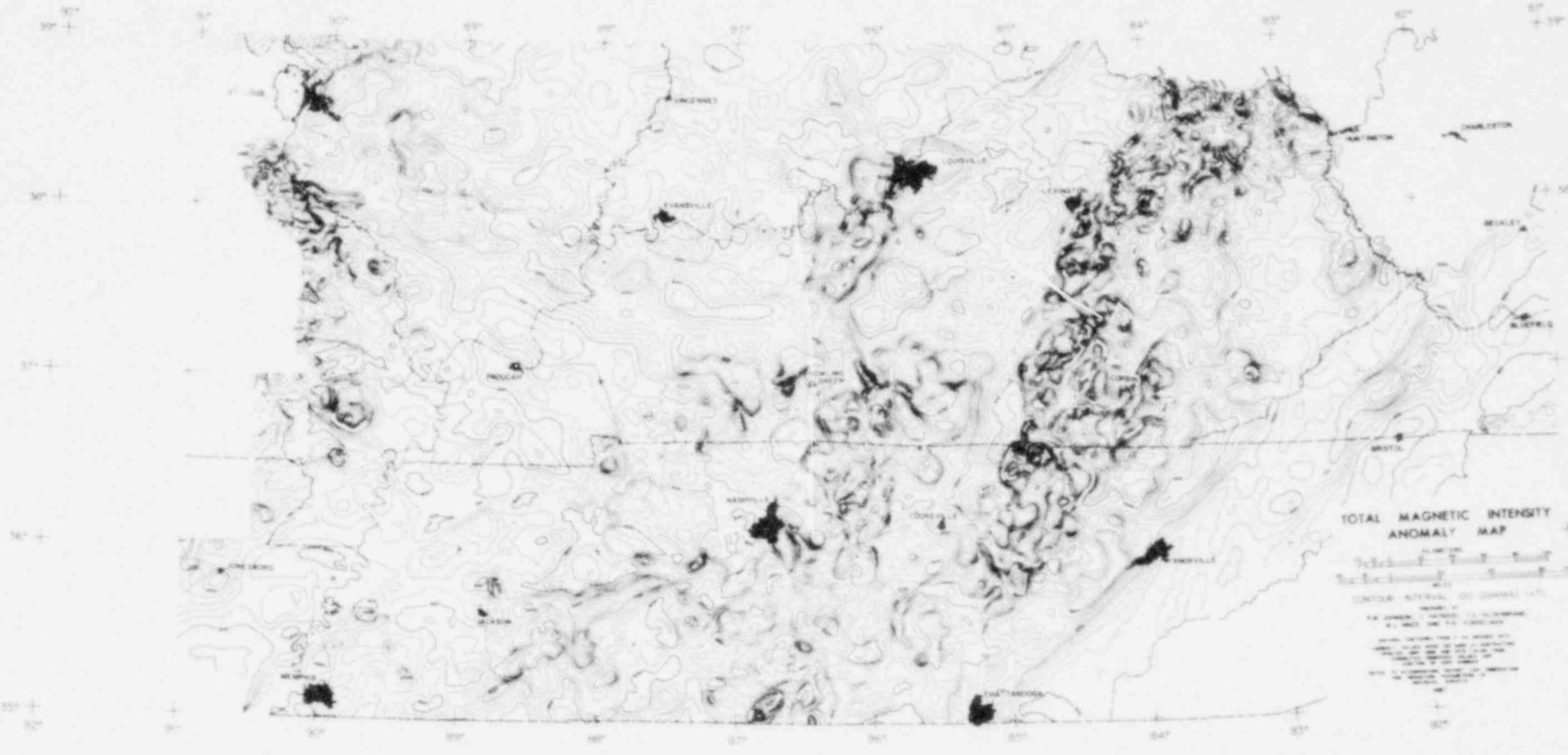


Figure 1. Total magnetic intensity anomaly map of the east-central midcontinent.

Figure 2. Western portion of the total magnetic intensity anomaly map shown in Figure 1.

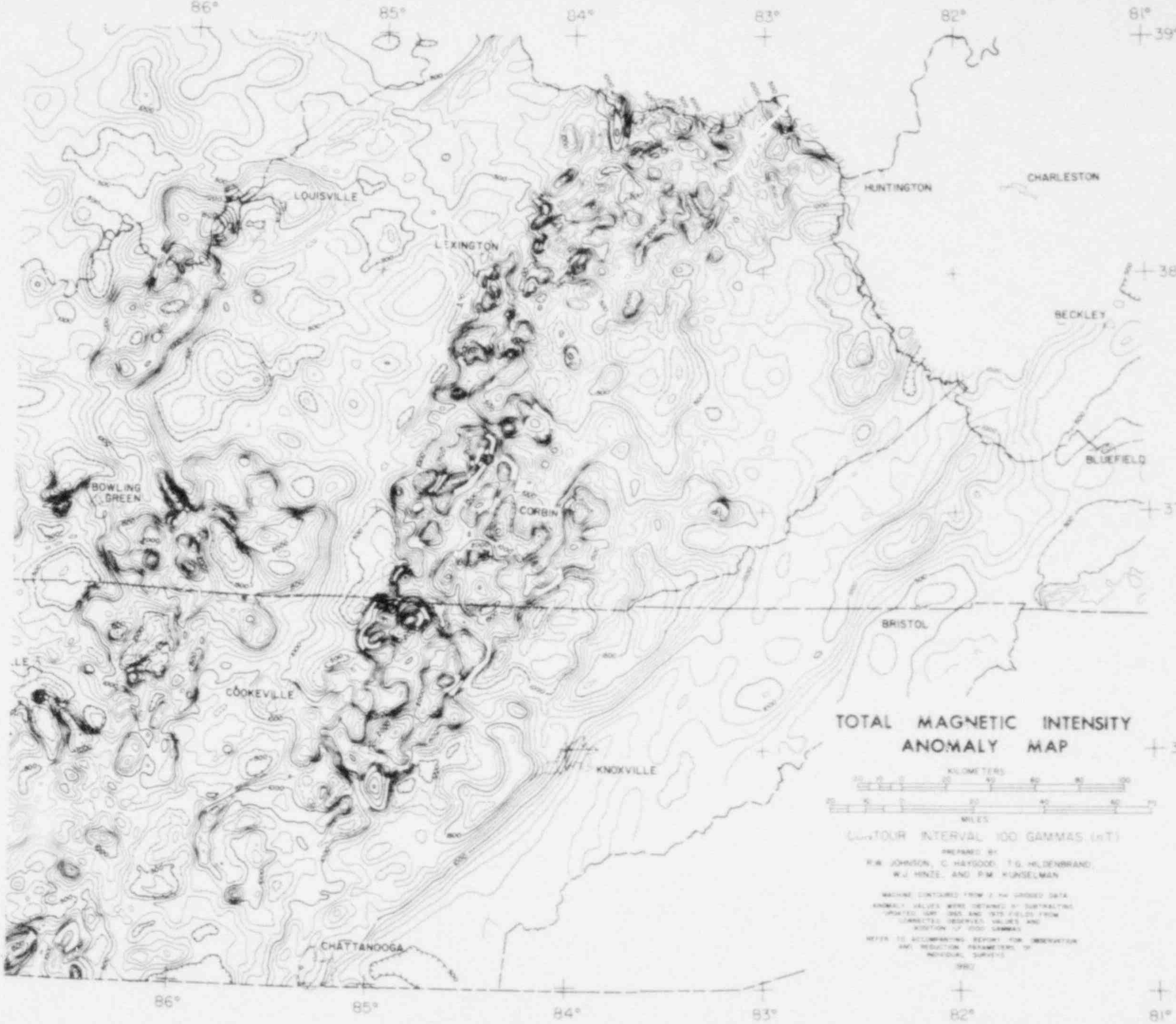


Figure 3. Eastern portion of the total magnetic intensity anomaly map shown in Figure 1.

"The Northeastern Extension of the New Madrid Fault Zone" by L.W. Braile, W.J. Hinze, G.R. Keller, and E.G. Lidiak. A paper entitled "The Tectonic Approach to Evaluation of Earthquake Hazards in the Midcontinent" by W.J. Hinze, L.W. Braile, G.R. Keller, and E.G. Lidiak was prepared and is presented in Appendix II.

A paper entitled "Gravity and Magnetic Anomaly Modeling of Mississippi Embayment Crustal Structure at Satellite Elevations" by Ralph R.B. von Frese, W.J. Hinze and L.W. Braile which is presented in Appendix III discusses the studies of the Purdue University group to investigate the crustal structure of the Mississippi Embayment with satellite elevation (≈ 450 km) magnetic and gravity anomaly data. The results of gravity and magnetic modeling of the regional positive gravity and negative magnetic anomalies utilizing a newly developed spherical earth modeling technique (von Frese and others, 1980) corroborate the crustal disturbance interpreted by Austin and Keller (1980) from seismic refraction and surface wave studies.

MAGNETIC ANOMALY STUDIES

During the current contract year, no magnetic data were acquired, but considerable effort has been put into compilation and synthesis of available data and development of procedures for processing large data sets. No data were acquired because coverage was completed of the original study area with aeromagnetic surveys. The aeromagnetic data are from a variety of sources including the U.S. Geological Survey, Tennessee Division of Geology, Kentucky Geological Survey, Tennessee Valley Authority, Illinois Geological Survey, and data collected for this study.

Twenty-eight individual magnetic surveys dating from 1947 to 1978 were gridded at a 2 km interval and compiled into a single data set and regional map by adjusting the data to a common datum. The survey parameters, data reduction procedures, and the compilation process are explained by Johnson and others (1980). The regional total magnetic intensity anomaly map (Figures 1, 2 and 3) extends from 35^{o} to 39^{o}N latitude and approximately 82^{o} to 91^{o}W longitude. This map is being published at the scale of $1:10^{6}$ in Johnson and others (1980). Computer codes for processing the data set with filters, derivatives, continuations, etc. in the frequency domain have

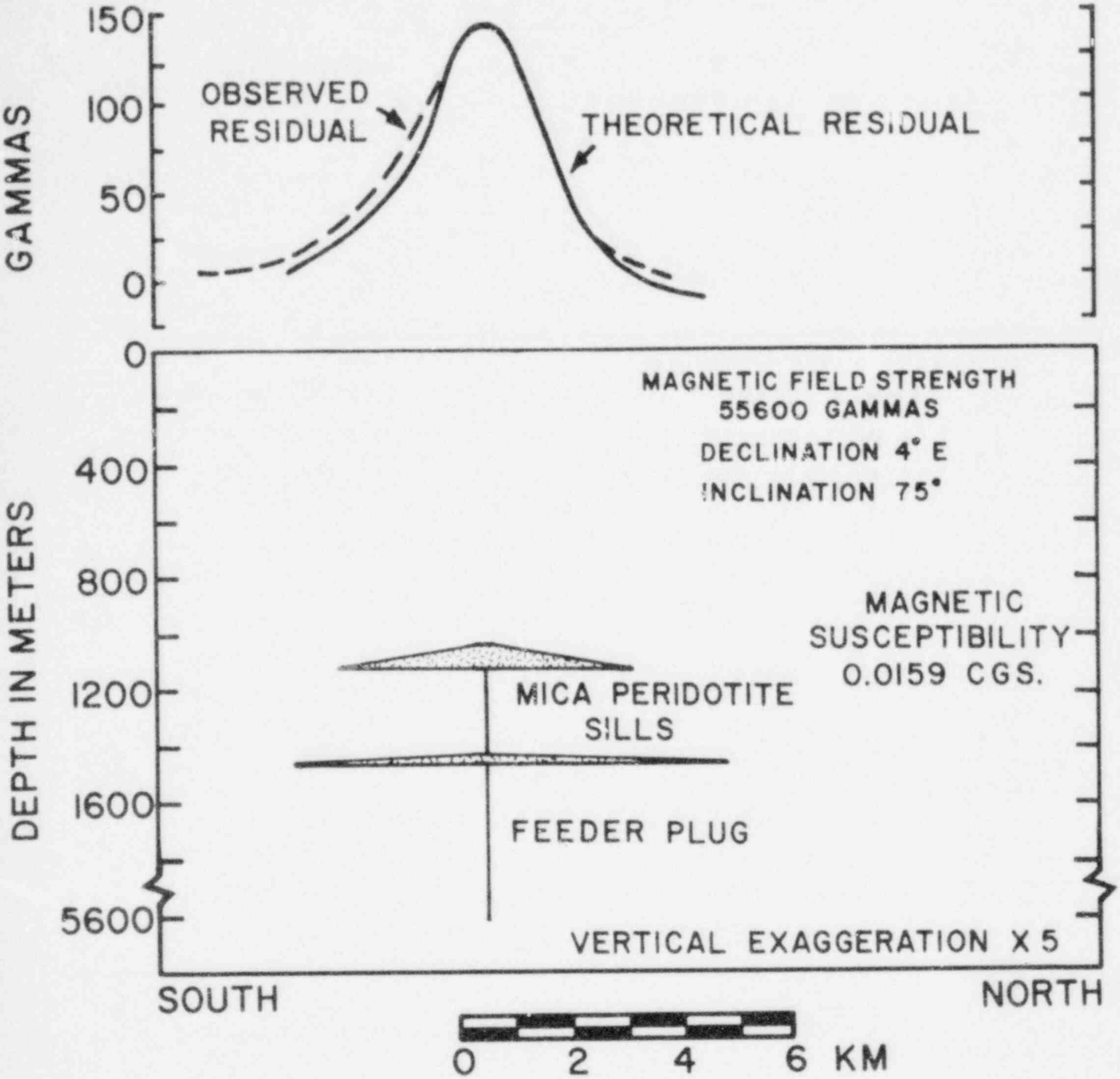


Figure 4. Observed and theoretical residual magnetic anomalies over the Omaha Oil Field, Illinois.

Figure 5. Vertical magnetic intensity anomaly map of Missouri based on 10 km grid of map prepared from ground survey. Contour interval 100 gammas (nT).

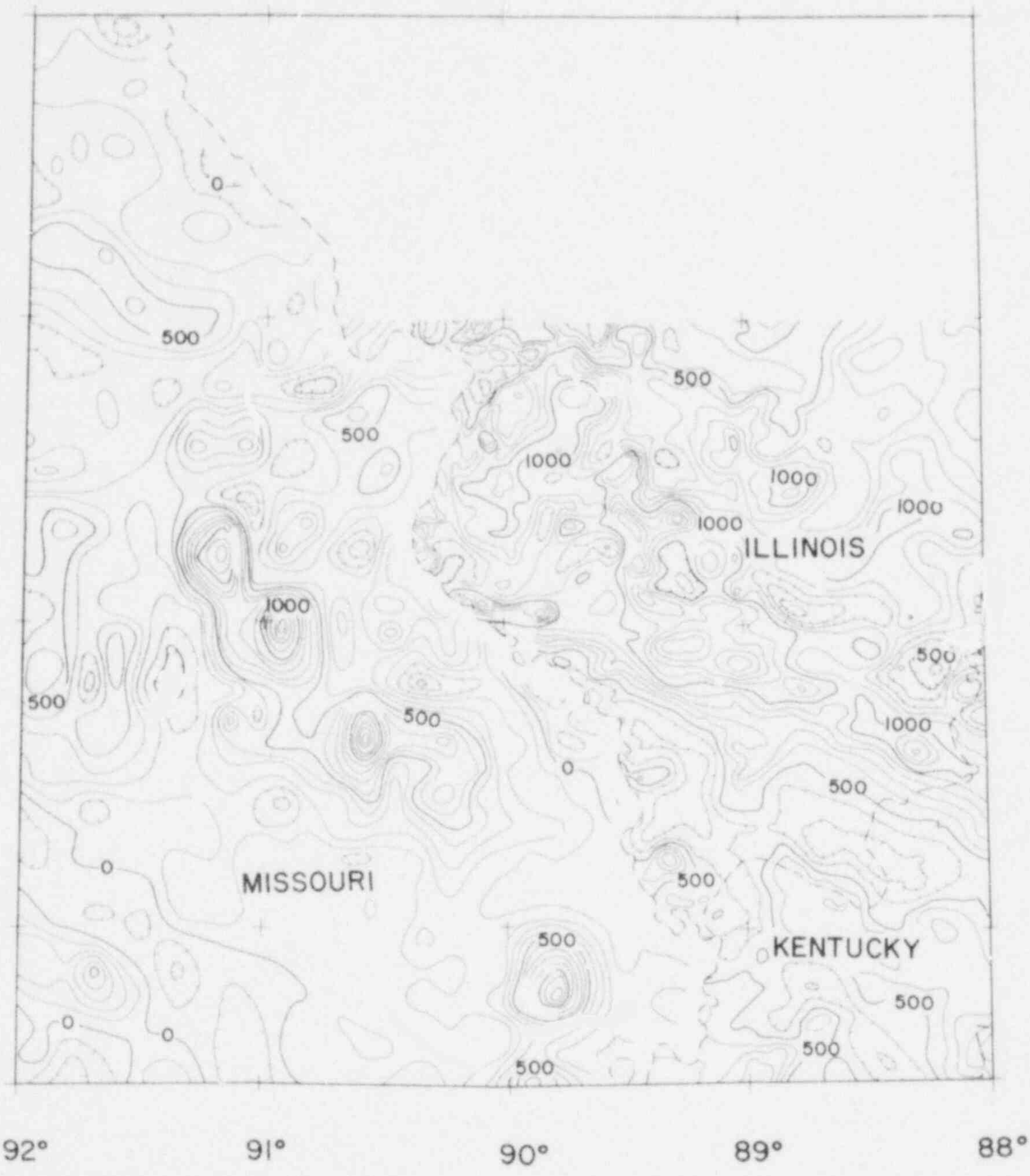


Figure 6. Combined total magnetic intensity anomaly map with ground-based vertical magnetic intensity anomaly map of Missouri.

undergone considerable improvement and the codes are being modified to handle the entire data set in a single step to avoid edge effect problems inherent in processing and compiling a series of individual areas.

An areally-limited anomaly observed over the Omaha Oil Field in the aeromagnetic survey of southeastern Illinois has been verified and studied by a ground survey. Limited drill cores, physical property analysis, and calculation of theoretical magnetic anomalies indicate that the anomaly is caused by a small diameter pipe of mica-peridotite and related sill-like intrusions within the Phanerozoic sedimentary rocks. This study illustrates in general the role of the magnetic method in studying the location, character, and geometry of the tectonically significant ultramafic intrusions and specifically that these intrusives have caused structural deformation of the Phanerozoic rocks (Figure 4).

The only complete magnetic map of Missouri is a ground vertical magnetic intensity anomaly map which dates from roughly 40 years ago. Despite the limitations of the map, it was digitized on a 10 km grid to provide a reconnaissance view of the magnetic anomaly field. The map, shown in Figure 5, achieves this goal very well. In lieu of better data, this map has been employed in our preliminary analyses which extend into Missouri. The Missouri magnetic anomaly map tied into aeromagnetic surveys to the east is shown in Figure 6.

GRAVITY ANOMALY INVESTIGATIONS

The original study area has been completely gravity surveyed plus Indiana has been surveyed as far north as 40°N latitude at a 2 to 3 km interval.

During the 1979 field season, the State of Indiana was surveyed between 39°-40°N latitude (Figure 7). Approximately 3500 additional stations were established (Figure 8). Consideration of repeat observations over the three years of surveying indicates a standard deviation (Figure 9) of the order of 0.07 mgals. The gravity stations are referenced to the national gravity datum through a network of base stations (Figure 10). Comparison of the previous gravity anomaly map of Indiana (Figure 11) with the Bouguer gravity anomaly map prepared from reduction of the data collected over the past three years (Figure 12) shows good correlation between the major maxima

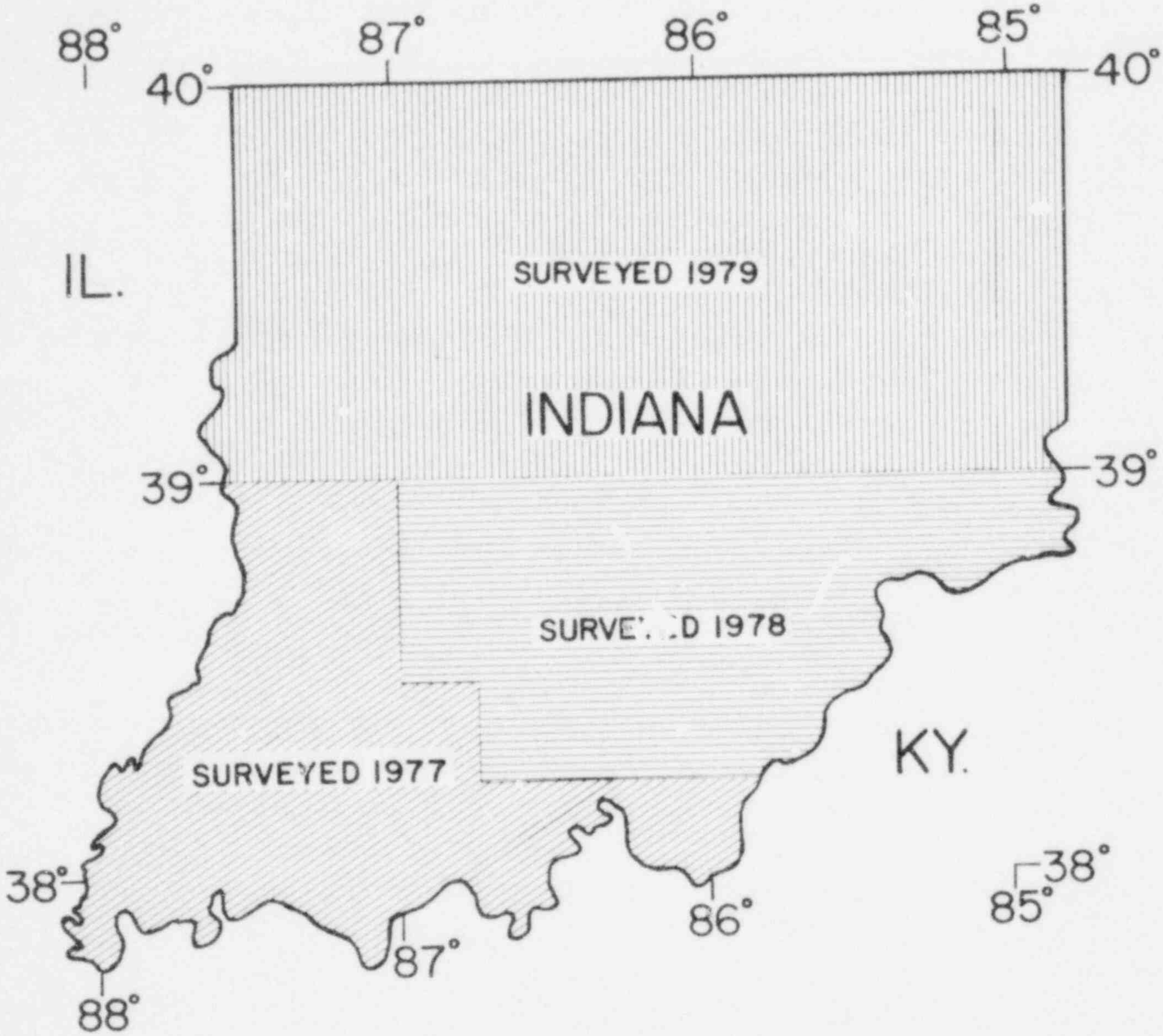


Figure 7. Map of southern Indiana showing year of gravity surveying.

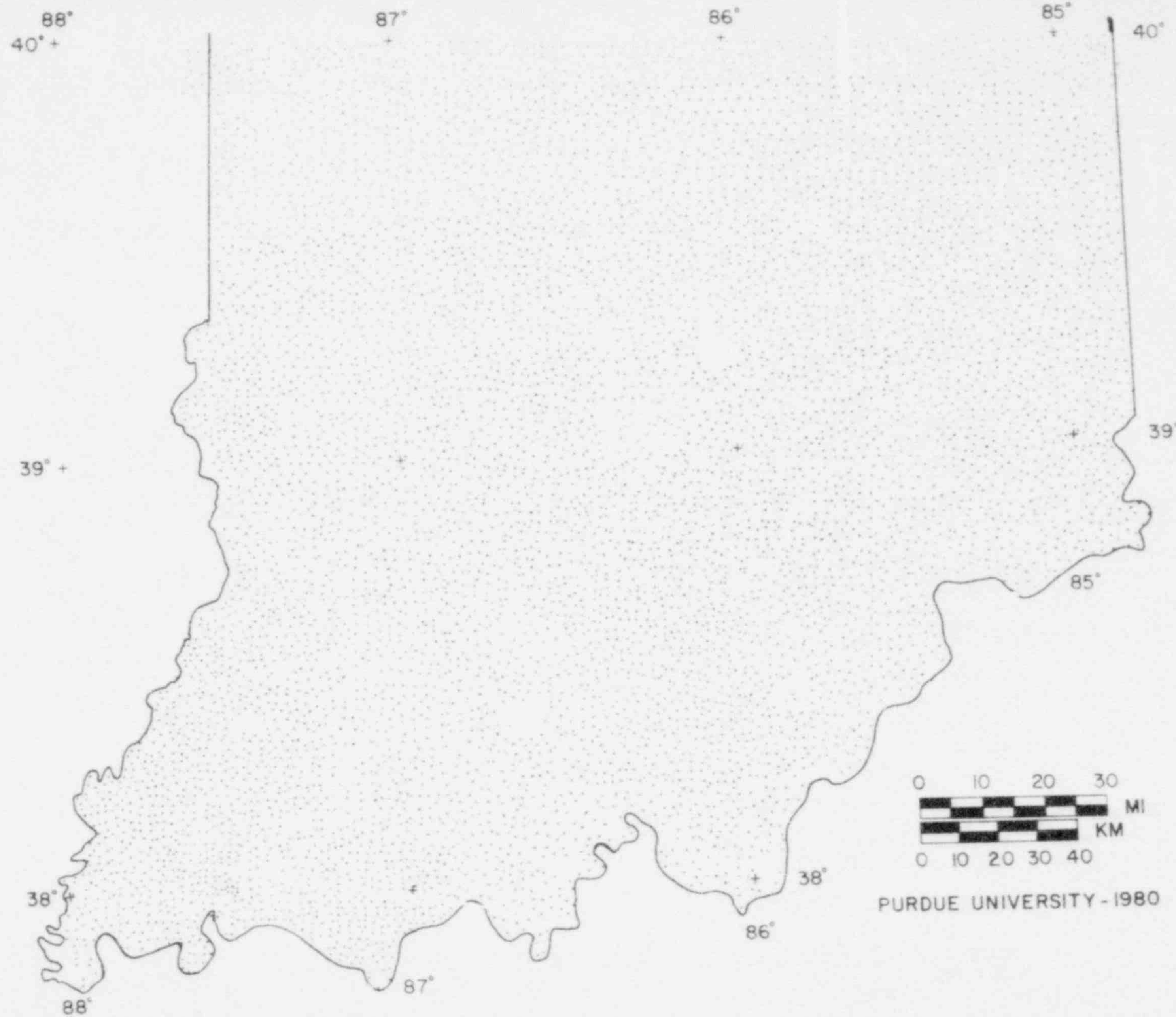
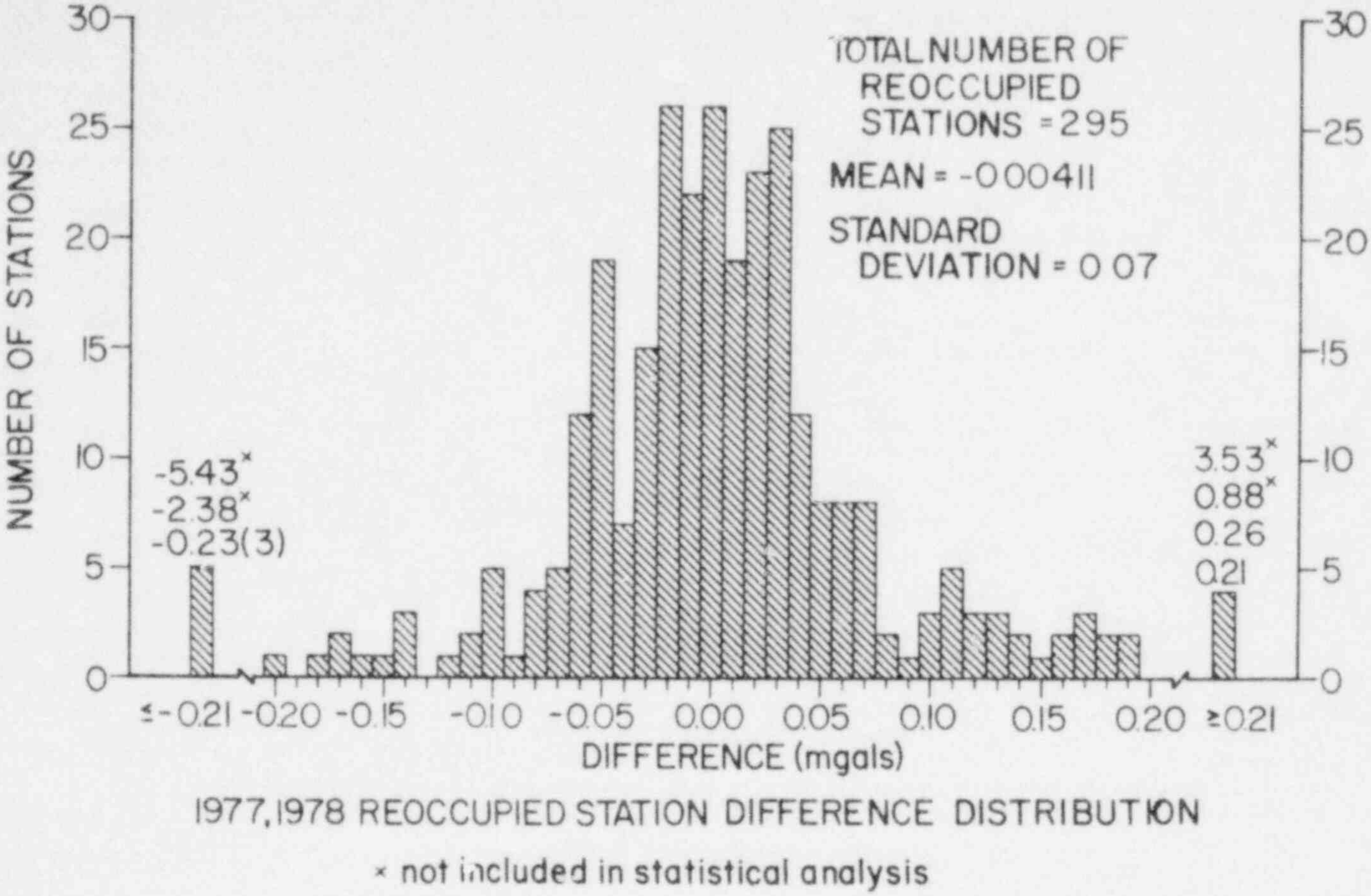


Figure 8. Gravity survey station location map-1978, 1979, 1980.



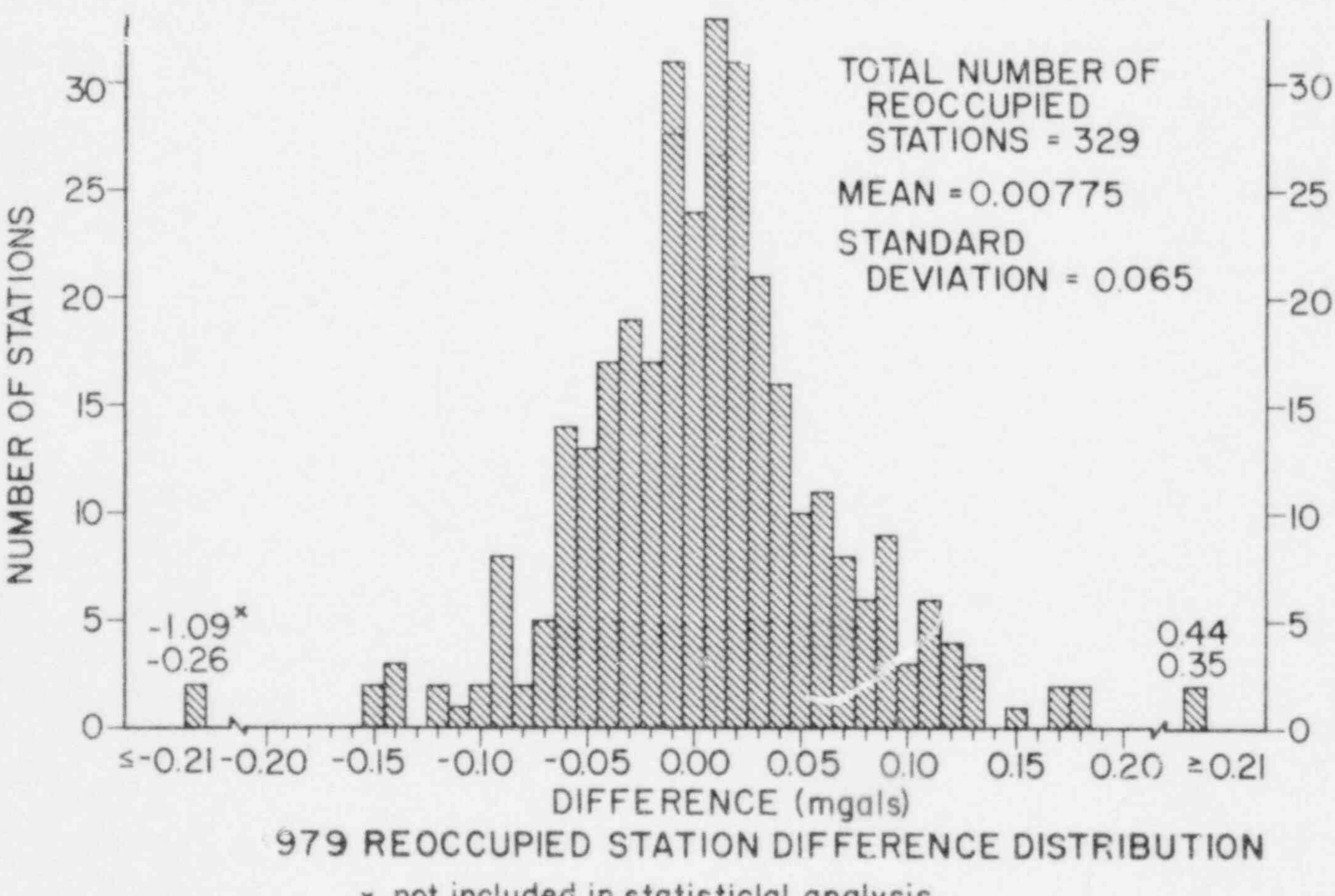


Figure 9. Reoccupied station value difference distribution-1977, 1978, 1979.

and 'nima. Gradients and anomaly maxima and minima values are better defined in the 1980 map (Figure 13) resulting in much higher confidence in the gravity analysis. Additional minor modifications in Figure 12 are anticipated as a result of current repeat and fill-in observations in critical areas.

Approximately 50,000 stations within the area bounded by 35° and 39°N latitude and 82° and 92°W longitude (Figure 14) have been gridded at a 2 km interval and registered on the magnetic anomaly grid west of 84°W longitude. The gridded data set is now available for processing with the computer codes currently under development for frequency domain analysis. The details of the source reduction, and compilation of the gravity data are discussed by Keller and others (1980). The data set has been used to prepare a 5 mgal contour map (Figures 15, 16 and 17) which is being published at the scale of $1:10^6$ in Keller and others (1980).

GEOLOGIC STUDIES

During the current contract year, research has been carried out on both the basement rocks and on the rocks immediately overlying the basement. It is becoming evident that the basal sedimentary rocks are significant because of their possible economic potential, distribution, and importance in understanding the early tectonic development of the area. A map showing the distribution of pre-Mt. Simon (Upper Cambrian) sedimentary rocks in the study area is shown as Figure 18. The presence of these rocks in the deeper parts of the Illinois Basin suggests that their distribution may, in part, be tectonically controlled. Another well in Lawrence County, Indiana, which occurs along the northeast extension of the New Madrid Fault Zone, also encountered similar clastic rocks underlain by Keweenawan-type basalt. We are continuing to study these rocks to gain a better understanding of their distribution and tectonic significance. We specifically want to investigate the possibility that these rocks accumulated in, and are thus partial indicators of, basement rift zones.

Geophysical characteristics of the basement rocks were measured as an aid to geophysical interpretations. Figure 19a and b summarize graphically the results of natural remanent magnetization (NRM) intensity

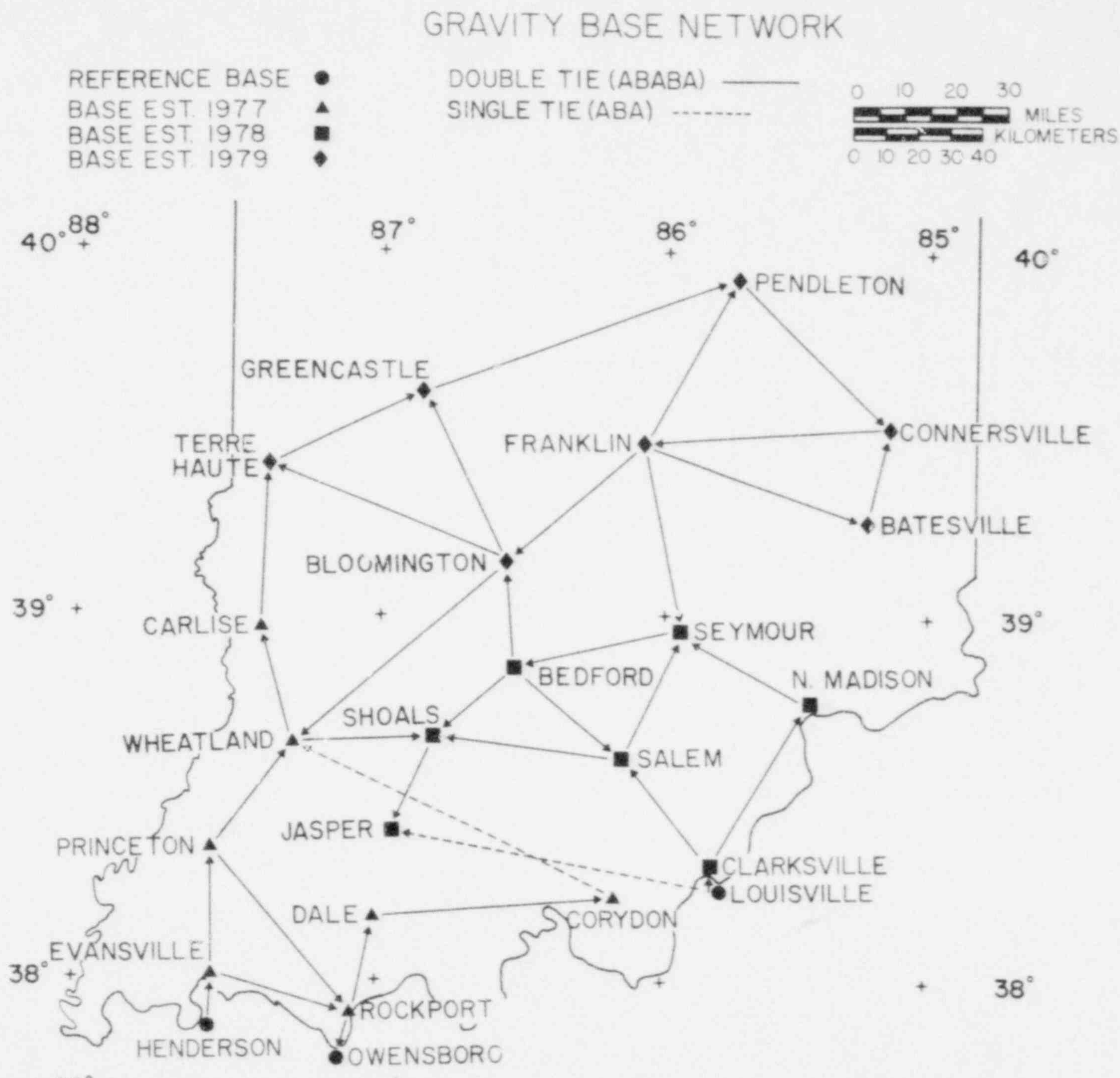


Figure 10. Southern Indiana gravity base station network-1977, 1978, 1979.

Figure 11. Relative Bouguer gravity anomaly map-1953.

Figure 12. Bouguer gravity anomaly map of southern Indiana-1980. Contour Interval is 2.5 mgals. Reduction based on I.G.S.N. 1971, G.R.S. 1967 and a density of 2.67 gm/cc.

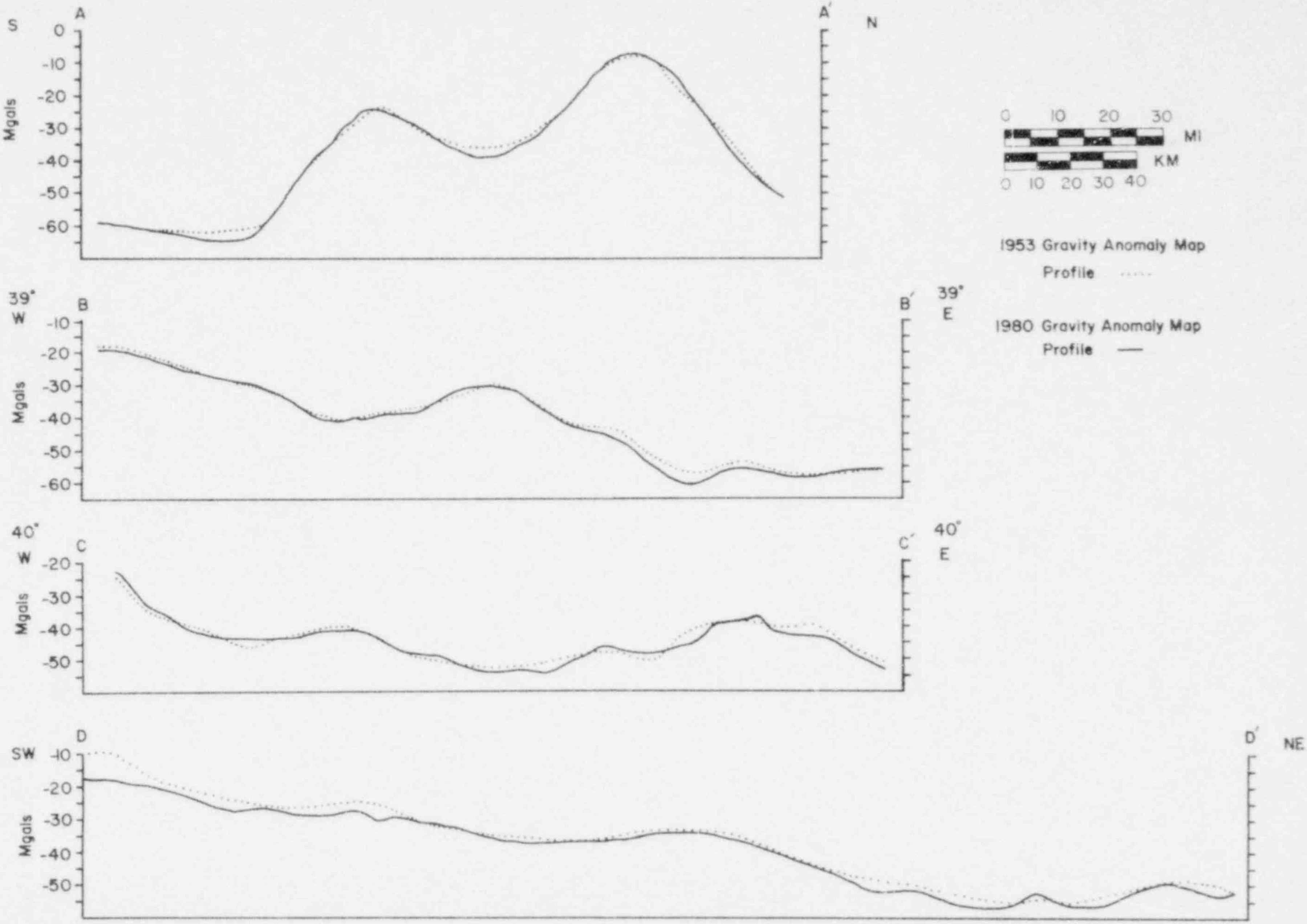


Figure 13. Comparison of 1953 and 1980 gravity anomaly maps by profiles.

Figure 14. Location of gravity observation in the study area.

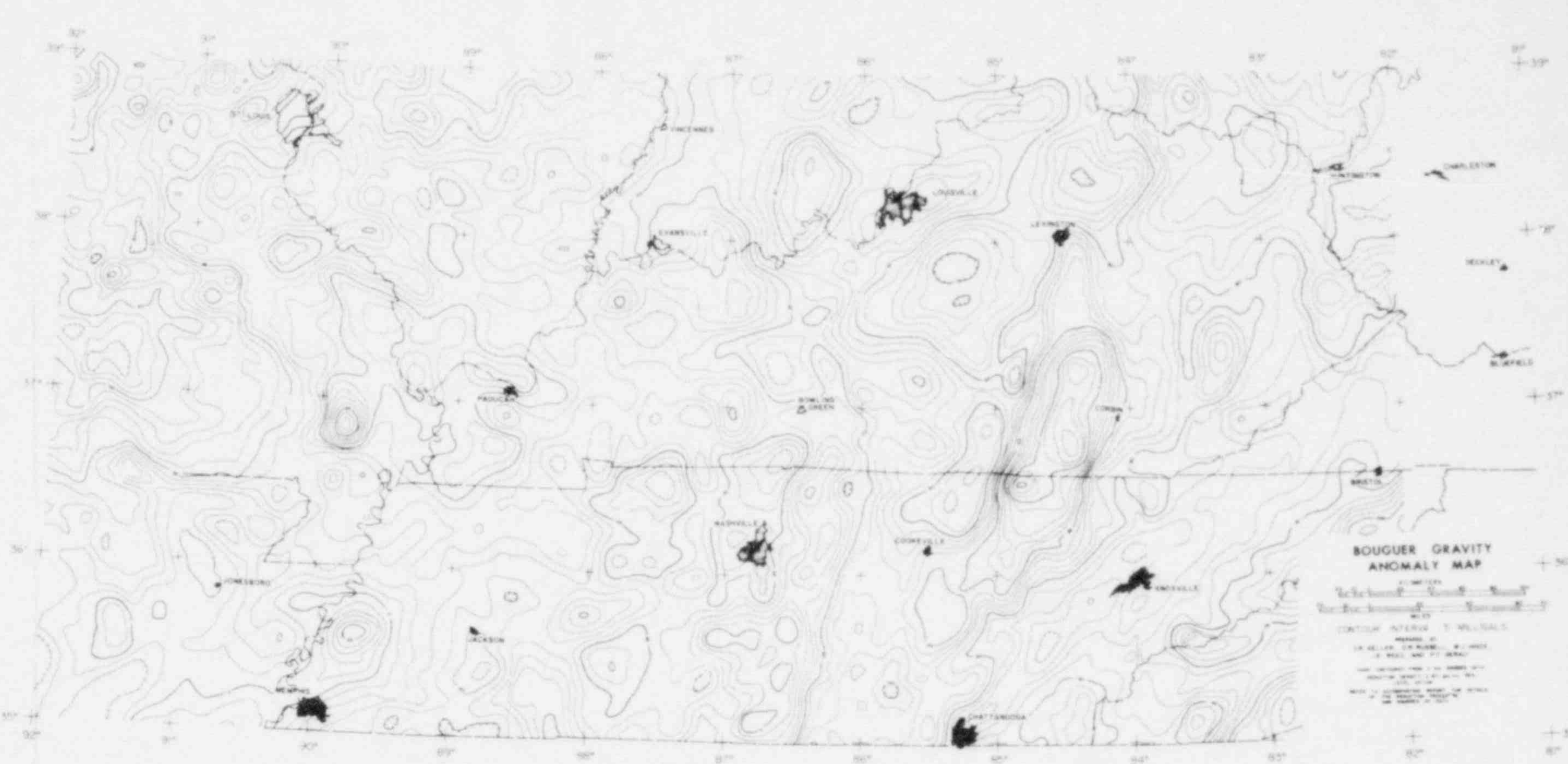


Figure 15. Bouguer gravity anomaly map of the east-central midcontinent.

Figure 16. Western portion of the Bouguer gravity anomaly map shown in Figure 15.

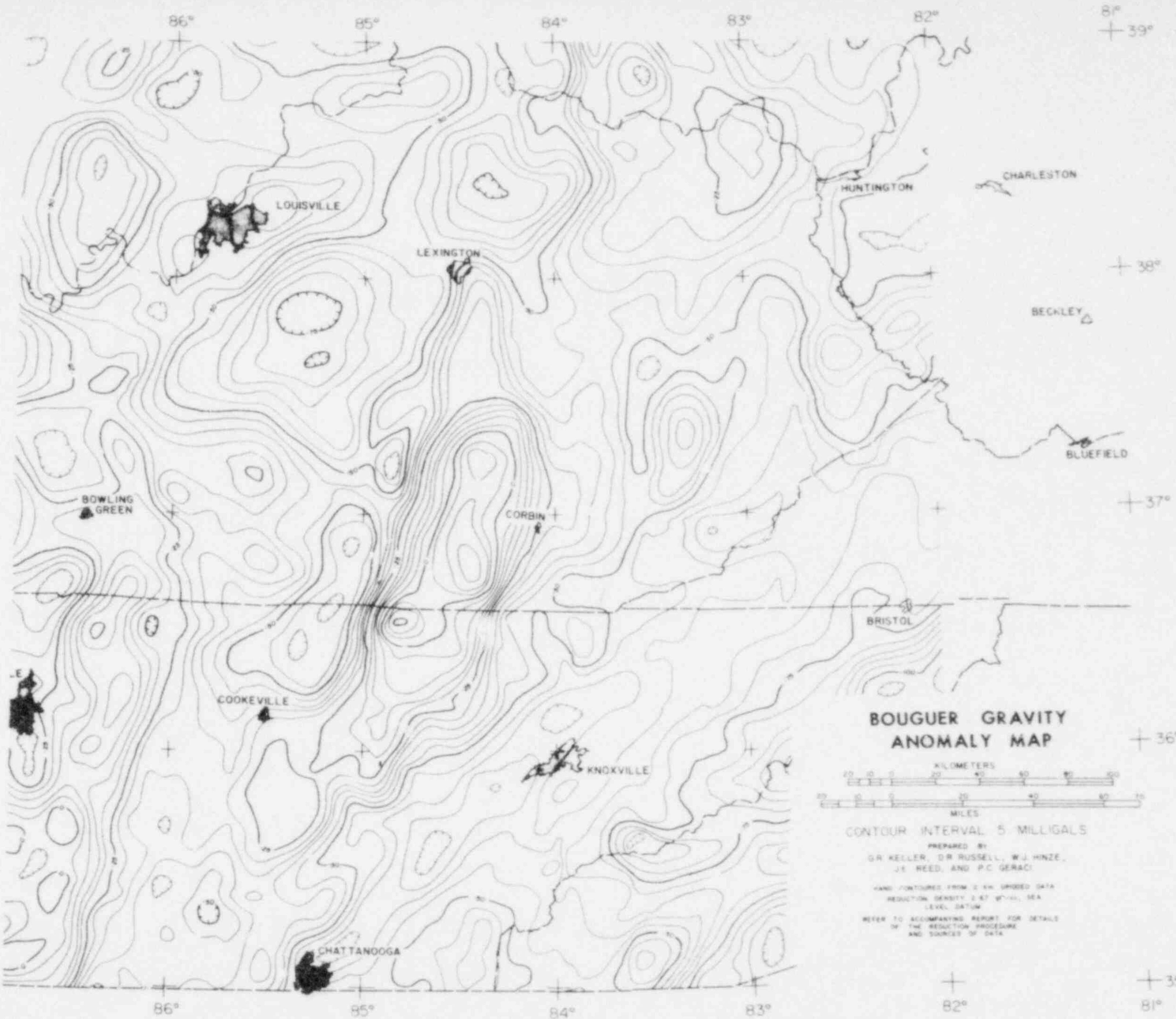


Figure 17. Eastern portion of the Bouguer gravity anomaly map shown in Figure 15.

measurements (Table 1) on 97 basement rock samples from the eastern midcontinent. Most of the measurements were made on drill cuttings (the only material available) using a cryogenic magnetometer. The methodology briefly is as follows: Ten of the largest and most representative fragments from each sample were selected, the magnetization of each fragment was measured separately, and the results were averaged to give the NRM of the sample. The specific gravity of 58 samples from the basement of Illinois and Indiana was also measured. The results are shown graphically by rock type on Figure 20. The measurements were made using a pycnometer for the drill cuttings and a Jolly balance for the cores. These physical measurements should be of considerable importance in helping to evaluate further the magnetic and gravity maps of the region. For example, the results of the NRM measurements suggest that remanent magnetization may be a factor in the magnetic polarization of the basement extrusive rocks, but not in the case of the basement intrusive, metamorphic or sedimentary rocks. The density measurements show that the basement sedimentary rock, rhyolite and trachyte, microgranite, and granite have similar density ranges. However, the basalt and metamorphic rocks have a notably higher density range.

Studies on the mafic and ultramafic intrusions is also continuing. Figure 21 shows the small kimberlitic, lamprophyric, and carbonatitic dikes, sills, and diatremes that have been identified at the surface and in the subsurface of southern Illinois and western Kentucky. These intrusions appear to be concentrated in the area of the intersection of the New Madrid Seismic Zone and the 38th Parallel Lineament, and are crudely centered around Hicks Dome at latitude $37^{o}30'$N, longitude $88^{o}22'30''$W (Figure 21). The dikes trend mainly to the north-northwest with a minor component to the north-northeast. The orientation and distribution of the intrusions suggest that they were emplaced during uplift of the central part of the region. The presence of these rocks has important tectonic implications as intrusions of this type are known to intrude along deep-seated fractures either bounding or cutting across continental plates during uplift or dilation. Comparison of these rocks to those occurring in large rift structures is continuing.

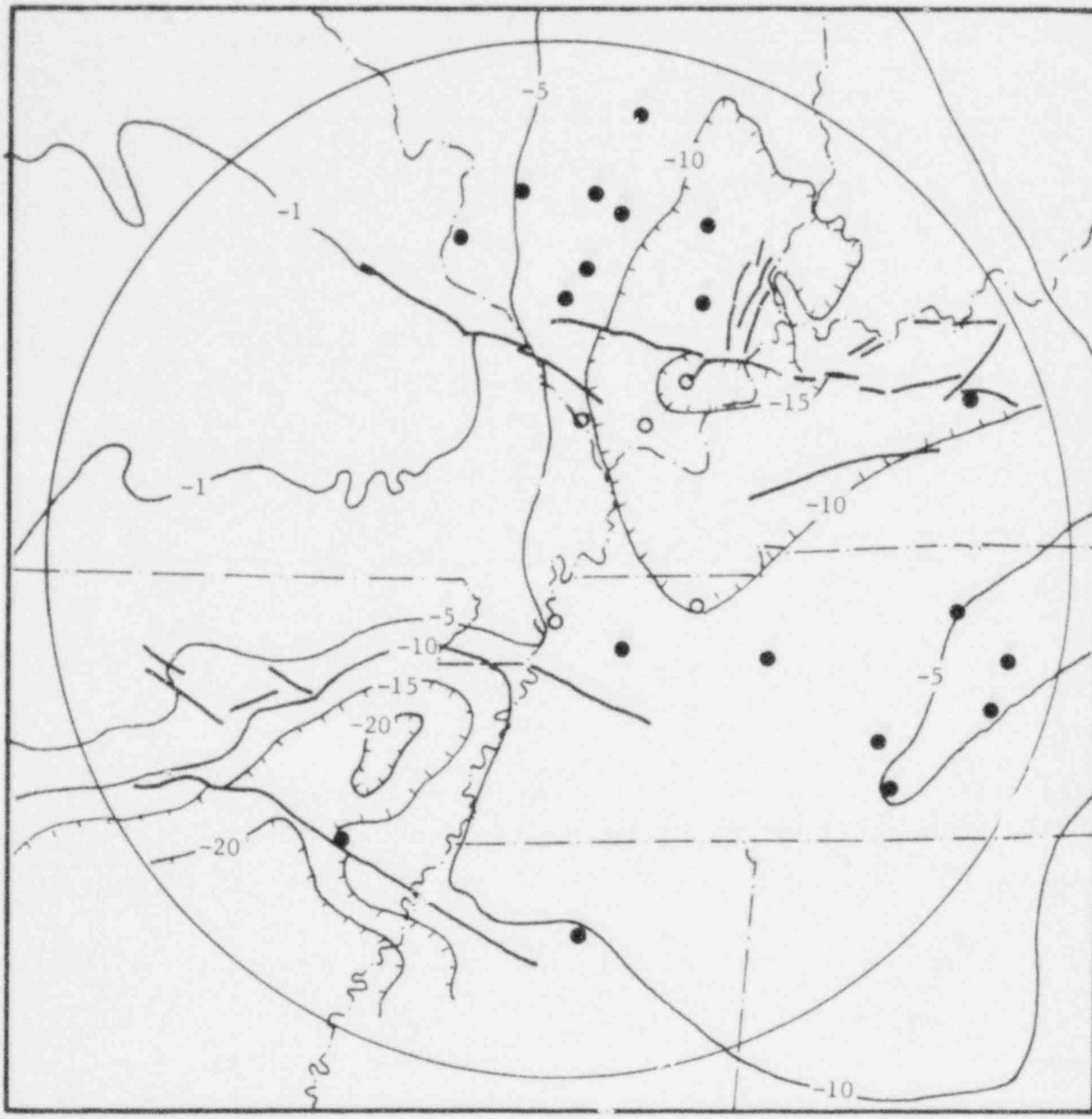


Figure 18. Distribution of pre-Mt. Simon sedimentary rocks in study area. Open circles, drill holes to pre-Mt. Simon sedimentary rocks; closed circles, drill holes to Precambrian basement rocks. Thick lines are faults. Contour interval is in kilofeet on the basement rocks.

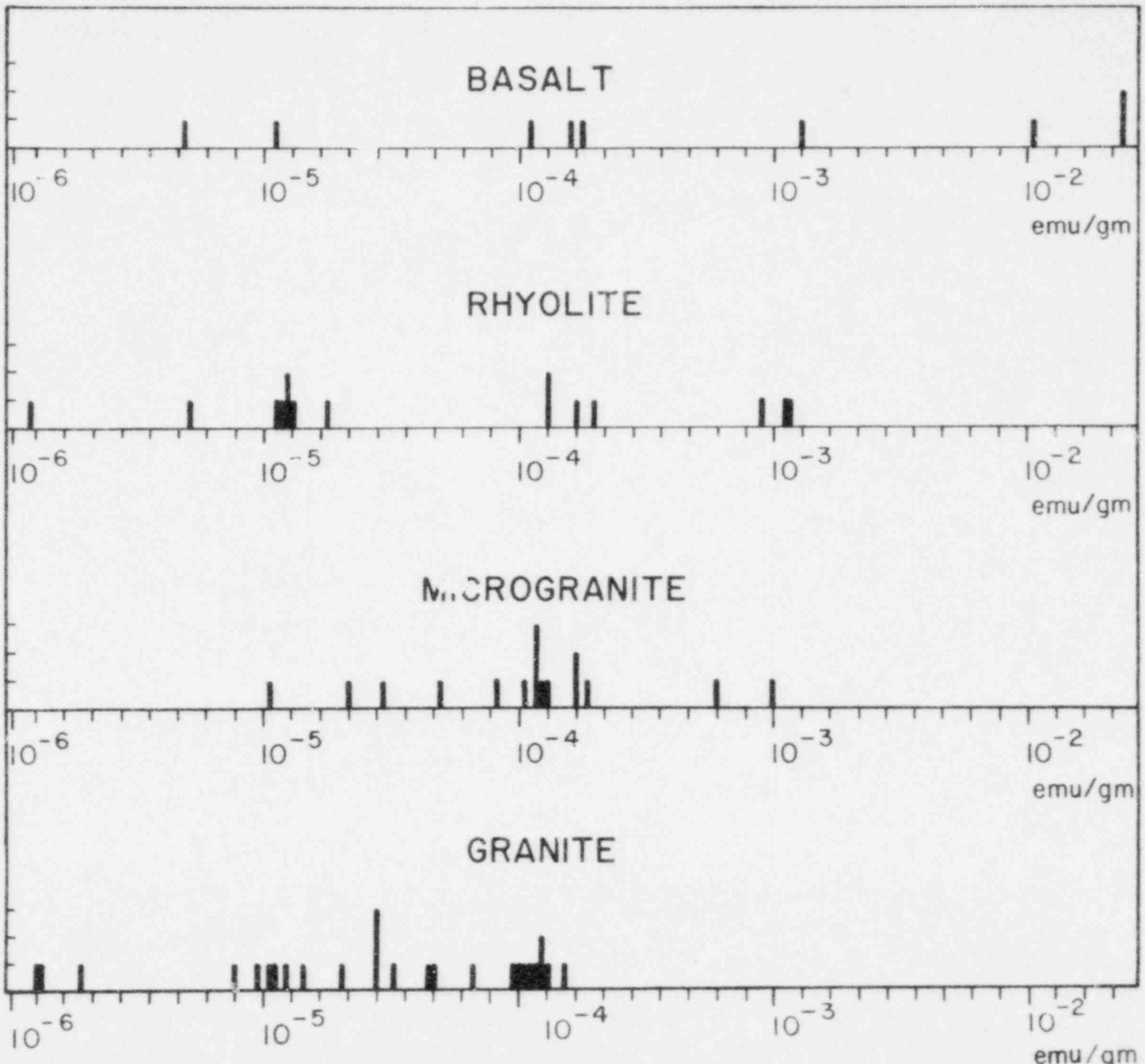


Figure 19a. NRM intensities of basement rocks in the east-central midcontinent.

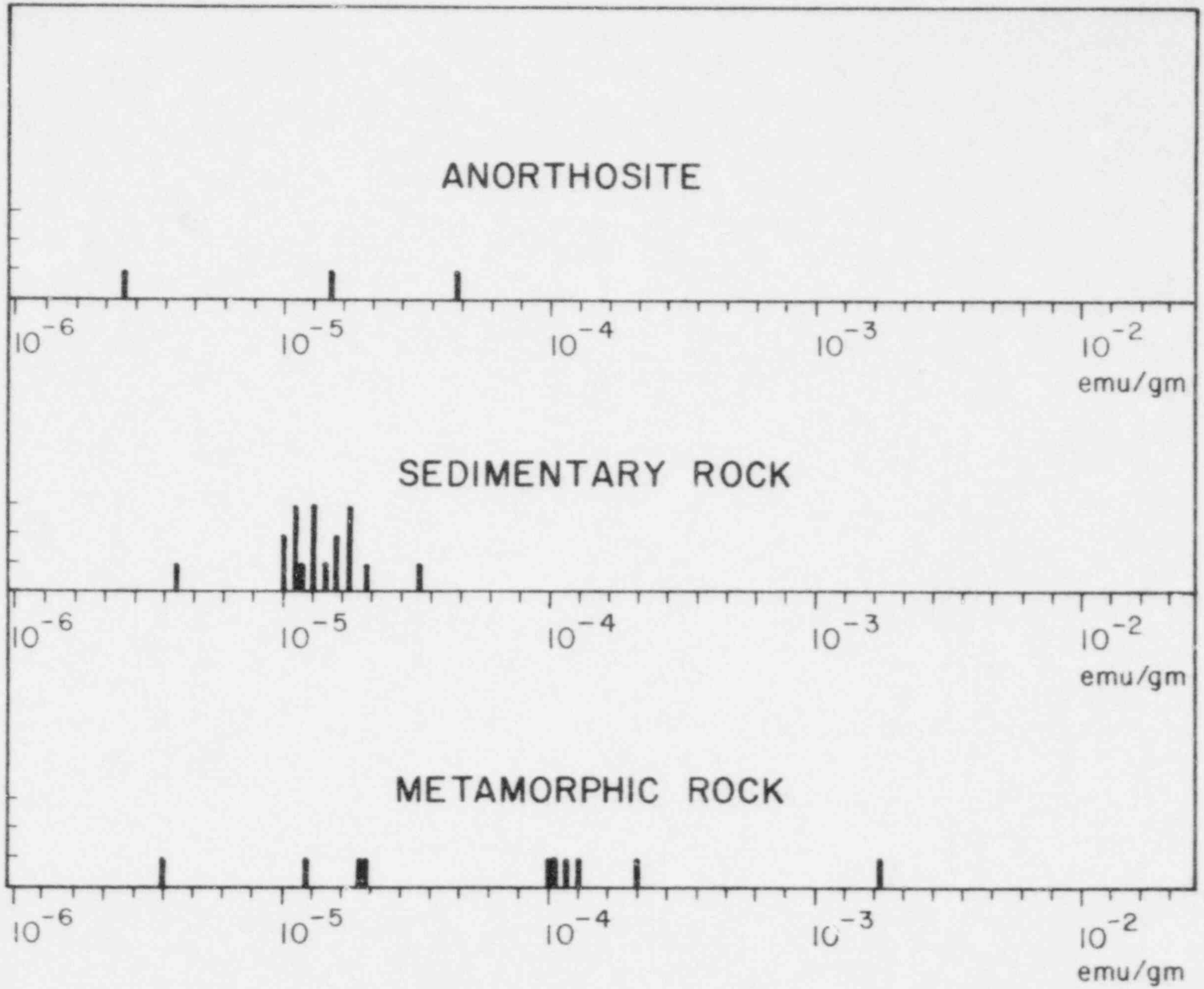


Figure 19b. NRM intensities of basement rocks in the east-central midcontinent.

Table 1. Natural remanent magnetization (NRM)

of basement rocks in the east-central midcontinent.

Well Name	County	Location	NRM ($\frac{emu}{gm}$)	Rock Type
Illinois				
Maryland #15 Kircheis	Madison	27-3N-6W	7.180×10^{-5}	potassic granite
P-E #1-21 Mumford	Pike	21-5S-4W	2.354×10^{-4}	microgranite
Schulte #1 Wyman	DeKalb	35-41N-5E	4.624×10^{-3}	granite
Carr #1 Vedovell	Lee	35-20N-10E	2.101×10^{-4}	microgranite
Mississippi R. #A-15 Theobald	Monroe	35-1S-10W	1.292×10^{-5}	granophyre
Lawinger #1 Miller	La Salle	1-36N-4E	1.745×10^{-4}	granite
Otto #1 Swenson	La Salle	1-36N-5E	7.790×10^{-5}	granite
Vickery #1 Mathesius	La Salle	32-35N-1E	1.906×10^{-4}	one flsp granite
Kelly #1 Fullerton	Mercer	19-13N-4W	1.816×10^{-4}	granite
Humble #1 Weaber-Horn	Fayette	28-8N-3E	3.689×10^{-4}	rhyolite prophyry
Reed #1 McCoy	Will	20-35N-9E	3.560×10^{-6}	granite
Brehm #1 Hemminghaus	Clinton	33-3N-1W	1.364×10^{-3}	rhyolite
Texas Pacific #1 Farley	Johnson	34-13S-3E	6.470×10^{-6}	sandstone
" "	"	" "	3.294×10^{-5}	red sandstone
" "	"	" "	3.715×10^{-5}	red sandstone
" "	"	" "	1.142×10^{-5}	red sandstone
" "	"	" "	2.074×10^{-5}	red sandstone
" "	"	" "	2.489×10^{-5}	red sandstone
" "	"	" "	1.447×10^{-5}	red sandstone
" "	"	" "	1.115×10^{-5}	red siltstone
" "	"	" "	1.393×10^{-5}	red sandstone
" "	"	" "	1.417×10^{-5}	red siltstone
" "	"	" "	5.536×10^{-5}	red sandstone
" "	"	" "	2.798×10^{-5}	red siltstone
" "	"	" "	3.287×10^{-5}	red sandstone
" "	"	" "	2.704×10^{-5}	red sandstone
" "	"	" "	1.635×10^{-5}	red sandstone
" "	"	" "	3.132×10^{-5}	red sandstone
Texaco #1 Cuppy	Hamilton	6-6S-7E	5.293×10^{-5}	granite
Texaco #1 Johnson	Marion	6-1N-2E	6.548×10^{-5}	granite
Union #1 Cisne	Wayne	3-1S-7E	1.597×10^{-4}	rhyolite prophyry
No. Illinois #1 Lillard	Henderson	14-9N-5W	5.056×10^{-5}	granite
Indiana				
NIPSCO 3L Leuenberger	Allen	14-29N-14E	1.480×10^{-5}	basalt
Tecumseh #1 Gibson	Allen	33-29N-12E	1.347×10^{-2}	basalt
Inland Steel #WD-1	Lake	14-37N-9E	9.830×10^{-6}	granite

Table 1. (cont.)

Well Name	County	Location	NRM $(\frac{emu}{gm})$	Rock Type
Texas #2614 Brown	Lawrence	20-5N-2E	7.264×10^{-6}	basalt
Texas #2614 Brown	Lawrence	20-5N-2E	7.455×10^{-5}	rhyolite
NIPSCO #1 Ames	Marshall	21-34N-3E	1.844×10^{-5}	rhyolite
NIPSCO #1 Ames	Marshall	21-34N-3E	1.381 x 10[illegible]	basalt
Stoltenberg #WD-1	Porter	16-35N-5W	1.345×10^{-5}	rhyolite
Bethlehem #WD-1	Porter	28-37N-6W	9.767×10^{-5}	granite
Bethlehem #WD-2C	Porter	29-37N-6W	8.945×10^{-6}	granite
Midwest #WD-1	Porter	25-37N-7W	1.949×10^{-6}	granite
Swager #1 Swager	Steuben	15-38N-14E	5.006×10^{-6}	granite
Swager #1 Swager	Steuben	15-38N-14E	4.350×10^{-2}	basalt
Swager #1 Swager	Steuben	15-38N-14E	4.296×10^{-2}	basalt
Swager #1 Swager	Steuben	15-38N-14E	2.220×10^{-6}	granite
Ashland #1 Collins	Switzerland	4-2N-1W	2.897×10^{-5}	arkose
Ashland #1 Hudson	Wabash	25-29N-6E	9.198×10^{-4}	microgranite
Gordon #1 Doddridge	Wayne	23-15N-13E	1.059×10^{-4}	microgranite
Farm #1 Binegar	Jay	29-24N-13E	3.766×10^{-5}	granite (?)
Kokomo #1 Greentown	Howard	32-24N-5E	1.048×10^{-3}	microgranite
Petroleum #1 Binegar	Jay	29-24N-13E	1.825×10^{-3}	sedimentary rock
Ohio #1 May	Henry	12-16N-11E	1.270×10^{-4}	microgranite
NIPSCO #2 Pfeil	Fulton	32-29N-1E	4.080×10^{-5}	microgranite
Gulf #1 Scott	Fayette	32-13N-13E	1.820 x 10-5	rhyolite
Kentucky				
Kentucky Cent. #1 Perkins	Rowan	21-T-74	9.55×10^{-4}	microgranite
Exxon #1 Bell	Webster	23-N-24	3.18×10^{-4}	basalt
Exxon #1 Bell	Webster	23-N-24	1.93×10^{-5}	Arkose
Union #1 Mynear	Nicholas	16-X-66	1.67×10^{-5}	rhyolite
California #1 Spears	Lincoln	13-L-57	2.0[illegible] x 10^{-4}	quartz trachyte
Signal #1 Elkhorn	Johnson	7-P-82	1.24×10^{-4}	mica schist
Monitor #1 Campbell	Menifee	14-Q-72	1.85×10^{-4}	granite
Monitor #1 Blanton	Morgan	23-R-73	1.83×10^{-5}	granite
Monitor #1 Blanton	Morgan	23-R-73	6.01×10^{-6}	mica schist
Signal #1 Stratton	Pike	8-L-85	5.60×10^{-5}	granite
Signal #1 Stratton	Pike	8-L-85	6.81×10^{-5}	granite
Signal #1 Stratton Pike	Pike	8-L-85	1.06×10^{-3}	granite
Inland #551 Smallridge	Boyd	25-W-83	6.75×10^{-5}	anorthosite
Texaco #1 Scherrer	Jessamine	6-P-60	2.49×10^{-5}	altered basalt
Texaco #1 Scherrer	Jessamine	6-P-60	2.78×10^{-4}	basalt
Ashland #1 Wilson	Campbell	25-DD-62	2.072×10^{-3}	basalt
Kin-Ark #1 Hager	Jessamine	2-P-60	1.753×10^{-5}	mica schist
Texaco #1 Wolfinbarger	Jessamine	1-P-60	3.245×10^{-5}	meta rhyolite
United #9061-T Rawlings	Mason	15-Y-71	3.944×10^{-4}	garnet gneiss
Benz #1 Nunnally	Metcalfe	16-F-46	3.024×10^{-4}	Na rhyolite
Amerada-Hess #1 Daulton	Pulaski	14-H-59	1.564×10^{-3}	rhyolite

Table 1. (cont.)

Well Name	County	Location	NRM ($\frac{emu}{gm}$)	Rock Type
Amerada-Hess #1 Edwards Pulaski	Pulaski	24-H-60	3.853×10^{-5}	chlorite schist
Inland #533 Fee	Boyd	11-V-81	4.510×10^{-6}	ancrthosite
Inland #537 Fannin	Boyd	22-W-82	3.602×10^{-5}	anorthosite
Cabot & Ashland #1 Stapleton	Carter	12-V-77	3.690×10^{-4}	diorite
Common wealth #1 Newell	Greenup	7-Z-78	3.624×10^{-5}	granite gneiss
Thomas #1 Adams	Lewis	13-Y-76	1.394×10^{-4}	diorite
United #9060T Shepherd	Lewis	19-W-75	2.930×10^{-4}	microgranite
Texaco #1 Perkins	Madison	11-P-61	3.133×10^{-3}	hornblende schist
F & B #16-1 Potter	Montgomery	8-7-67	1.661×10^{-4}	granite gneiss
Ashland #1 Lee Clay	Morgan	14-S-75	1.976×10^{-4}	granite gneiss
Pennzoil #1 Jones	Rowan	4-T-75	1.065×10^{-4}	granite gneiss
Tennessee				
California #1 Beeler	Giles	4-15S-29E	8.04×10^{-4}	microgranite
Big Chief #1 Taylor	Gibson	19-5S-6E	6.92×10^{-5}	granite
Stauffer #1 Fee	Maury	16-12S-28E	1.81×10^{-5}	rhyolite
Stauffer #1 Fee	Maury	16-12S-28E	1.94×10^{-4}	granite
Dupont #1 Fee	Davidson	16-3S-35E	1.30×10^{-4}	granite
Driver	DeKalb	25-6S-44E	2.58×10^{-5}	rhyolite

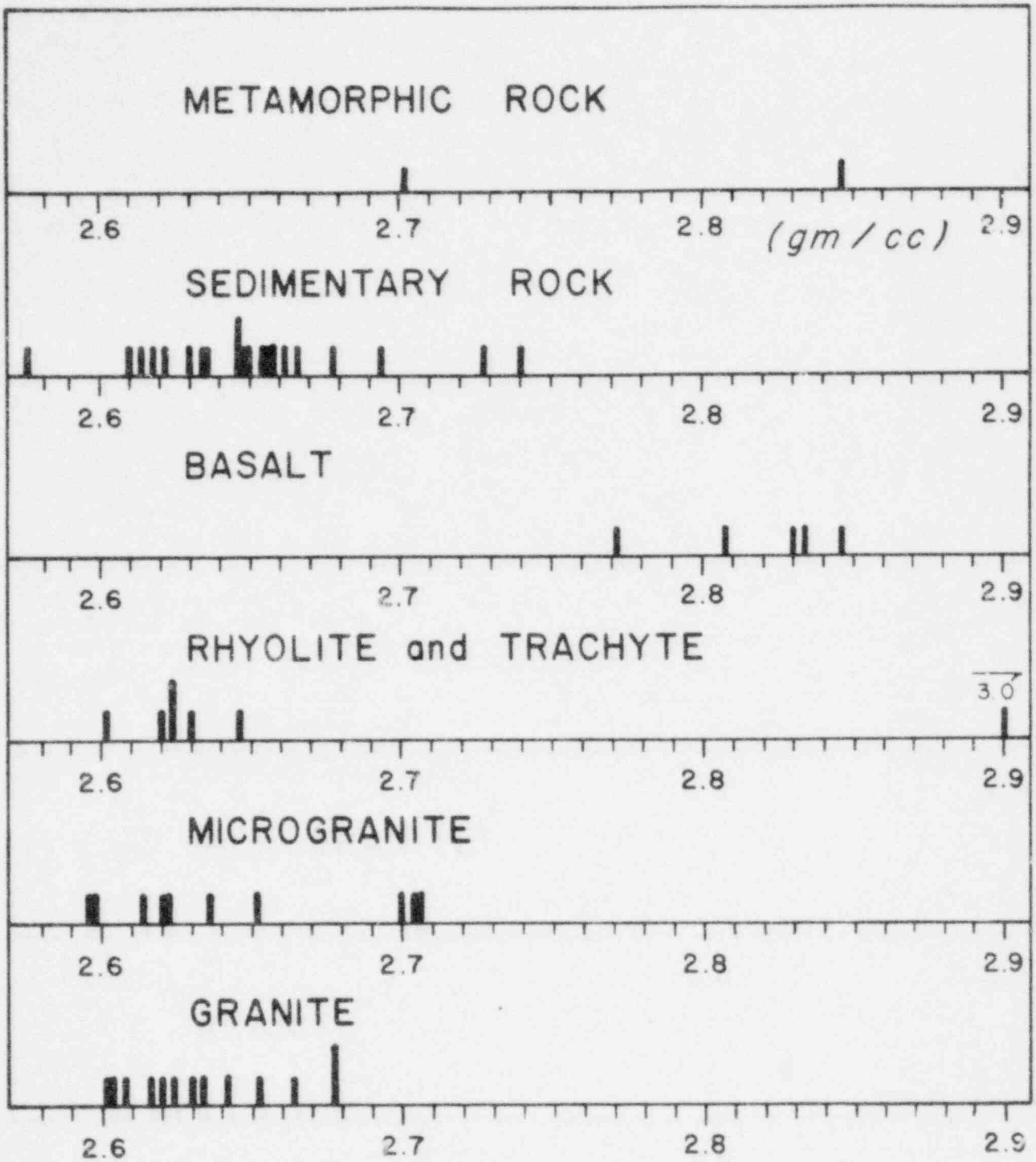


Figure 20. Density (gm/cc) of basement rocks from Illinois and Indiana.

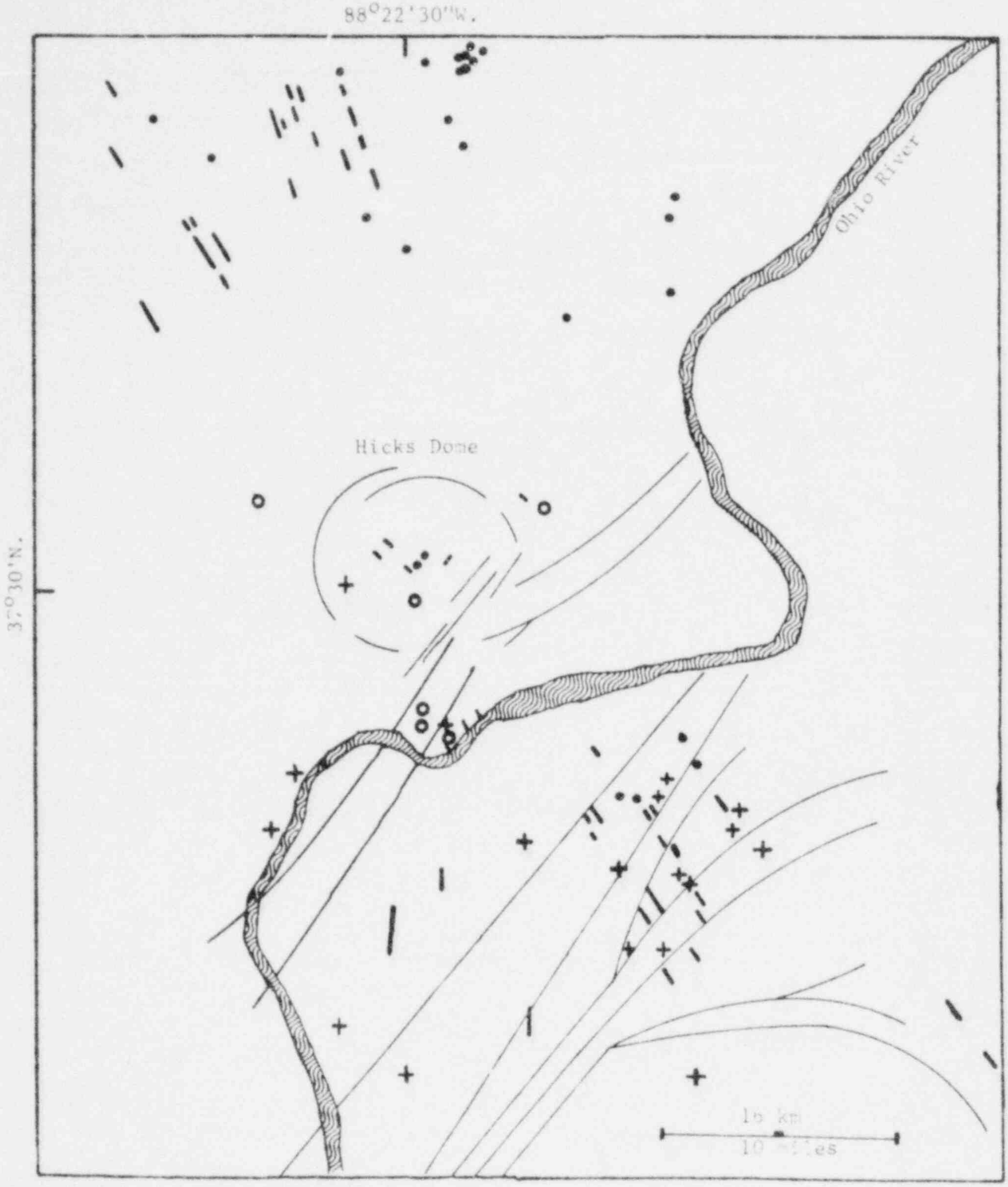


Figure 21. Distribution of mafic and ultramafic intrusions in southern Illinois and western Kentucky. Thin solid lines, high angle faults; thick solid lines, surface dikes showing trend; plus symbol, surface dike with unknown trend; open circle, surface igneous diatreme; closed circle, subsurface dikes in drill holes.

Two Rb-Sr age determinations on granite xenoliths incorporated in ultramafic intrusions of nearby southeastern Missouri have been completed. Ages of 1215 ± 20 m.y. and 1345 ± 21 m.y. (half-life = 4.8 b.y.) are comparable to ages of granites from the St. Francois Mountains.

SEISMIC MEASUREMENTS AND ANALYSIS

Crustal Seismic Studies - Nine seismic profiles have been recorded from coal mine blasts in the Wabash River Valley area of southwestern Indiana and adjacent portions of Illinois to investigate the crustal structure in the area of the possible extension of the New Madrid Fault Zone. Statistics of the profiles are given in Table 2 and their geographic location is shown on Figure 22. Profiles 2 and 6 were analyzed together and profile 9 is too short to obtain meaningful results.

Record sections for the profiles are presented (Figures 23 to 36) based upon a reducing velocities of 6.0 km/sec for compressional wave analysis and 3.5 km/sec for shear wave analysis. A flow chart illustrating the data processing sequence is shown in Figure 37. A significant aspect of the data is the relatively strong energy of the shear waves - direct, reflected and refracted - probably as a result of the ripple-fired areal patterns of the explosive sources (Figure 38). As a result, interpretation generally is based on both independent shear and compressional wave data, thereby reducing the ambiguity. The data were interpreted utilizing the assumption that the layers are horizontal and of homogeneous properties. The lines connecting similar events on the record sections (Figures 23 to 36) are largely derived from models which best fit the observed data. The results of this analysis are presented in Table 3. Layer velocities, thicknesses, and depth for each model are presented in Table 4 for compressional waves and in Table 5 for shear waves. Table 6 summarizes the number and general region of the crust from which refractions were interpreted and Figures 39 to 45 present in schematic form the results of the analysis for the individual profiles.

The models resulting from the analysis of the profiles confirm geologic studies that suggest the sedimentary layers thicken toward the Wabash River in the vicinity of its intersection with the Ohio River. The thickness of the basement layer is rather consistent on the profiles on which they were observed (1, 2, 4 and 7) except for Profile 7. The basement is thinner along

Table 2. Crustal seismic profile characteristics.

Line Number	Mine Source	Line Direction	Line Length (km)	Year Recorded
1	Minnehaha	SW	106	1978
2	Ayrshire	EW	147	1978
3	Burning Star #4	WE	69	1978
4	Ayrshire	NE	172	1979
5	Ayrshire	SE	33	1979
6	Ayrshire	EW	7[illegible]	1979
7	Wright	WE	50	1979
8	Wright	SE	25	1979
9	Wright	NW	6	1979

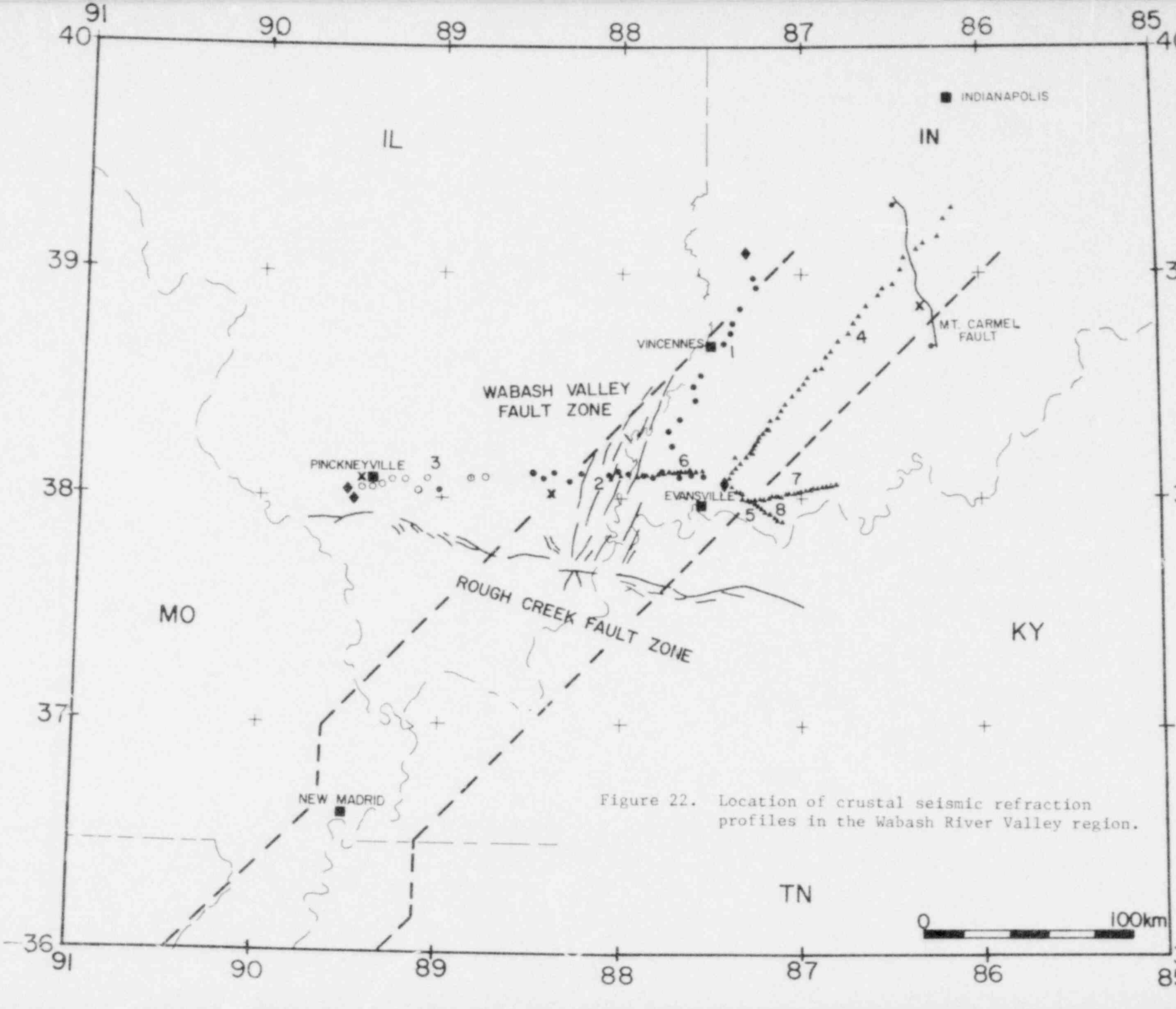


Figure 22. Location of crustal seismic refraction profiles in the Wabash River Valley region.

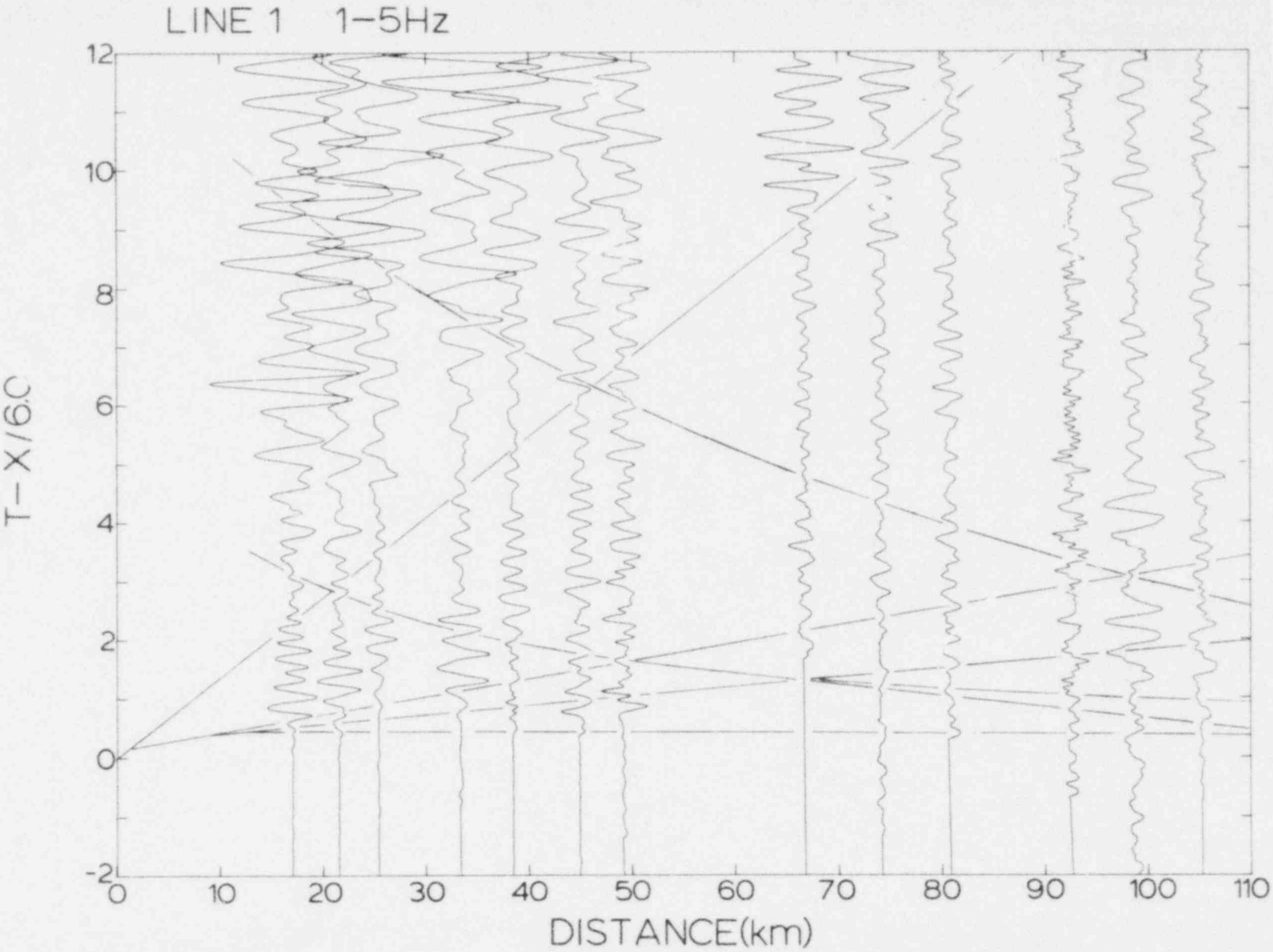


Figure 23. Crustal seismic refraction record section of Profile 1 based upon a reducing velocity of 6.0 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

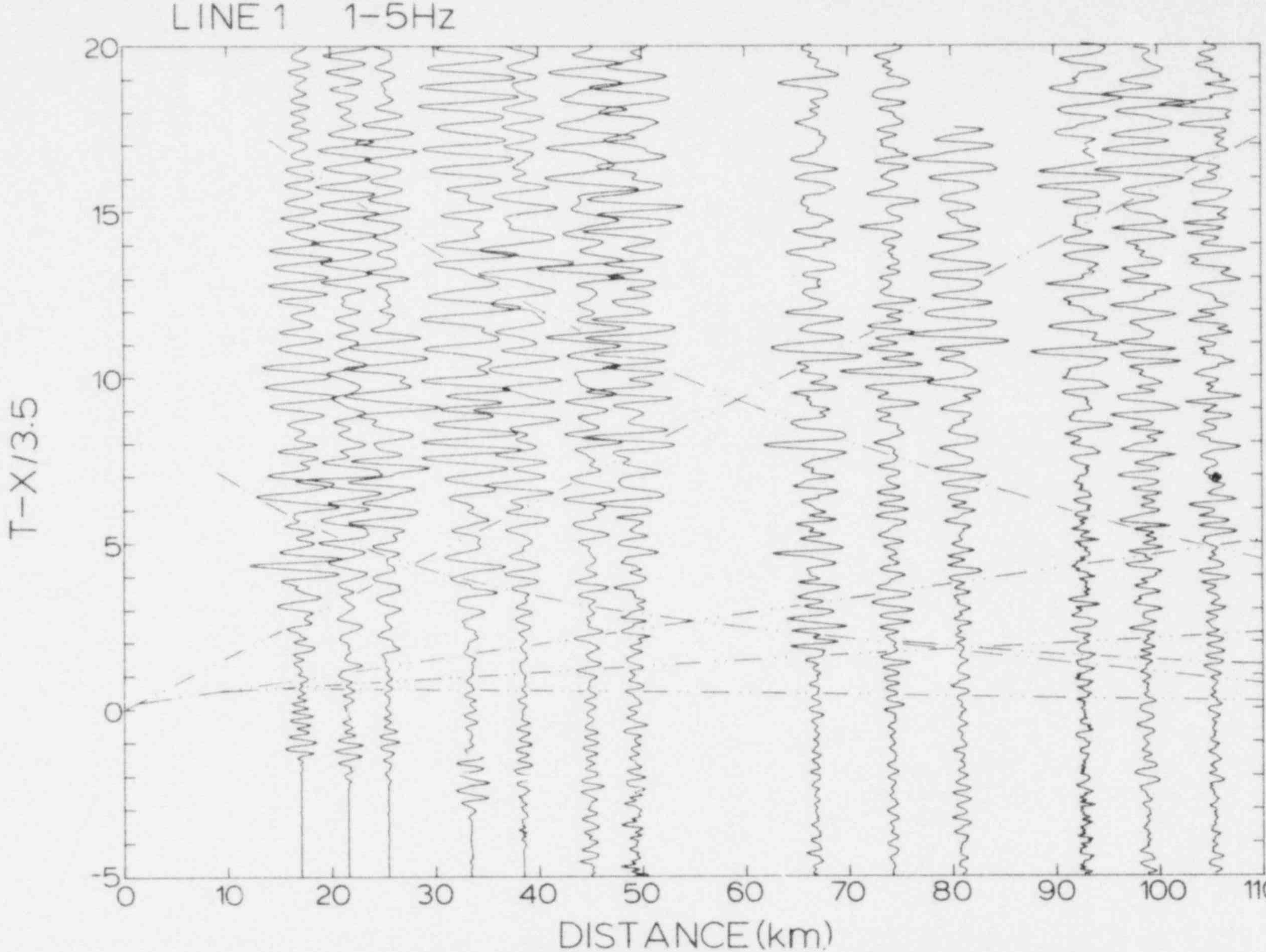


Figure 24. Crustal seismic refraction record section of Profile 1 based upon a reducing velocity of 3.5 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

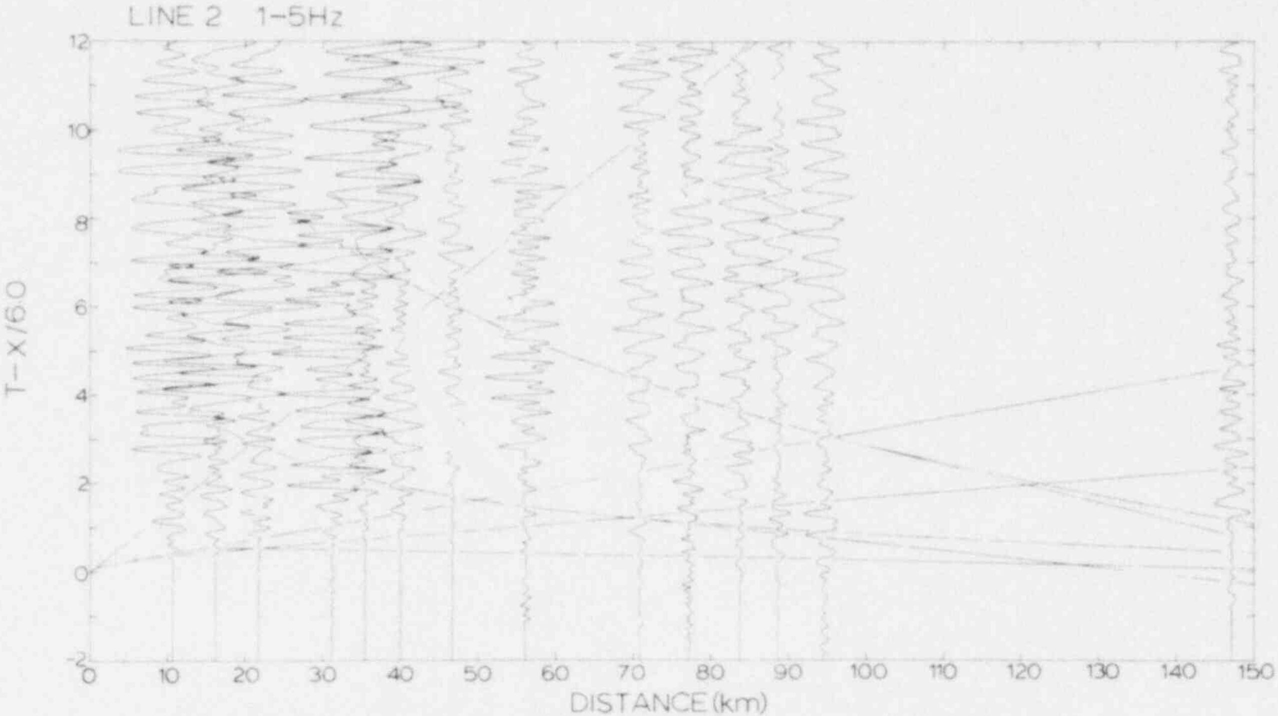


Figure 25. Crustal seismic refraction record section of Profile 2 based upon a reducing velocity of 6.0 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

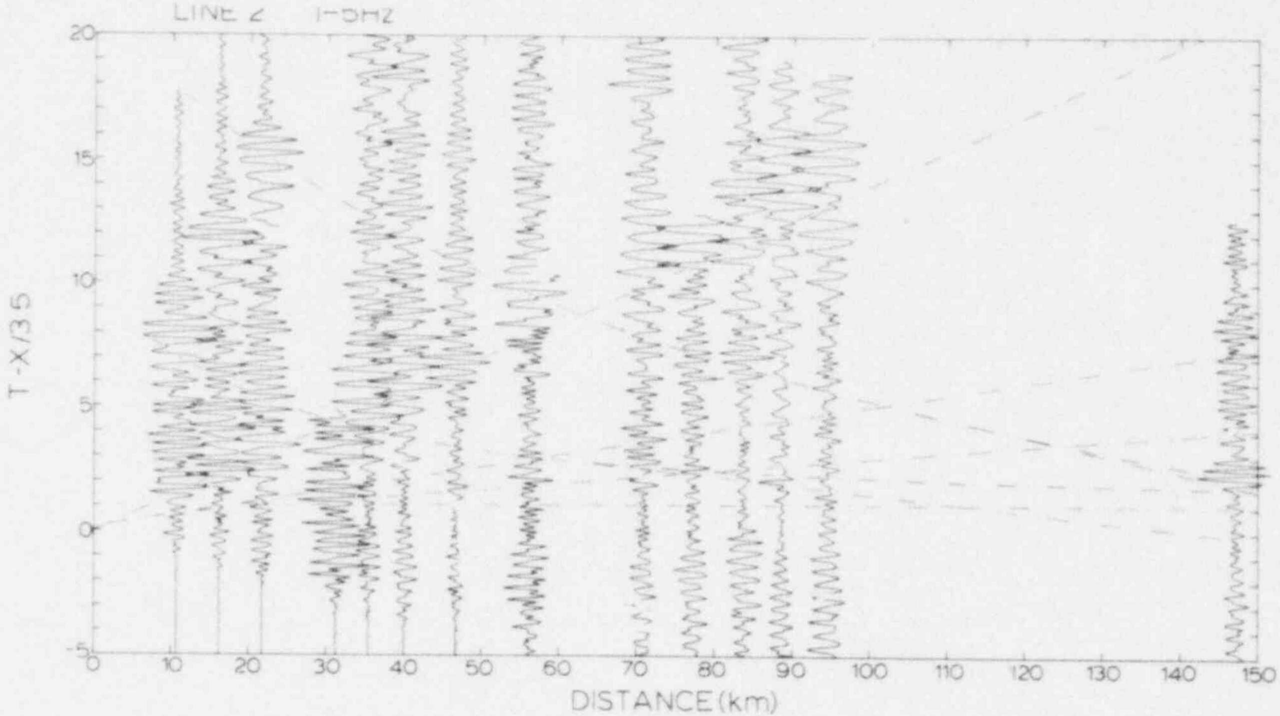


Figure 26. Crustal seismic refraction record section of Profile 2 based upon a reducing velocity of 3.5 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

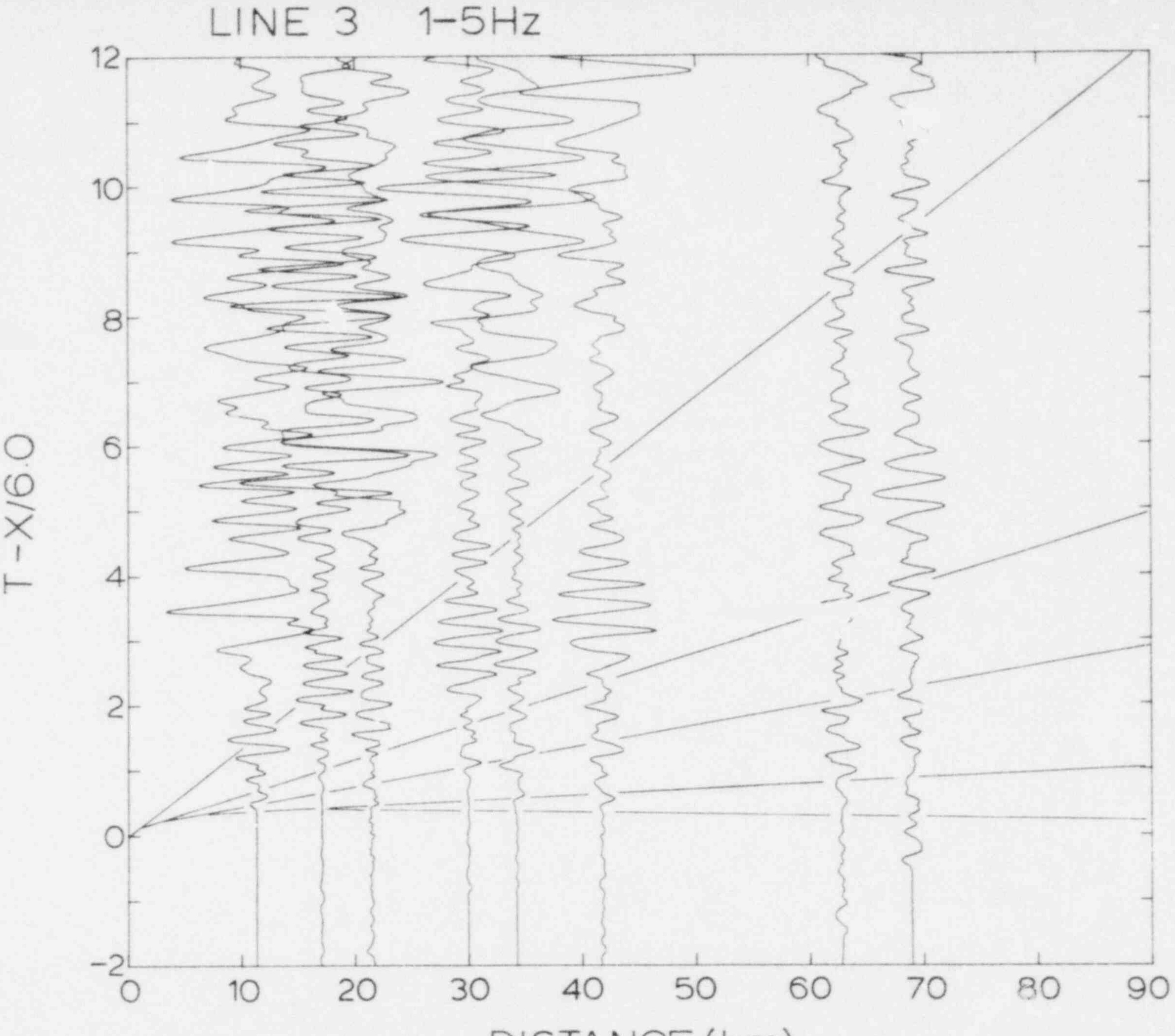


Figure 27. Crustal seismic refraction record section of Profile 3 based upon a reducing velocity of 6.0 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

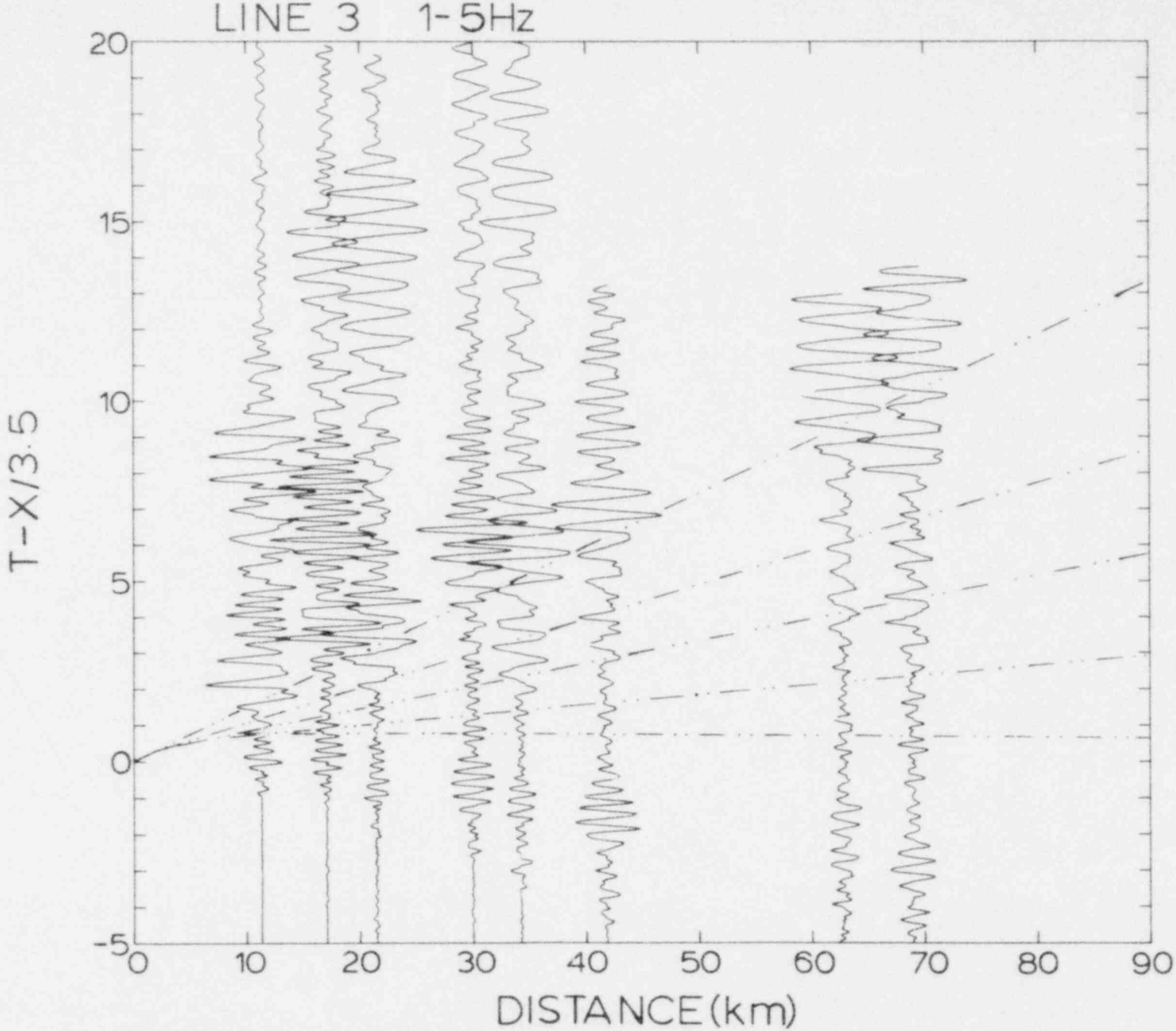


Figure 28. Crustal seismic refraction record section of Profile 3 based upon a reducing velocity of 3.5 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

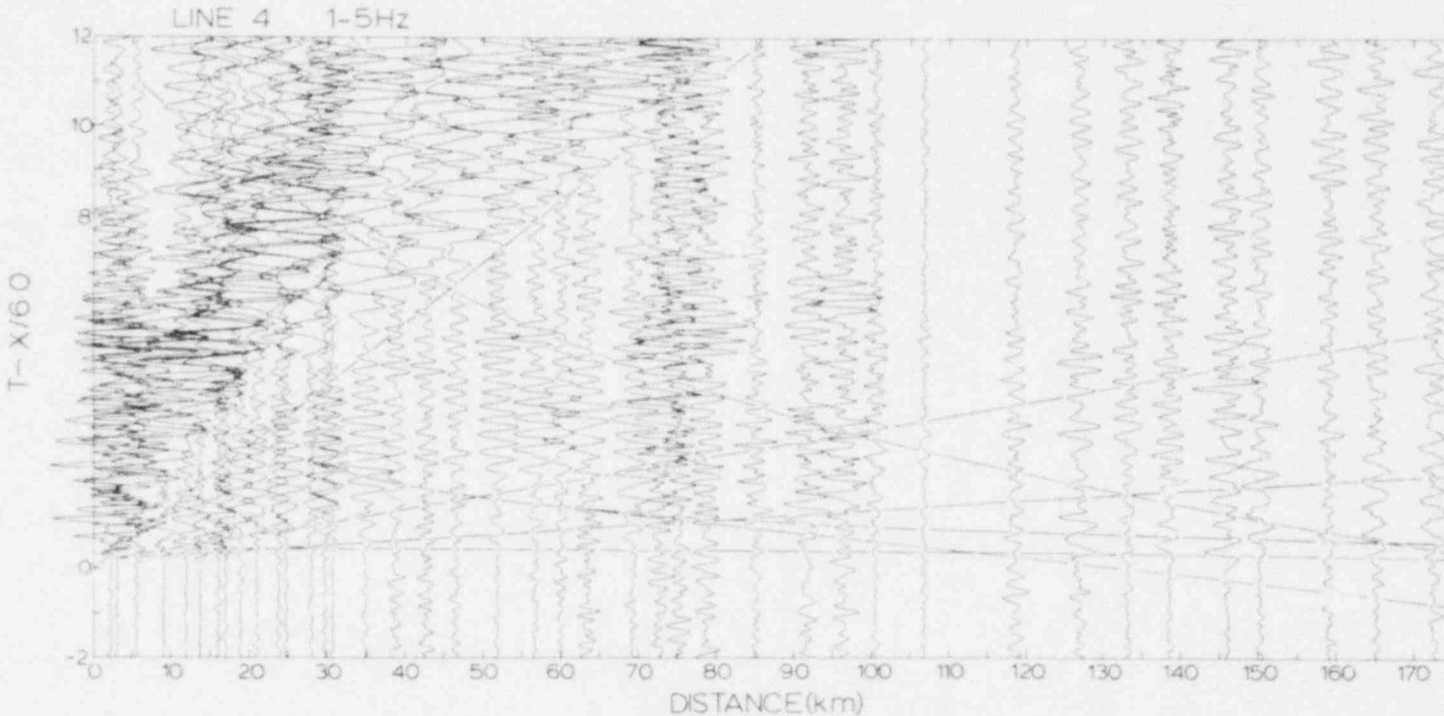


Figure 29. Crustal seismic refraction record section of Profile 4 based upon a reducing velocity of 6.0 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

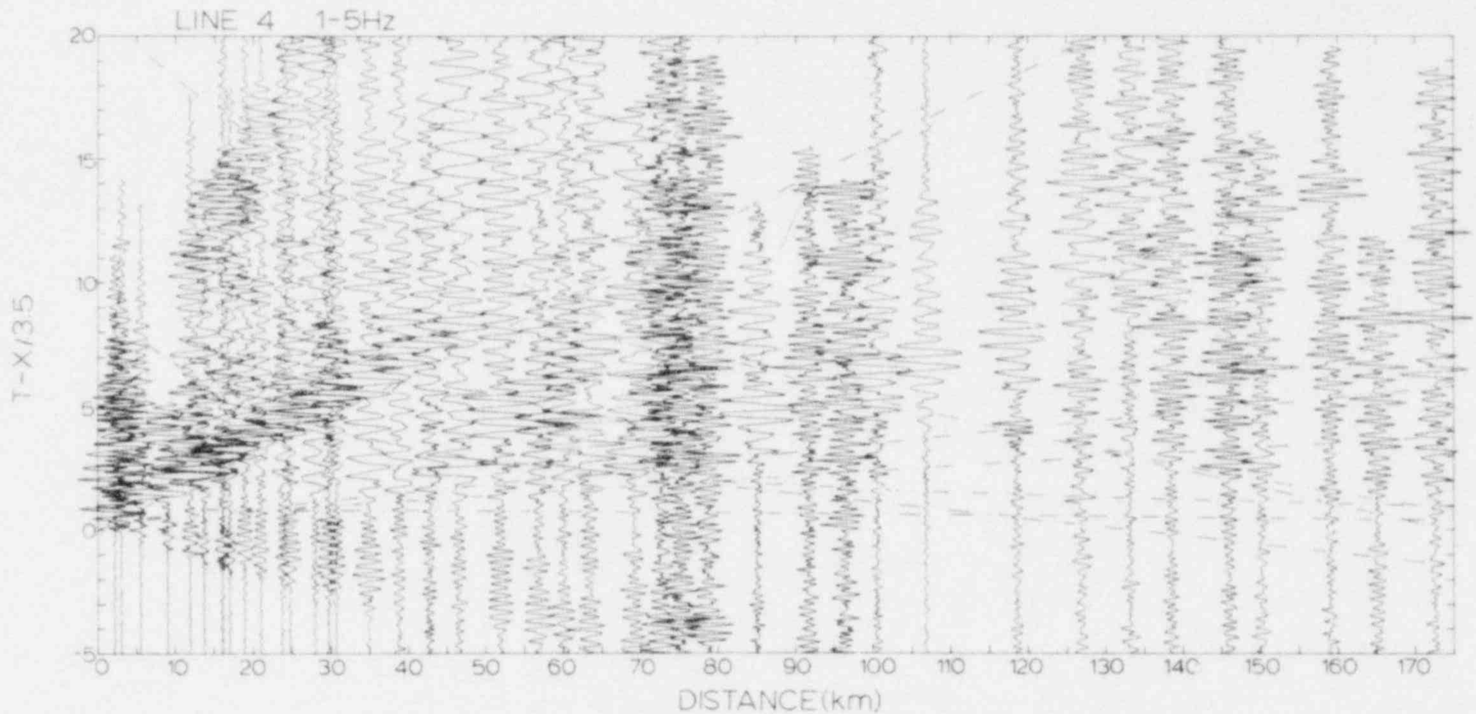


Figure 30. Crustal seismic refraction record section of Profile 4 based upon a reducing velocity of 3.5 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

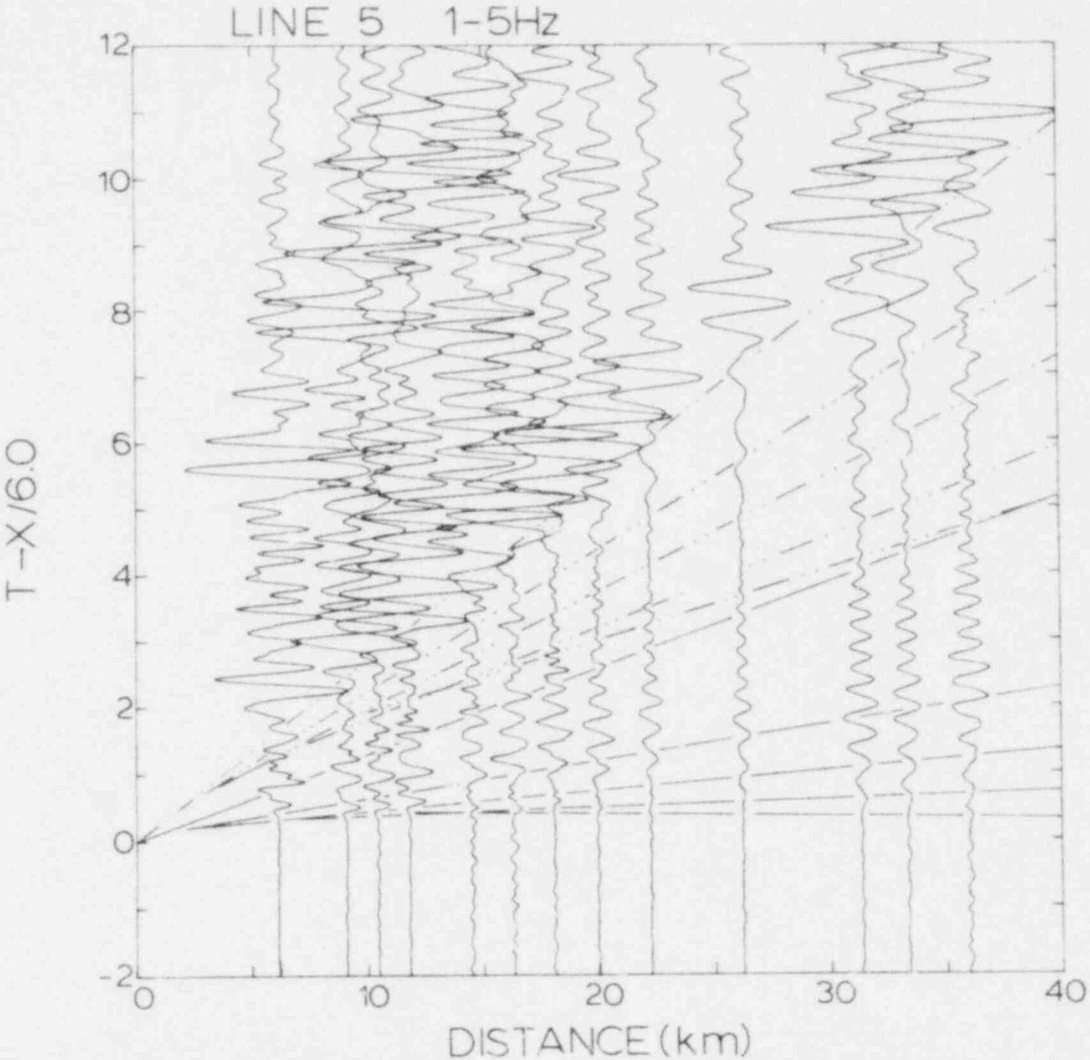


Figure 31. Crustal seismic refraction record section of Profile 5 based upon a reducing velocity of 6.0 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

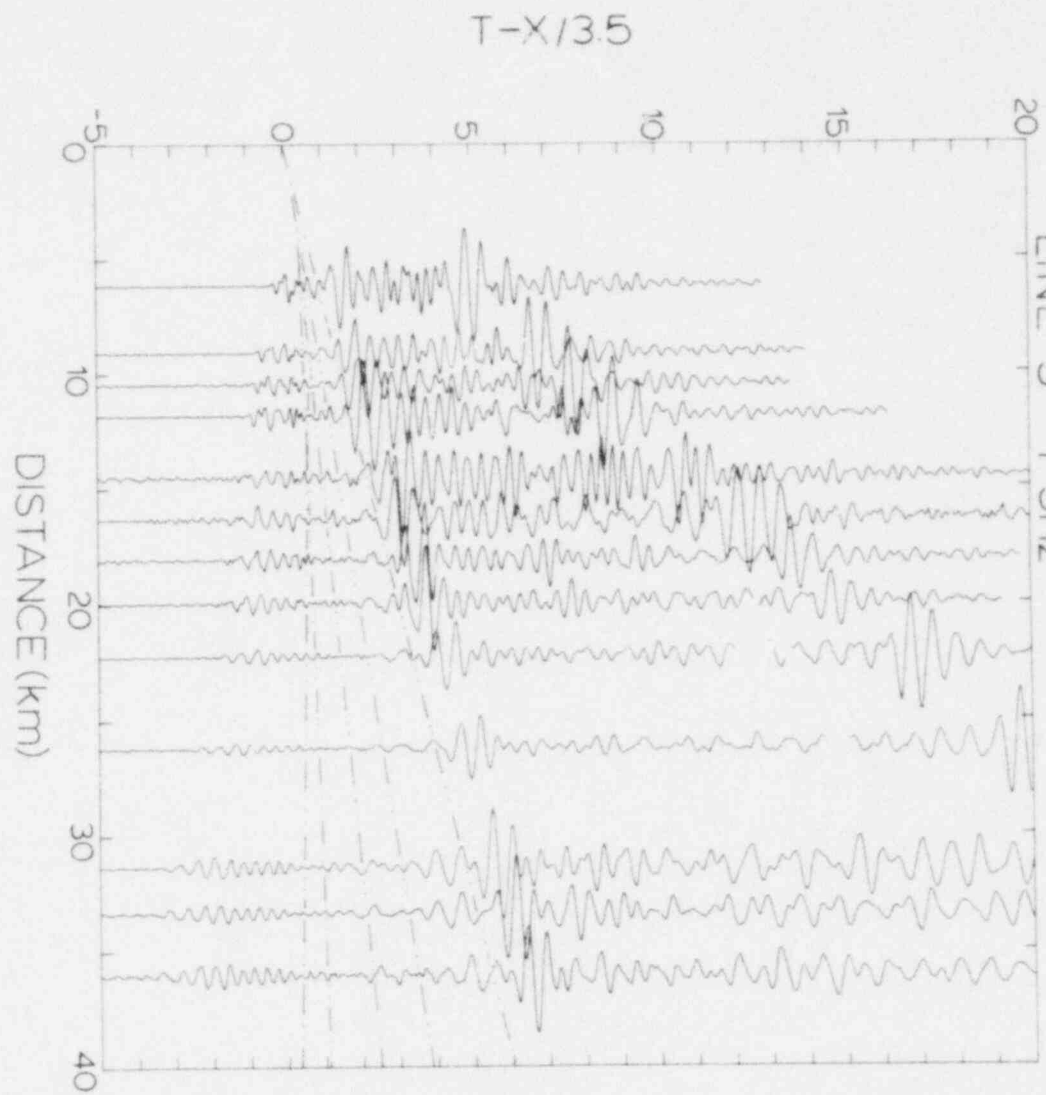


Figure 32. Crustal seismic refraction record section of Profile 5 based upon a reducing velocity of 3.5 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

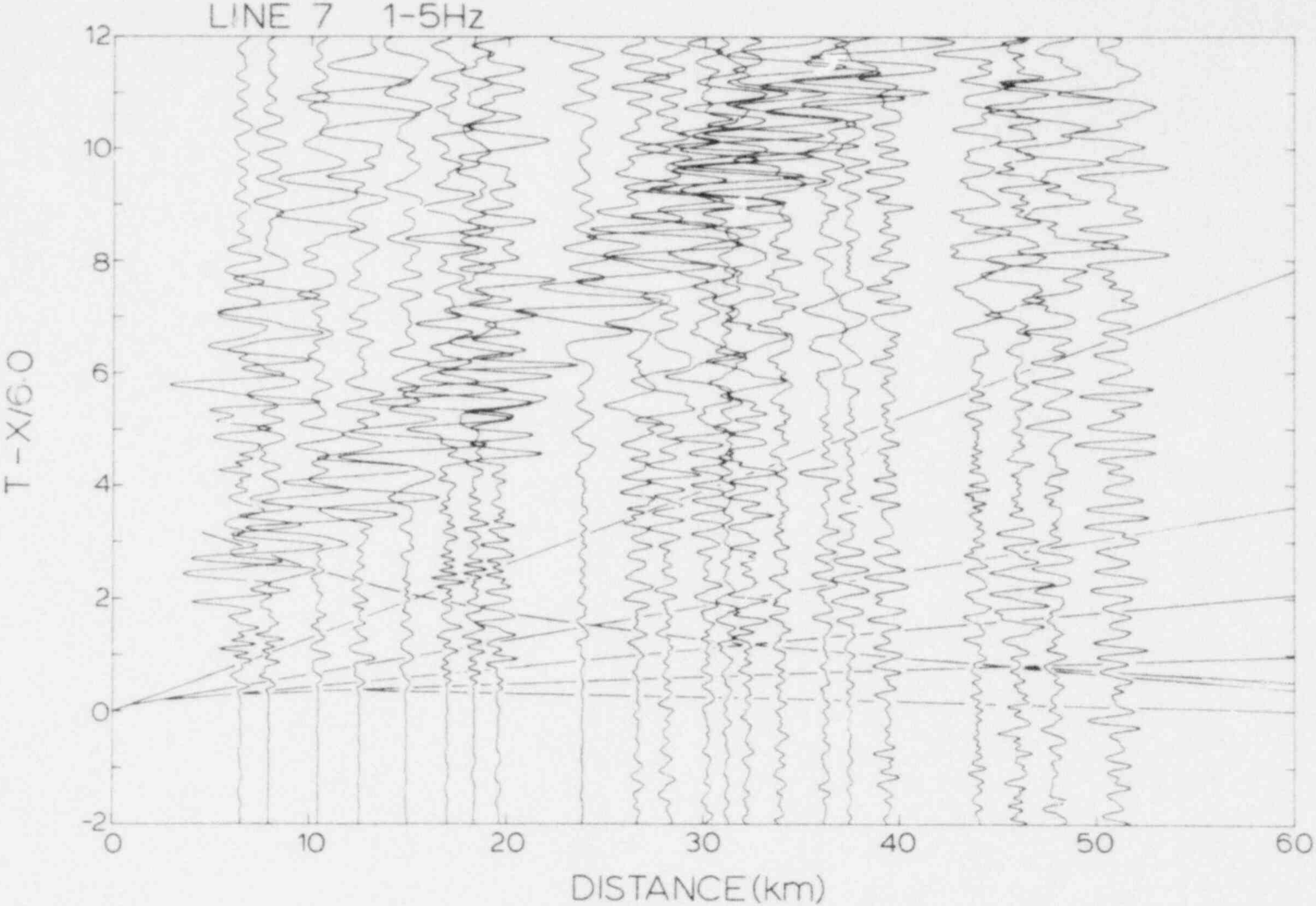


Figure 33. Crustal seismic refraction record section of Profile 7 based upon a reducing velocity of 6.0 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

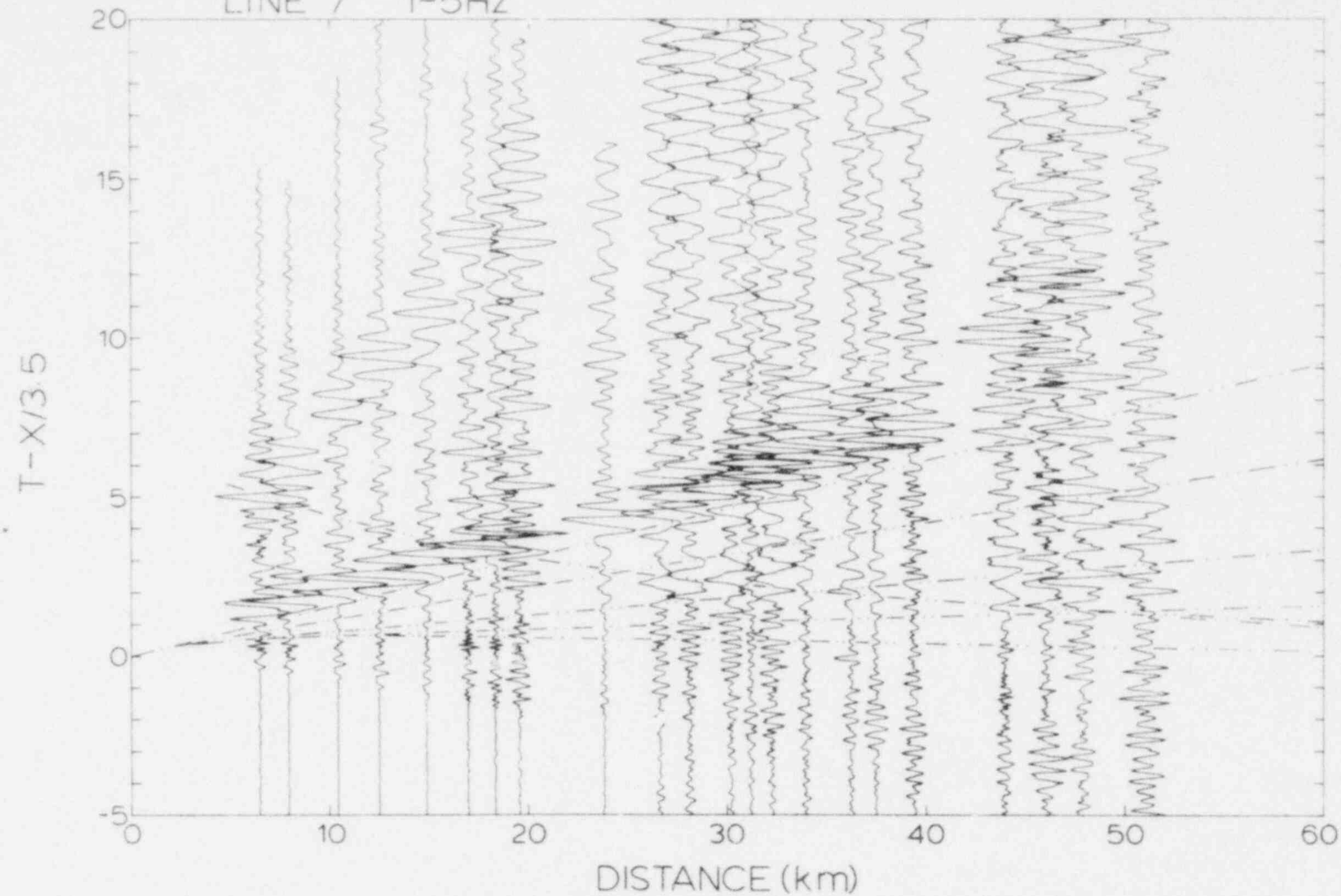


Figure 34. Crustal seismic refraction record section of Profile 7 based upon a reducing velocity of 3.5 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

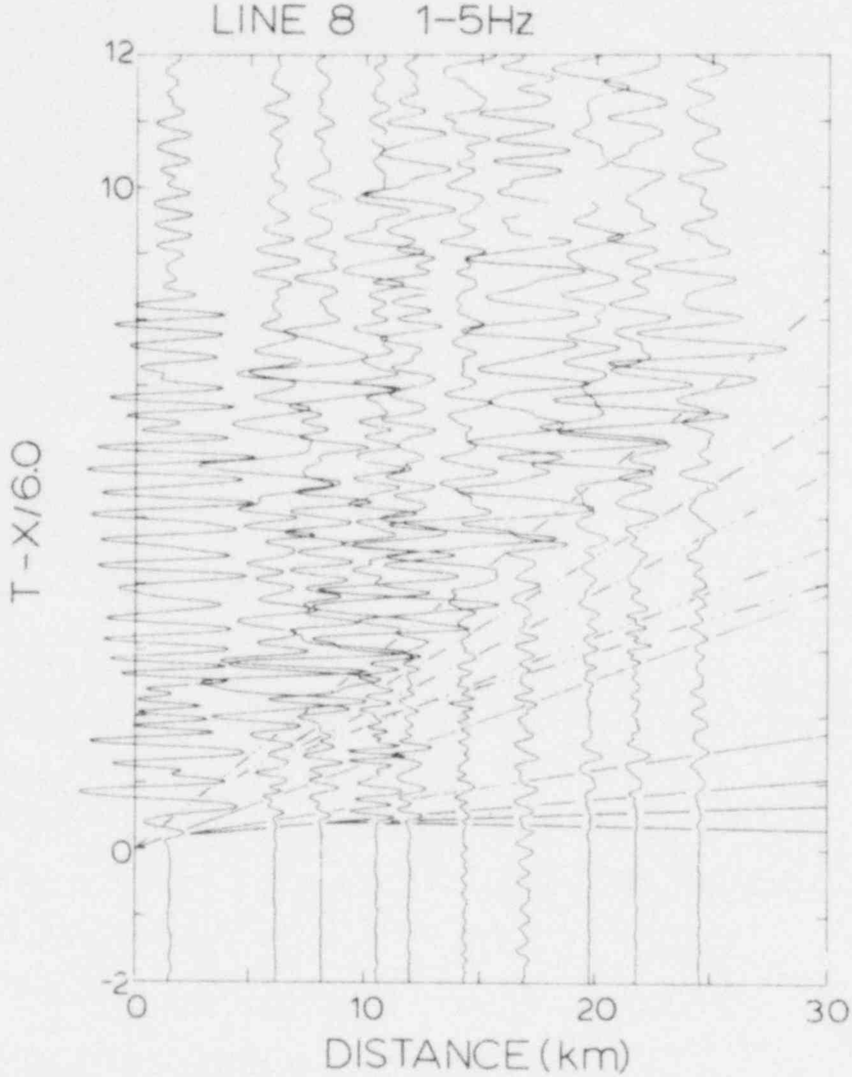


Figure 35. Crustal seismic refraction record section of Profile 8 based upon a reducing velocity of 6.0 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

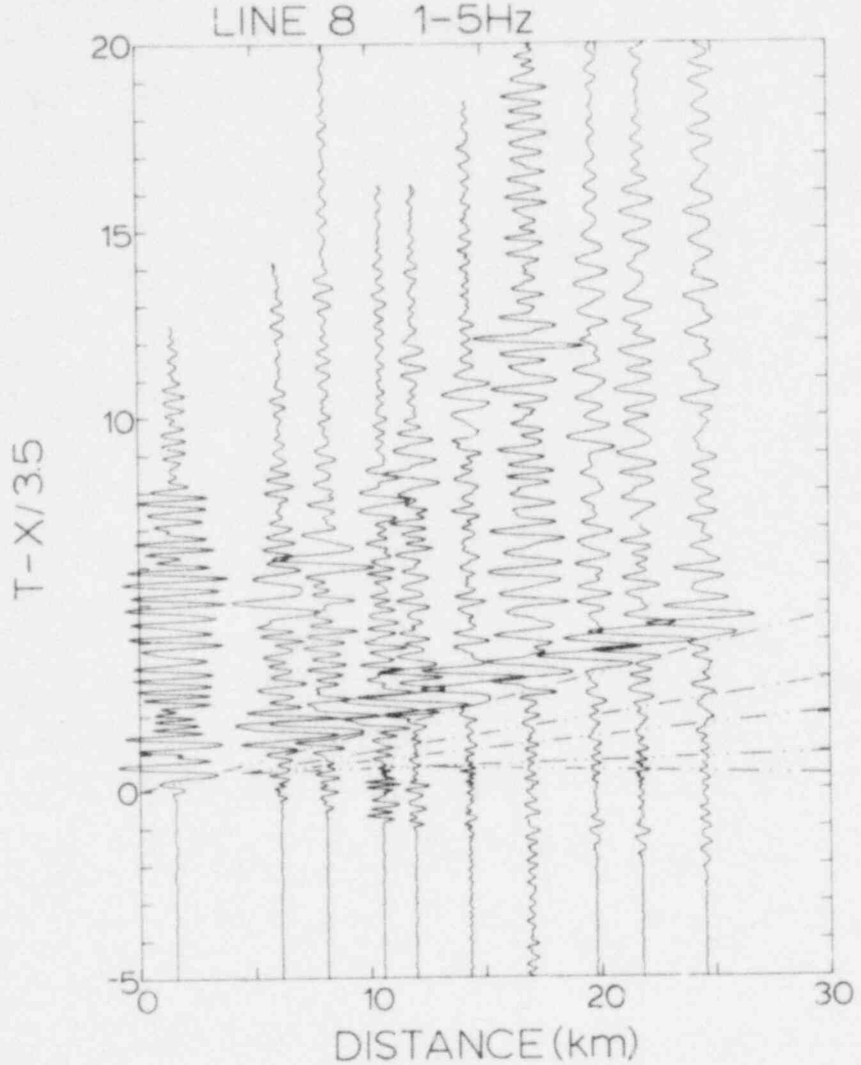


Figure 36. Crustal seismic refraction record section of Profile 8 based upon a reducing velocity of 3.5 km/sec. Lines are interpretation based upon modeled synthetic seismograms.

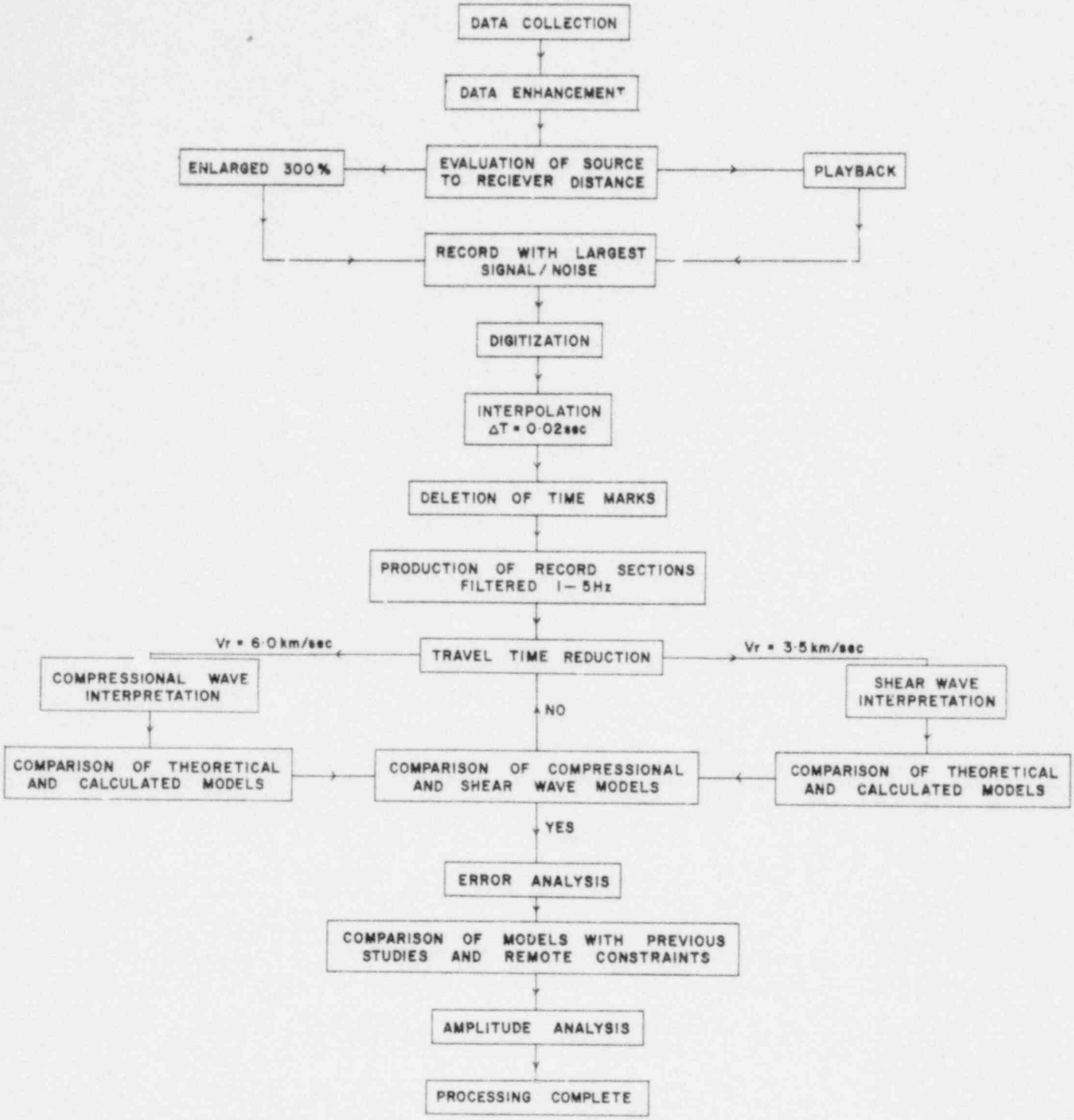


Figure 37. Crustal seismic refraction investigation flow chart.

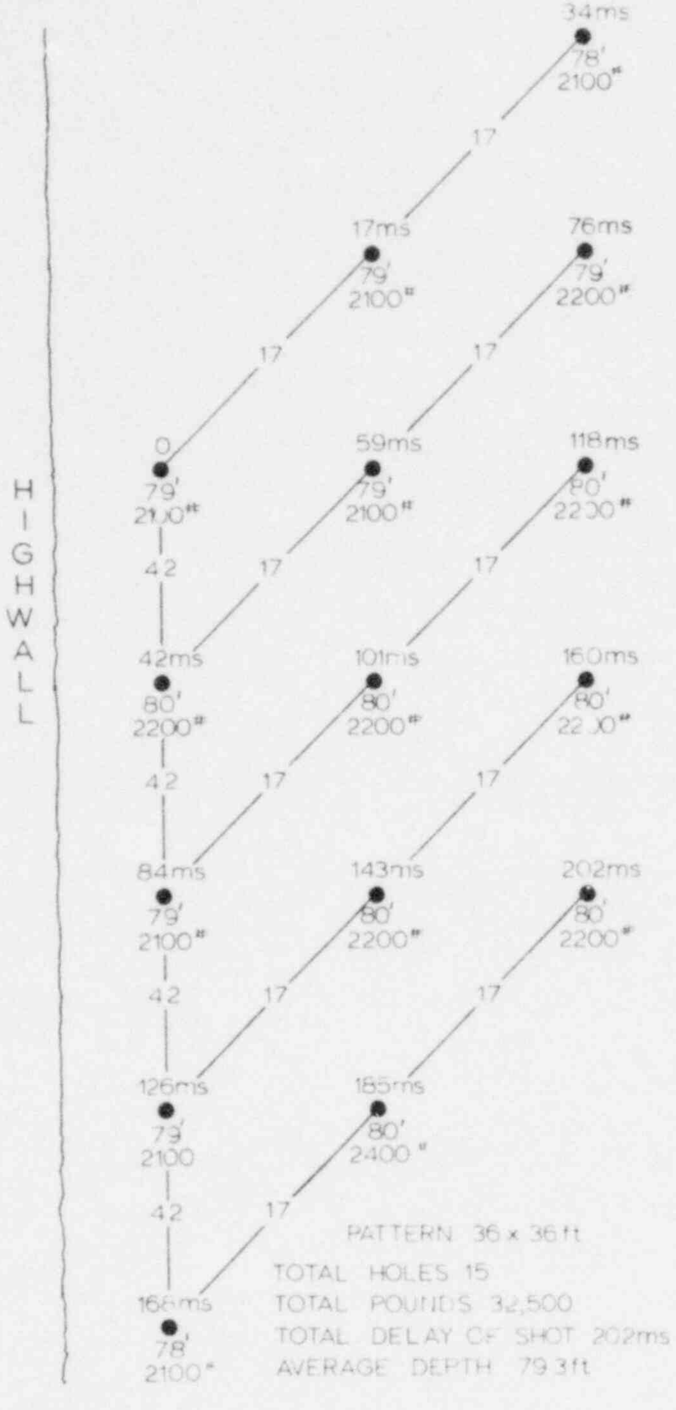


Figure 38. Typical areal pattern of ripple-fired coal mine blasts used as energy sources in crustal seismic investigations.

Table 3. Results of Wabash River Valley crustal seismic study.

Profile	Refractor	Shear Intercept sec	Velocity km/sec	Thickness km	Compressional Intercept sec	Velocity km/sec	Thickness km	Density** gm/cc	(V_P/V_S)
1	direct	0.0	2.25	.29	0.0	3.28	.28	1.68	1.46
	1	0.17	3.02	.91	0.13	5.08	.89	2.27	1.68
	2	0.43	3.30	1.11	0.27	5.49	1.03	2.41	1.66
	3	0.77	3.56 Sg	14.05	0.49	6.04 Pg	13.11	2.59	1.70
	4	4.47	3.97 S*	23.01	2.60	6.80 P*	23.08	2.84	1.71
	5	12.27	4.65 Sn	-	7.29	8.1 Pn	-	3.26	1.74
2 & 6	direct	0.0	2.34	.38	0.0	3.23	.34	1.67	1.38
	1	.20	2.99	1.00	.16	5.04	1.09	2.26	1.68
		.47	3.22	2.06	.35	5.52	1.98	2.42	1.71
	3	1.09	3.50 Sg	12.90	.74	6.13 Pg	12.63	2.62	1.75
	4	5.00	3.99 S*	22.15	2.60	6.74 P*	21.48	2.82	1.69
	5	12.27	4.65 Sn	-	7.29	8.1 Pn	-	3.26	1.74
3	direct	0.0	2.30	.20	0.0	3.31	.19	1.69	1.44
	1	.08	2.62	.23	.08	4.41	.24	2.05	1.68
	2	.18	2.87	.78	.142	5.07	.76	2.27	1.77
	3	.46	3.19	.96	.30	5.66	.94	2.46	1.77
	4	.82	3.52 Sg	-	.46	6.1 Pg	-	2.61	1.73
4	direct	0.0	2.26	.29	0.0	3.27	.29	1.68	1.45
	1	.18	3.14	.89	.13	5.08	.91	2.27	1.62
	2	.34	3.27	1.70	.30	5.65	1.73	2.46	1.73
	3	.84	3.53 Sg	12.83	.56	6.06 Pg	12.47	2.60	1.72
	4	4.47	3.97 S*	23.49	2.60	6.80 P*	23.02	2.84	1.71
	5	12.27	4.65 Sn	-	7.29	8.1 Pn	-	3.26	1.74
5	direct	0.0	2.24	.20	0.0	3.35	.20	1.71	1.49
	1	.09	2.61	.22	0.80	4.47	.22	2.07	1.71
	2	.19	2.89	.68	0.13	5.03	.69	2.26	1.74
	3	.46	3.28	1.16	.27	5.57	1.19	2.44	1.70
	4	.85	3.63 Sg	-	.50	6.10 Pg	-	2.61	1.68

Table 3 (cont.) Results of Wabash River Valley crustal seismic study.

Profile	Refractor	Shear Intercept sec	Velocity km/sec	Thickness km	Compressional Intercept sec	Velocity km/sec	Thickness km	Density gm/cc	(V_p/V_s)
7	direct	0.0	2.27	.22	0.0	3.36	.20	1.71	1.48
	1	.09	2.57	.16	.08	4.42	.16	2.06	1.72
	2	.18	2.94	.68	.12	5.01	.68	2.25	1.70
	3	.42	3.26	1.03	.26	5.59	1.05	2.44	1.71
	4	.78	3.61 Sg	9.59	.49	6.30 Pg	9.59	2.67	1.74
	5	3.44	4.08 S*	-	(?)	7.06 P*	-	2.92	1.73
8	direct	0.0	2.25	.20	0.0	3.38	.19	1.72	1.50
	1	.09	2.61	.23	.08	4.49	.22	2.08	1.72
	2	.18	2.85	.64	.13	5.05	.68	2.26	1.77
	3	.46	3.29	1.11	.26	5.53	1.07	2.42	1.68
	4	.84	3.66 Sg	-	.50	6.22 Pg	-	2.65	1.70

**Density = 0.61 + 0.33 V_p ("Solution 2" specified in Birch, F., 1961, "The velocity of compressional waves in rocks to 10 kilobars, 2", J. Geophys. Res., 66, 2199-2224).

Table 4. Wabash River Valley compressional wave models.

Velocity (km/sec)

Profile		1	2&6	3	4	5	7	8	Average
Direct		3.28	3.23	3.31	3.27	3.35	3.36	3.38	3.31
Sedimentary 1		-	-	4.41	-	4.47	4.42	4.49	4.44
Sedimentary 2		5.08	5.04	5.07	5.08	5.03	5.01	5.05	5.05
Sedimentary 3		5.49	5.52	5.66	5.65	5.57	5.59	5.53	5.57
Basement	P_g	6.04	6.13	6.10	6.06	6.10	6.30	6.22	6.14
Lower Crust	P^*	6.80	6.74	-	6.80	-	7.06	-	6.85
Moho	P_n	8.10	8.10	-	8.10	-	-	-	8.10

Thickness (km)

Profile		1	2&6	3	4	5	7	8	Average
Direct		0.28	0.34	0.19	0.29	0.20	0.20	0.19	.24
Sedimentary 1		-	-	0.24	-	0.22	0.16	0.22	.21
Sedimentary 2		0.89	1.09	0.76	0.91	0.69	0.68	0.68	.81
Sedimentary 3		1.03	1.98	0.94	1.73	1.19	1.05	1.07	1.28
Basement	P_g	13.11	12.63	-	12.47	-	9.59	-	11.95
Lower Crust	P^*	23.08	21.48	-	23.02	-	-	-	22.53

Depth (km)

Profile	1	2&6	3	4	5	7	8	Average
Basement Depth	2.20	3.41	2.13	2.93	2.30	2.09	2.16	2.46
Basement Thickness	13.11	12.63	-	12.47	-	9.59	-	11.95
Lower Crust Depth	15.31	16.04	-	15.40	-	11.68	-	14.61
Lower Crust Thickness	23.08	21.48	-	23.02	-	-	-	22.53
Moho Depth	38.39	37.52	-	38.42	-	-	-	38.11

- not observed

Table 5. Wabash River Valley shear wave models.

Velocity (km/sec)

Profile		1	2&6	3	4	5	7	8	Average
Direct Wave		2.25	2.34	2.30	2.26	2.24	2.27	2.25	2.27
Sedimentary 1		-	-	2.62	-	2.61	2.57	2.61	2.60
Sedimentary 2		3.02	2.99	2.87	3.14	2.89	2.94	2.85	2.95
Sedimentary 3		3.30	3.22	3.19	3.27	3.28	3.26	3.29	3.25
Basement	S_g	3.56	3.50	3.52	3.53	3.63	3.61	3.66	3.57
Lower Crust	S^*	3.97	3.99	-	3.97	-	4.08	-	4.00
Moho	S_n	4.65	4.65	-	4.65	-	-	-	4.65

Thickness (km)

Profile		1	2&6	3	4	5	7	8	Average
Direct Wave		0.29	0.38	0.20	0.29	0.20	0.22	0.20	.25
Sedimentary 1		-	-	0.23	-	0.22	0.16	0.23	.21
Sedimentary 2		0.91	1.00	0.78	0.89	0.68	0.68	0.64	.80
Sedimentary 3		1.11	2.06	0.96	1.70	1.16	1.03	1.11	1.30
Basement	S_g	14.05	12.90	-	12.83	-	9.59	-	12.34
Lower Crust	S^*	23.01	22.15	-	23.49	-	-	-	22.88

Depth (km)

Profile	1	2&6	3	4	5	7	8	Average
Basement Depth	2.31	3.44	2.17	2.88	2.26	2.09	2.18	2.48
Basement Thickness	14.05	12.90	-	12.83	-	9.59	-	12.34
Lower Crust Depth	16.36	16.34	-	15.71	-	11.68	-	15.02
Lower Crust Thickness	23.01	22.15	-	23.49	-	-	-	22.88
Moho Depth	39.37	38.49	-	39.20	-	-	-	39.02

- not observed

Table 6. Summary of refractions observed and interpreted from Wabash River Valley seismic profiles.

Profile Number	Profile Length (km)	Number of Sedimentary Layers	Basement (P_g, S_g)	Lower Crustal Layer (P^*, S^*)	Moho (P_n, S_n)
1	106	3	+	+	+
2 & 6	147	3	+	+	+
3	69	4	+	-	-
4	172	3	+	+	+
5	33	4	+	-	±
7	50	4	+	+	-
8	25	4	+	-	-

\+ indicates refraction observed

\- indicates refraction not observed

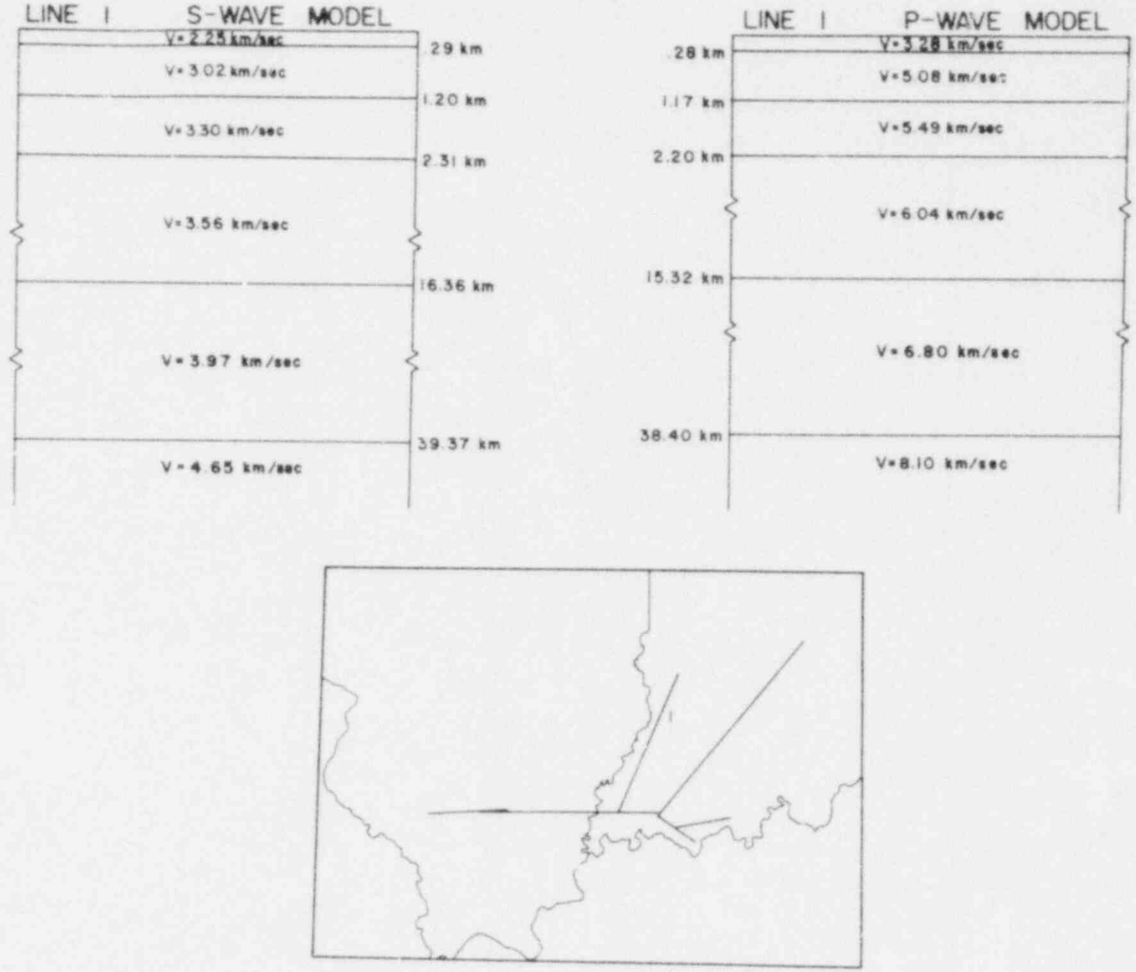


Figure 39. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 1.

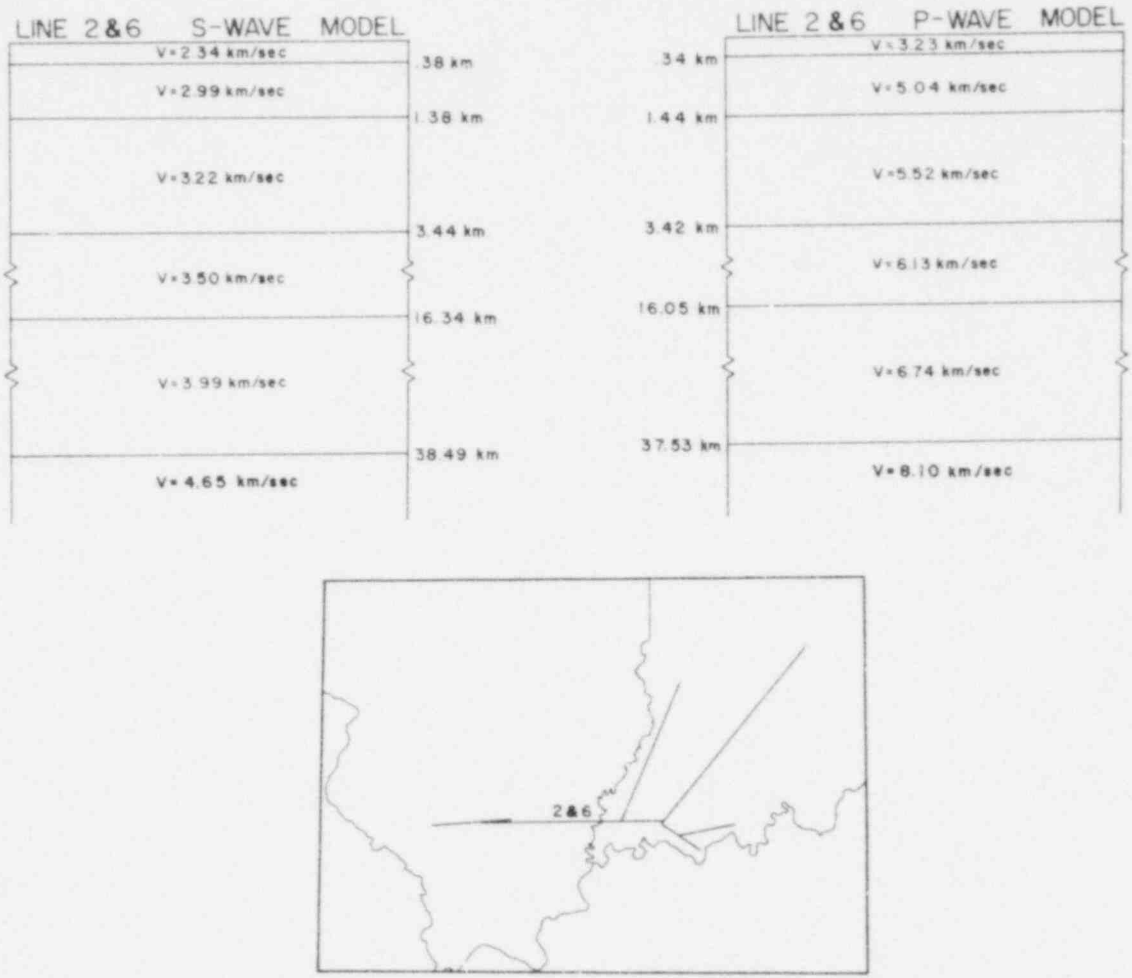


Figure 40. Crustal models derived from compressional (P) wave and shear (S) wave data of Profiles 2 & 6.

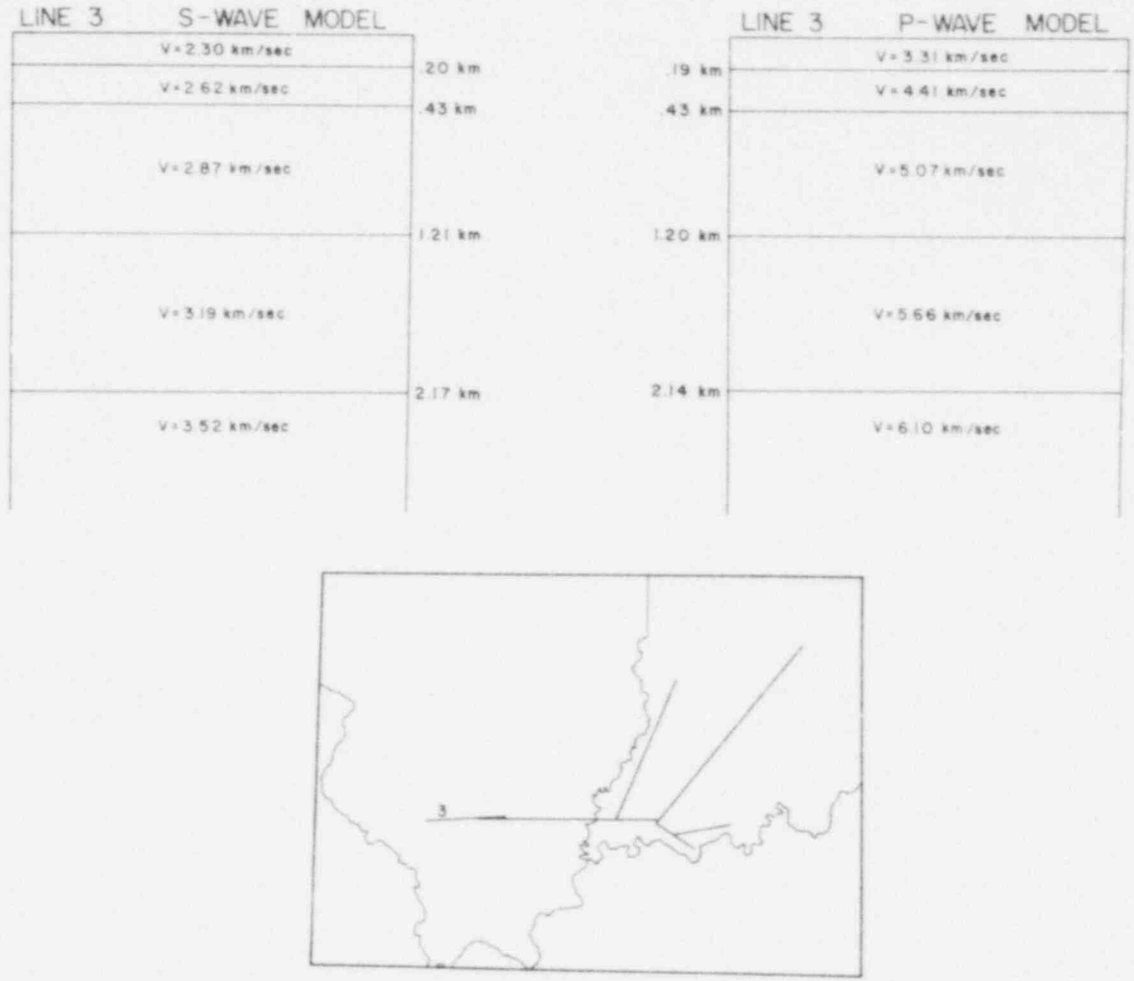


Figure 41. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 3.

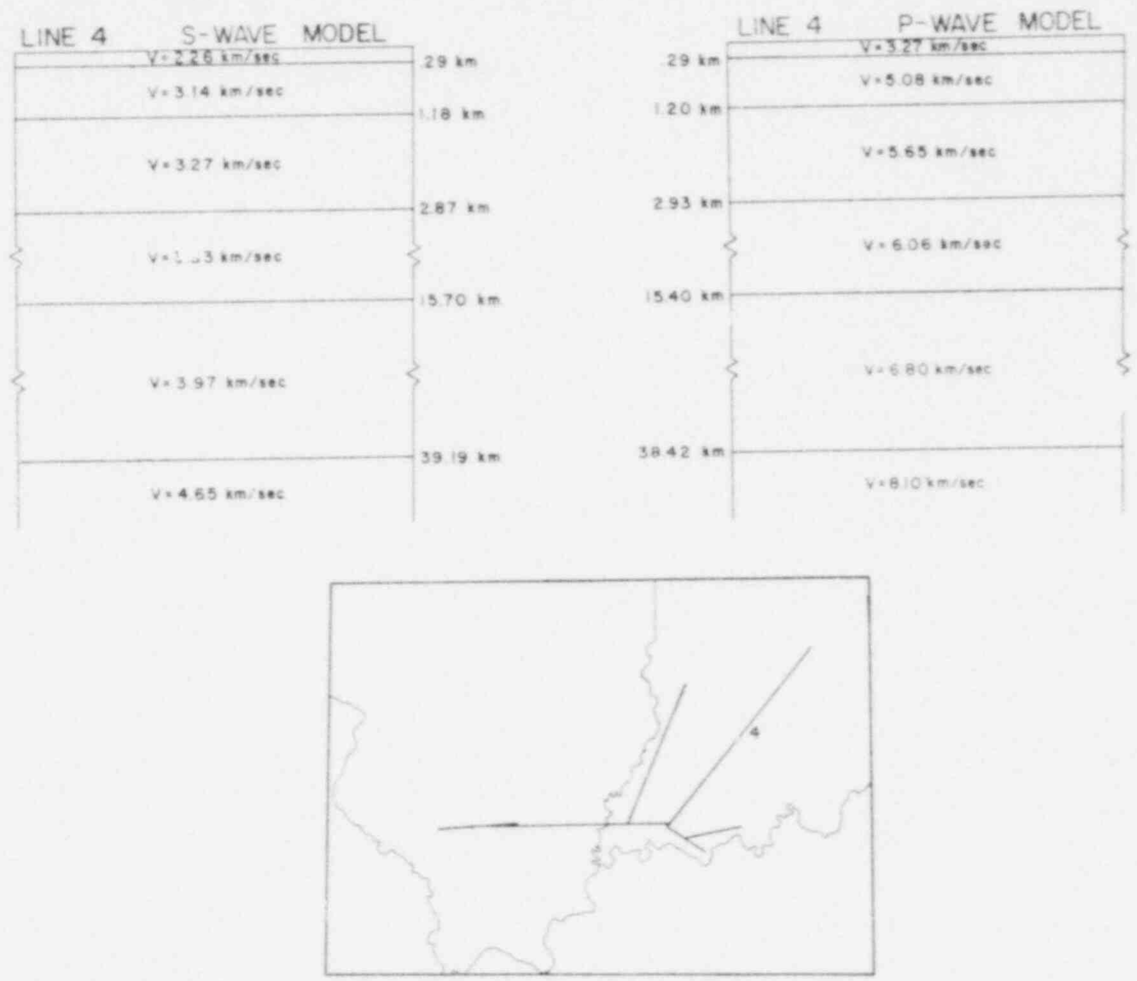


Figure 42. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 4.

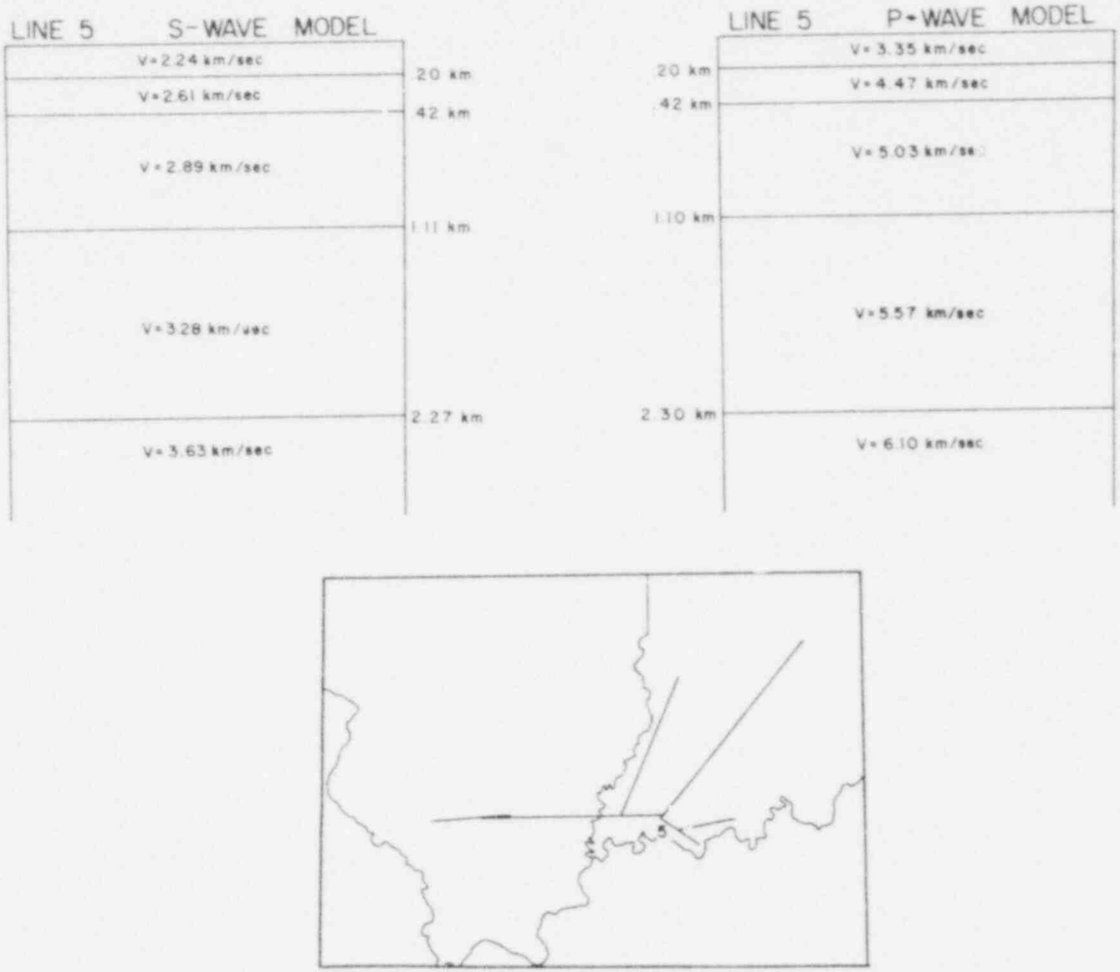


Figure 43. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 5.

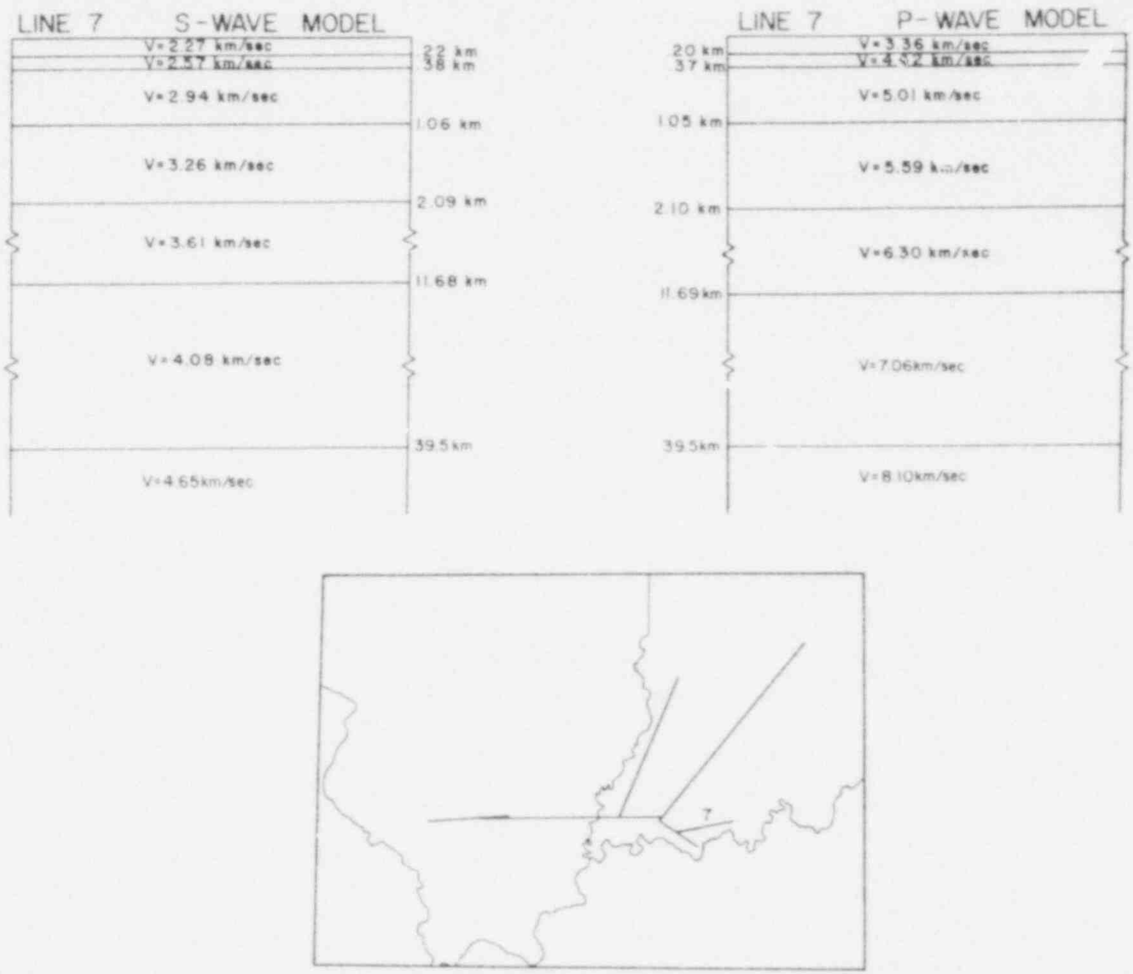


Figure 44. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 7.

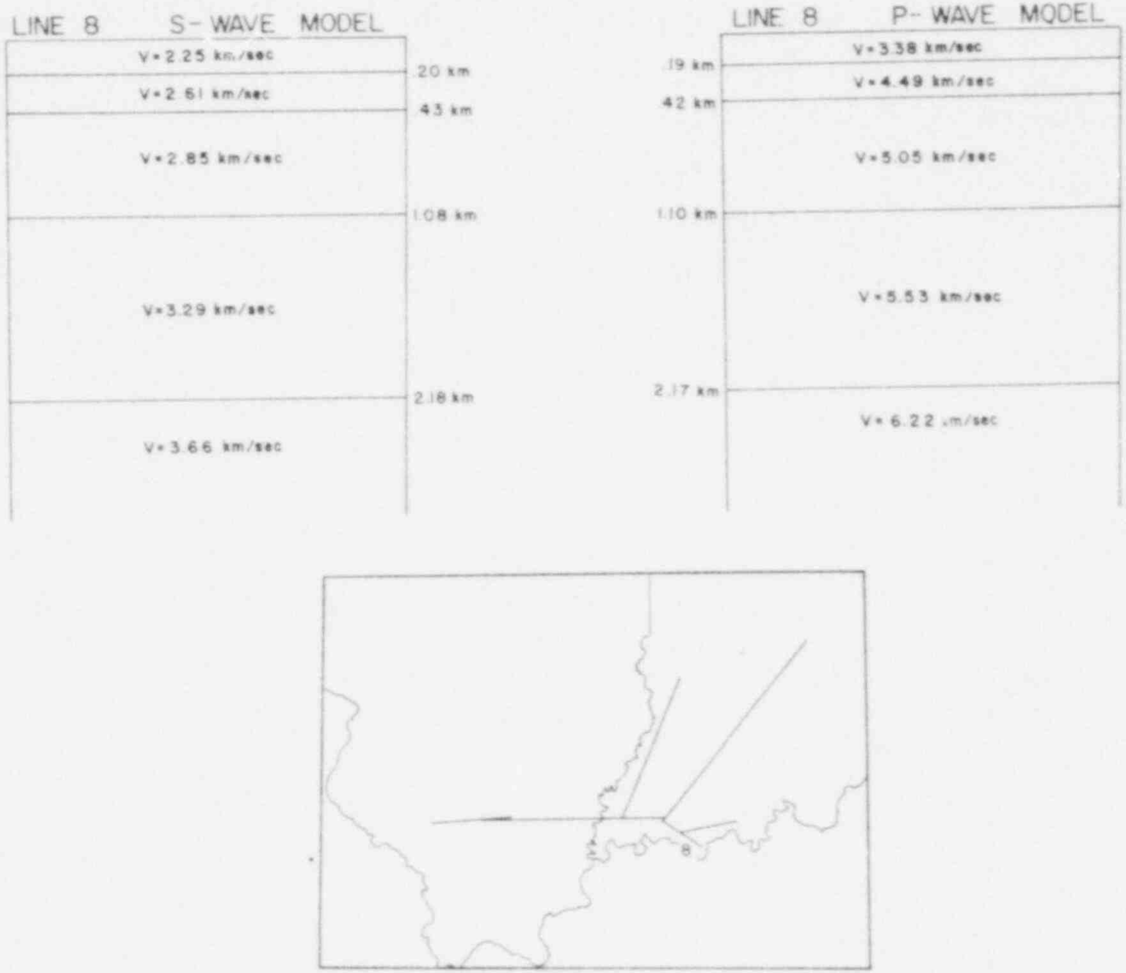


Figure 45. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 8.

Profile 7. This profile crosses a gravity and magnetic positive anomaly which is used to define the extension of the New Madrid Fault Zone into Indiana (Figures 46 and 47). The potential-field anomalies probably are caus by this thinning of the crust supplemented by increased densities in the basement and lower crust as reflected in increased velocities. This is interpreted to be the result of intrusive activity along lines of weakness within the New Madrid Fault Zone. At the northeastern end of the study area, the basement on Profile 1 shows a slightly increased thickness, although the depth to the base of the basement is not greater than observed on the other profiles. The density of the basement as indicated by the compressional wave velocities (Table 3) are approximately equivalent to the densities measured in basement drill holes.

Moho depths as obtained from the records of Profiles 1, 2, and 4 are quite consistent at about 39 km. Lower crustal velocities average 6.78 km/sec and 3.09 km/sec for the compressional and shear waves respectively, considerably less than those observed on Profile 7. Upper mantle compressional and shear wave velocities average 8.10 and 4.65 km/sec respectively.

Previous seismic refraction studies of interest in the general area include the studies of McCamy and Meyer (1966) and Stewart (1968). An anomalous high velocity (7.4 km/sec) zone at the base of the crust was interpreted by McCamy and Meyer for a profile on the western edge of the Mississippi Embayment between Little Rock, Arkansas and Cape Girardeau, Missouri. In contrast, a model derived by Stewart (1968) for seismic refraction profiles between St. Joseph and Hannibal in Northern Missouri does not contain the high velocity zone. The McCamy and Meyer and Stewart models are presented in Figure 48. The Stewart models for Northern Missouri (east and west) are thought to represent normal crust while the Mississippi Embayment model of McCamy and Meyer represents an anomalous crust. The Embayment crustal structure exhibits three anomalous characteristics.

1) The 6.5 km/sec layer is shallower (8 km) than for the equivalent layer (6.6 km/sec at about 24 km depth at the west end of the seismic profile and about 18 km depth at the east end of the profile) in the normal crust defined by the Stewart model.

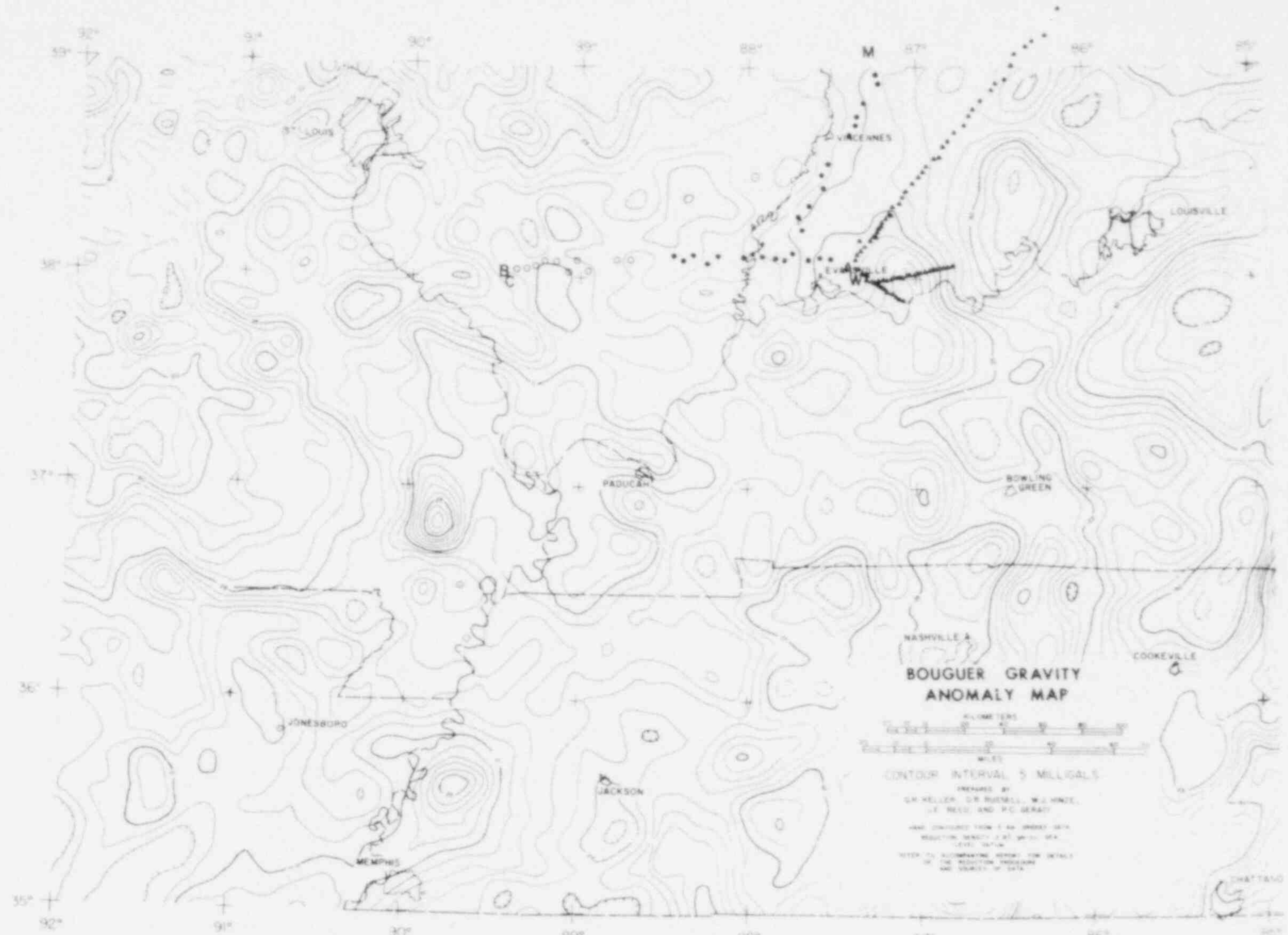


Figure 46. Bouguer gravity anomaly map showing positions of recording stations for crustal seismic investigation in the Wabash River Valley (see Figure 22.)

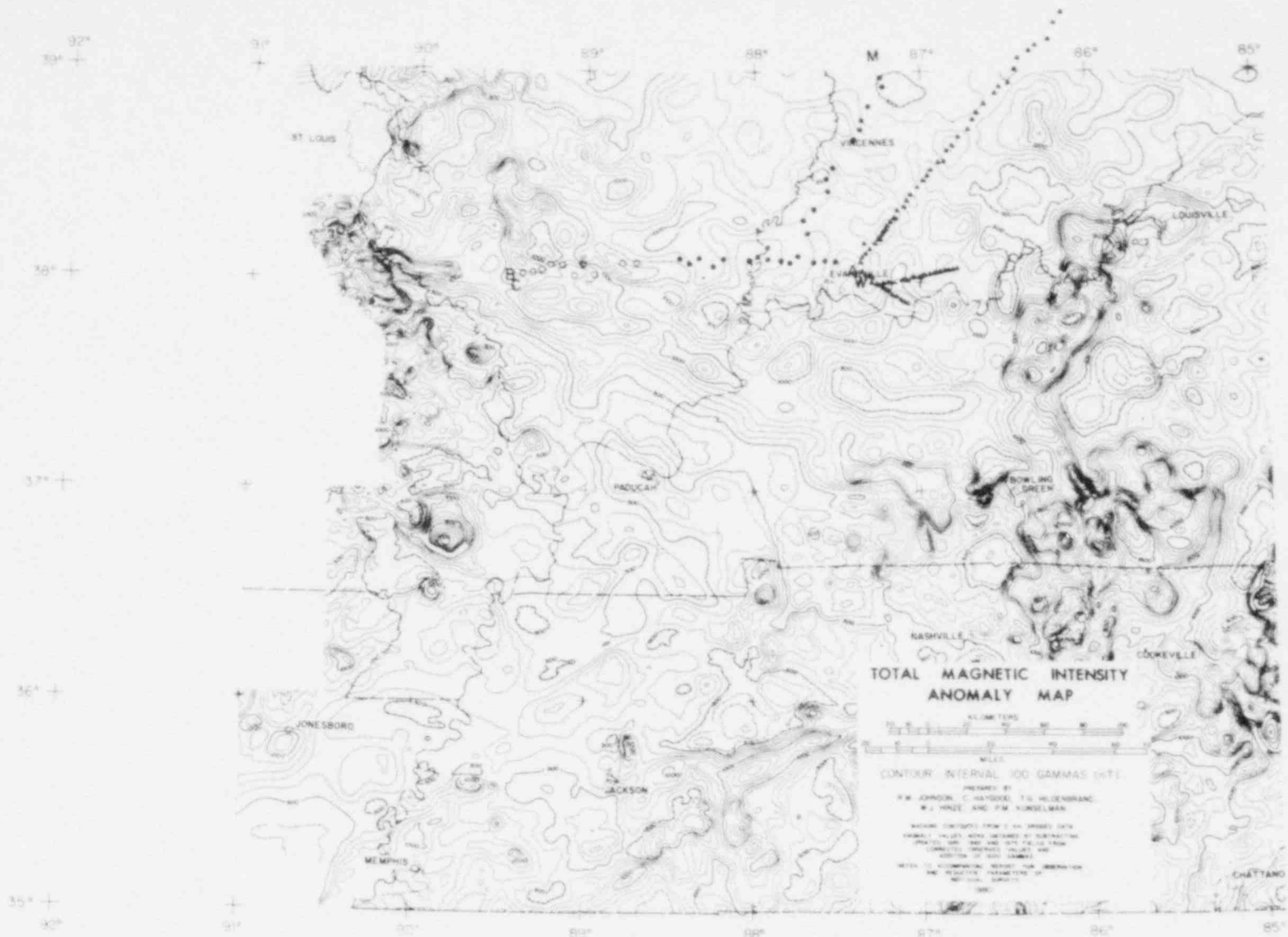


Figure 47. Total magnetic intensity anomaly map showing seismograph locations used in the Wabash River Valley crustal seismic study.

2) The presence of the anomalous high velocity (7.4 km/sec) zone at the base of the crust. The velocity of the lower crustal layer for the normal crust as defined by the Stewart model is 6.6 km/sec.
3) A greater depth (45 km) to the crust-mantle boundary (defined as the 8.1 km/sec zone) compared to the normal crust-mantle boundary depth of about 42 km for the Stewart model at the west end of the profile and about 38 km at the east end.

The lateral extent of the high velocity lower crustal layer and its extension to the north is unknown. The question then arises as to whether or not the anomalous zone is present in southeastern Illinois and southwestern Indiana, and if it is present what is its relationship to the basement geological feature representing the possible northeast extension of the New Madrid Fault Zone?

Interpretation of the data results in models which differ in detail from line to line, with the most significant differences being in depth to basement, basement velocity, depth to lower crustal layers (or basement thickness), and velocity of the lower crustal layers. Each model may be compared to the Stewart's (1968) "normal" crustal models, McCamy and Meyer's (1966) "anomalous" crustal model, and Austin and Keller's (1966) "Mississippi Embayment" model. An "average" model (Figure 48) may be used as an indicator of whether the crust is normal or anomalous. The average model derived from the refraction data along with the normal and anomalous crustal models are presented in Figure 48. The average model derived from the data is different from both the normal and anomalous models. Depths for the average model were determined by averaging the depths derived from both compressional and shear wave data presented. The average compressional velocity for the sedimentary layers was determined by simply averaging velocities of the refractors of the individual layers. The same procedure was used to determine average shear velocity of the sedimentary layers. The other velocities are taken from Table 4 (compressional velocity) and Table 5 (shear velocity) from the columns headed "average". The following observations are made concerning the new crustal model:

1) Compressional velocity of the basement r ts is essentially the same as for the other two models 6.14 (average), 6.10 (normal) 6.20 (anomalous).

Figure 48. Comparison of crustal models of the Mississippi Embayment region.

2) The normal and anomalous models contain a layer (upper crustal layer) between the basement and the lower crustal layer with intermediate velocity of 6.20 km/sec for normal crust and 6.50 km/sec for the anomalous crust. The Wabash River Valley model does not contain this layer.
3) This intermediate layer in both the normal and anomalous models overlies the basal crustal layer which has a velocity of 6.60 km/sec in the normal crust and 7.40 km/sec in the anomalous crustal layer. The two Stewart models differ only in depths to the interfaces, but all interfaces are shallower at the east end of the seismic profile near Hannibal, MO. The Wabash River Valley model has a single layer between the basement and the mantle, and its velocity is 6.85 km/sec, which lies between the values of 6.60 km/sec and 7.40 km/sec for the lower crustal layers of the normal and anomalous models. The interesting feature about the 6.85 km/sec layer is that it is quite shallow at about 15 km. Thus, this average model for the area surveyed contains a relatively high velocity layer at a more shallow depth than either normal or anomalous crustal models. Therefore, the crust in the Wabash River Valley also may be referred to as somewhat anomalous if the northern Missouri models of Stewart are representative of normal crust. This somewhat different crustal structure may be directly related to the basement structural feature interpreted to exist on the basis of gravity and magnetic data and which is inferred to be the northeast extension of the New Madrid Fault Zone.
4) The average depth to the Moho is about 39 km which is less than the anomalous model as well as the Stewart model for the west end of the northern Missouri profile (near St. Joseph, MO). However, the Stewart model for the east end (near Hannibal, MO) has a depth of 38 km to the Moho, essentially the same depth as for the average model.

Stewart's model (normal) for the eastern end (Hannibal, MO) most closely resembles the model derived in this study. However, significant differences do exist. The relatively high velocity crustal layer (6.85 km/sec) is only

15 km deep in the average model and no intermediate layer exists between basement and lower crust for this model. For the Stewart model near the east end of the seismic profile, an interface exists at 18 km depth, but it corresponds to a velocity of 6.60 km/sec, significantly less than the 6.85 km/sec boundary which is located at a depth of 15 km in the average model. Thus, the crust derived from the seismic refraction data indicates a somewhat anomalous crust in the vicinity of the inferred northeast extension of the New Madrid Fault Zone. Further analysis and interpretation of these seismic data are underway. In particular, an amplitude analysis is underway and a thorough integration of the results of this study with the results of the potential-field analysis has been initiated.

Ohio River Seismic Reflection Study - A seismic reflection survey was conducted to determine the feasibility of using reflection methods in the Ohio River to detect faults which may be associated with the northeast extension of the New Madrid Fault Zone. The goal was to detect offsets in the bedrock surface and to examine reflection continuity within the overlying sediments and Quaternary alluvium for the purpose of dating the last period of fault movement. Deep reflections were to be studied if recorded. Participants in the survey included the Geophysics Group at Purdue University, the Illinois Geological Survey, and the Geophysics Group of the University of Wisconsin at Milwaukee.

The survey was performed between the Post Creek Cutoff to 1.5 miles upstream of Metropolis, IL (Figure 49). Preliminary tests were conducted in August, 1979 using a 40 cubic inch capacity air-gun source. A typical record section is shown in Figure 50. Examination of the record section indicates only two strong reflections, one corresponding to the water bottom and another corresponding to the bedrock surface. Because of the high reflection coefficient at the bedrock surface, little energy penetrates below it. It is possible that after the data have been processed and displayed as wiggle line traces (rather than the electrostatic display from the real-time plotter), more coherent energy may be seen beneath the bedrock reflector. No faults are seen in the data from the August, 1979 test runs.

On May 19, 1980 the survey was resumed. Initial testing was performed to determine instrument filter settings to be used with the 1 cubic inch

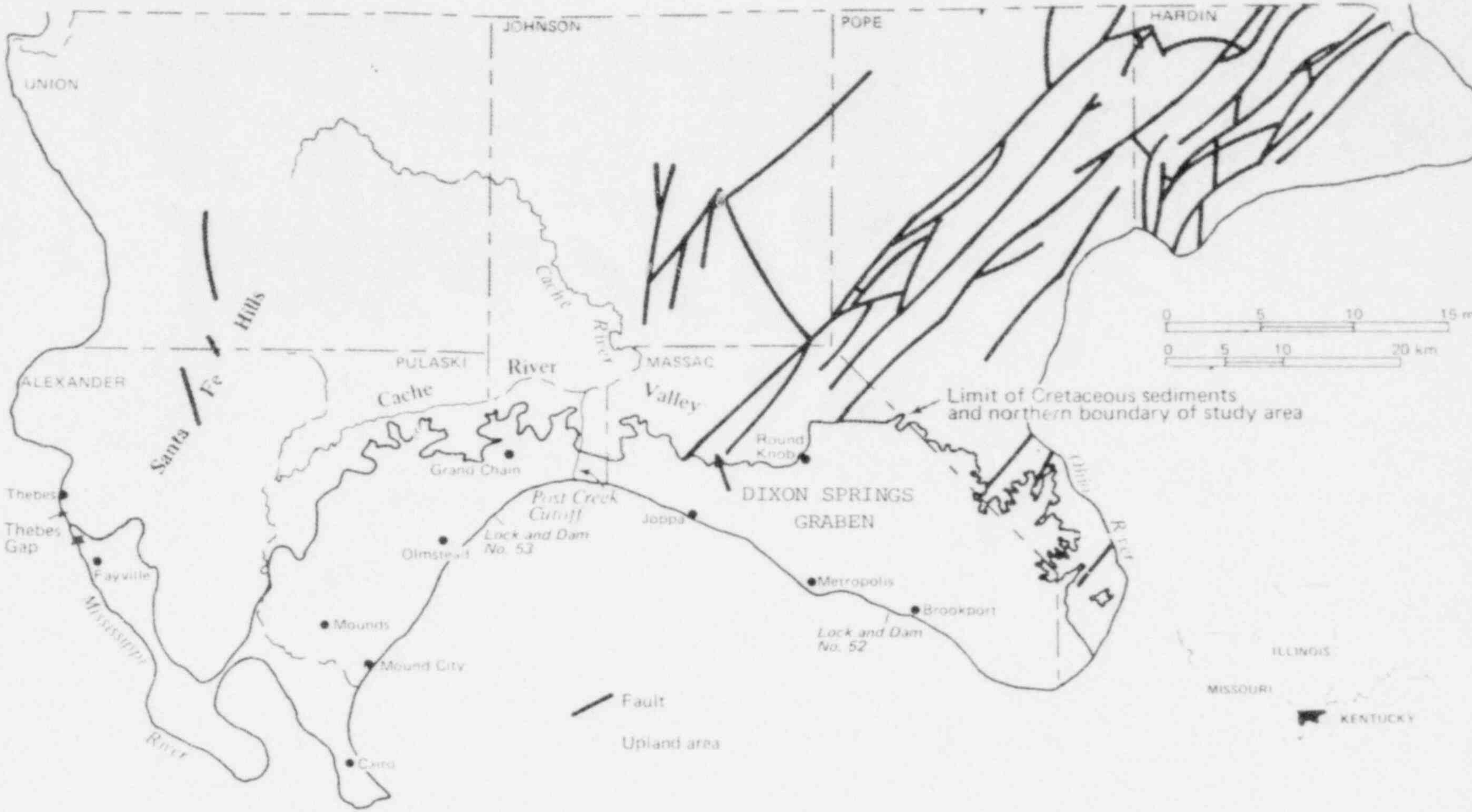


Figure 49. Location map for Ohio River seismic reflection study.

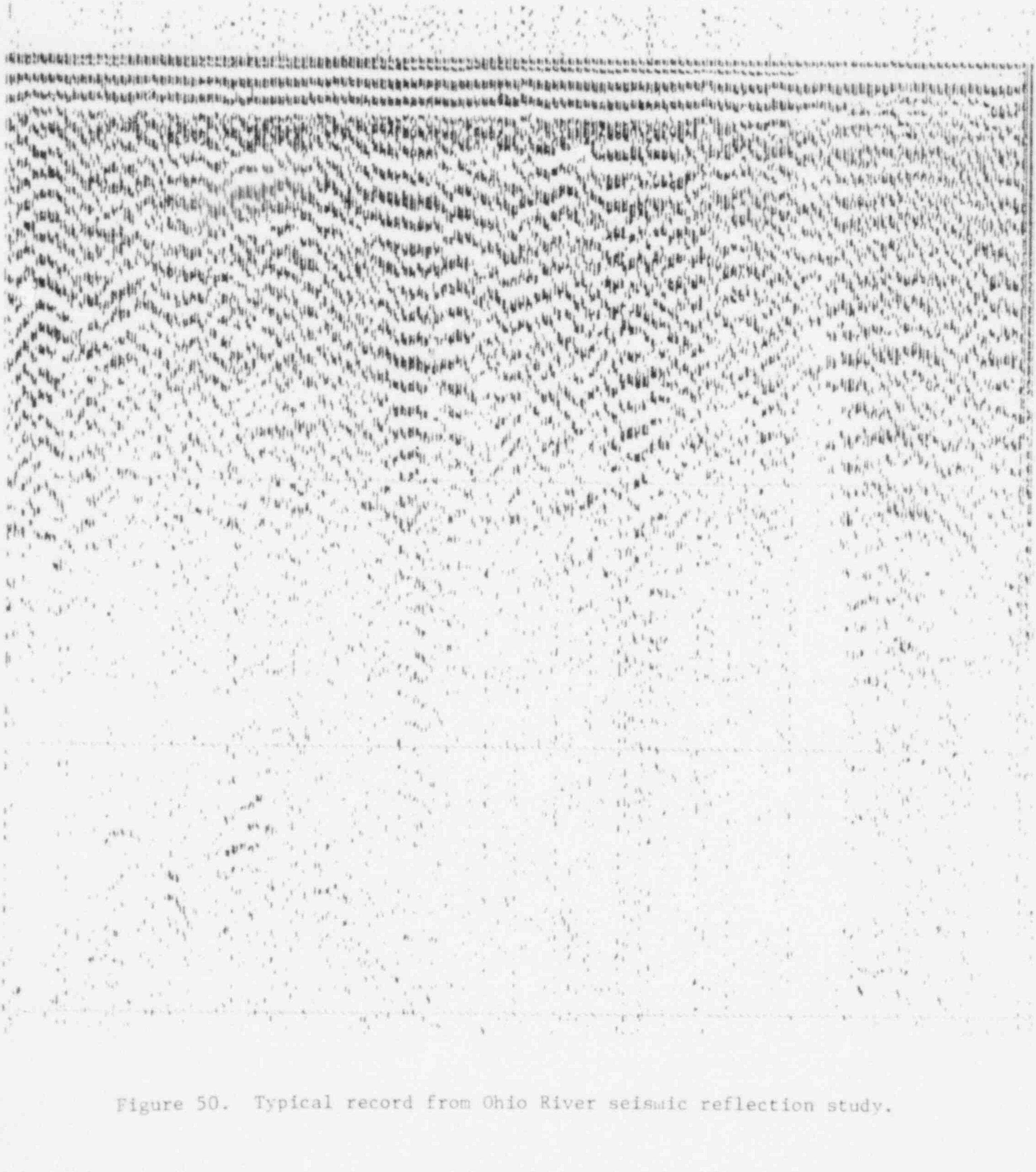


Figure 50. Typical record from Ohio River seismic reflection study.

air-gun source, to test the air-gun and sparker sources, and to determine a useful firing rate and record length for each source. Following the testing phase, a short sparker profile was run starting near the Metropolis launch area and extending about 1 mile upstream. Along this same line, an air-gun (1 cubic inch) survey was conducted from the Metropolis launch area and extending upstream about 1.5 miles to the site of the I-24 highway bridge. A sparker survey was then initiated at a location 1.5 miles downstream of Post Creek Cutoff and extending 1.5 miles upstream of Joppa. A second sparker line was run from downstream of Joppa (at location mile number 954.2) to upstream of Joppa for a total length of about 7 miles. Only the paper record is available for this run. At this point, a malfunction of the recording boat caused the survey to be terminated. A summary of the survey parameters [illegible] data follows:

I. Data from August, 1979

1) Air-gun survey from Douglas' landing [illegible] Post Creek Cutoff) to Joppa. Air-gun firing rate was 1 shot every eight seconds. Boat spead was 2 miles/hour. These data have been digitized and recorded on hard disks. The source was near the boat and created high noise recorded with the signals.

II. Data from May, 1980

1) Metropolis launch area to 1 mile upstream - Sparker.
2) Metropolis launch area to 1.5 miles upstream - 1 cubic inch air-gun.
3) From 1.5 miles downstream of Post Creek Cutoff to 1.5 miles upstream of Joppa - sparker.
4) From mile 954.2 downstream ≈ 3 miles downstream of Joppa to 4 miles upstream of Joppa for a total length of 7 miles - sparker (no tape record) paper record only.
5) Boat speed was 2 miles/hour.
6) Sparker firing rate was 1 shot every 2 seconds giving a shotpoint approximately every 6 feet.
7) Air-gun firing rate was 1 shot every 8 seconds giving a shotpoint approximately every 23 feet.
8) From the above figures it is noted that a large amount of data has been collected, but it covers limited areas on the river.

One mile of sparker data (using spatial sample interval of six feet) results in 880 shotpoints. While one mile of air-gun data (with spatial sample interval of 23 feet) results in 230 shotpoints.

9) Useable record length from the sparker source appears tc be 150 miliiseconds two way time.
10) Useable record length from the air-gun source is difficult to determine due to the presence of multiples, but may be 250-500 milliseconds.
11) Data were collected with three active hydrophone sections each 50 feet long. The source was towed 200 feet behind the boat and the first active section also started 200 feet behind the boat. Two of the channels were stacked to obtain paper records.
12) Water depth in the area is approximately 40 feet deep.
13) Data were recorded on magnetic tape at 3.5 inches per second recording tape speed.
14) Records of the water bottom channel were obtained from a sonar-type source.

Preliminary examination of the record sections from the plotter on board the survey boat indicate that two reflections, one from the river bottom, and one from the bedrock surface are recorded. As an example, consider Figure 51 which is a portion of the sparker survey line from downstream of Joppa to upstream of Joppa (see Item 4 above). This portion of the record section crosses the location which corresponds to the straight-line extrapolation of the Dixon Springs Graben (Figure 49). No clear evidence is seen for the Graben, however, bedrock reflections in this area are not as coherent as those obtained outside the suspected faulted area. This may be an indication of faulting. More convincing evidence of faulting exists in a zone about 740 feet wide which is located between 1900 feet and 11601 feet downstream of mile 952 (which is near Joppa). Here there appears to be an offset in the bedrock reflection of about 0.02 seconds two way time. If an estimate of 6500 ft/seconds is used as an average velocity of material between surface and bedrock, then the vertical offset is 65 feet. This figure, however, is a rough estimate. The analysis of the data will be facilitated by processing and

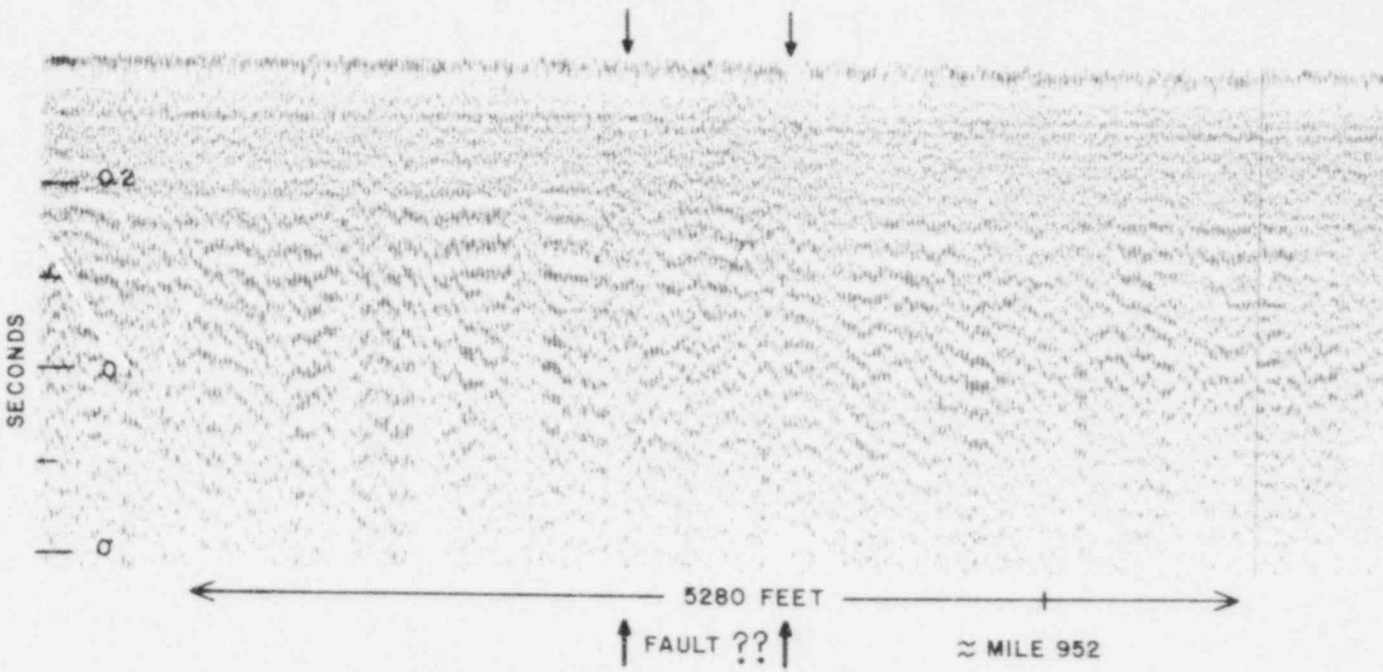


Figure 51. Possible bedrock fault indicated in sparker seismic reflection record downstream of Joppa, Illinois.

higher-quality display of the data. Thus, it appears that seismic reflection methods are feasible for mapping faults in this area, providing high-quality equipment is available. Further analysis of these data will reveal whether it is possible to study continuity of possible reflections above the bedrock and in the Quaternary alluvium. High frequency sparker record sections for this area are recorded on tape and will be examined for further evidence of faulting as soon as record sections can be processed and displayed.

SYNTHESIS AND INTERPRETATION

To assist in the synthesis and interpretation of the various data being compiled we have obtained from Professor Otto Nuttli of St. Louis University, a computer file of the historical epicenters in the area of 35°-40°N latitude and 84°-92°W longitude. Due to the truncation biasing in the latitude-longitude locations (many epicentral locations are rounded-off to the nearest 0.1°) we have added a random latitude and longitude 'error' distributed between $\pm$ 0.1° to each coordinate to remove the appearance of epicenters lining-up on even latitude-longitude lines on the plot. This epicenter file has been plotted on the same scale as the gravity, magnetic and fault maps that we have previously prepared (Figure 52). The epicentral patterns display the following general features when compared with the fault maps and the gravity and magnetic maps which have been used to define the New Madrid Linear Tectonic Feature (NMLTF) (Braile and others, 1980):

(1) A concentration of epicenters is visible along the NMLTF although the occurrence decreases considerably north of 37°N,

(2) A few clusters or zones of epicenters appear to be associated with mapped faults including the Cottage Grove Fault Zone, the St. Genevieve Fault Zone and the Wabash Valley Fault Zone,

(3) The zone of epicenters trending from New Madrid to St. Louis (which is oblique to the trends of the St. Genevieve and Cottage Grove Fault Zones) may be related to a basement geologic feature reflected in the gravity and magnetic anomalies.

Interpretation of available gravity and magnetic maps for the area surrounding New Madrid indicates the existence of linear trends of correlative gravity and magnetic anomalies. These anomalies have been previously noted by Hildenbrand and others (1978 and 1979) for the Reelfoot area and by Braile and others (1980) for the northeastern extension of the New Madrid Fault Zone. An additional pair of parallel trends of anomalies has been identified from New Madrid to St. Louis on either side of the Mississippi River. These anomalies are best seen on the vertical component ground magnetic map of Missouri and on the new gravity and magnetic maps by Johnson and others (1980) and Keller and others (1980) (Figures 1, 2, 6, 15, and 16). A summary diagram of the patterns of earthquake epicenters and their relationship to basement structures as evidenced by the gravity and magnetic anomalies is shown in Figure 53. The major trends of historical epicenters are delinated by the basement structures along the Reelfoot Rift (New Madrid Fault Zone), the northeastern extension of the New Madrid Fault Zone into southwestern Indiana and along the Mississippi River from New Madrid to St. Louis. The significance of the correlation of these basement structures with the historical seismicity can be clearly demonstrated in the contour map of the number of earthquakes per 10^4 km^2 (from Hadley and Devine, 1974) which is shown in Figure 54.

One of the primary areas of investigation remaining is the northern extension of these basement structures. Recent gravity studies in Indiana (Figure 12) display an anomaly pattern at about 39.5°N which appears to terminate the northeastern extension of the New Madrid Fault Zone. Also the Missouri magnetic map and the gravity map of the area surrounding New Madrid show a termination of the New Madrid to St. Louis structure at 39°N. It is considered significant that the termination of these structures coincides with the rather abrupt decrease in seismicity (Figure 53) along these trends.

We are currently continuing our investigation of these structures to determine their origin and relate the basement structures to a model to explain the occurrence of earthquakes in the midcontinent area as a localization of stresses along zones of weakness. One possible origin for the basement structures is a Precambrian triple junction associated with continental rifting during break-up of the continents. A schematic diagram illustrating this rift structure is shown in Figure 53. Continuing field studies, synthesis of data, and interpretation is aimed at confirmation and improved interpretation of the basement structures which are associated with contemporary seismic activity.

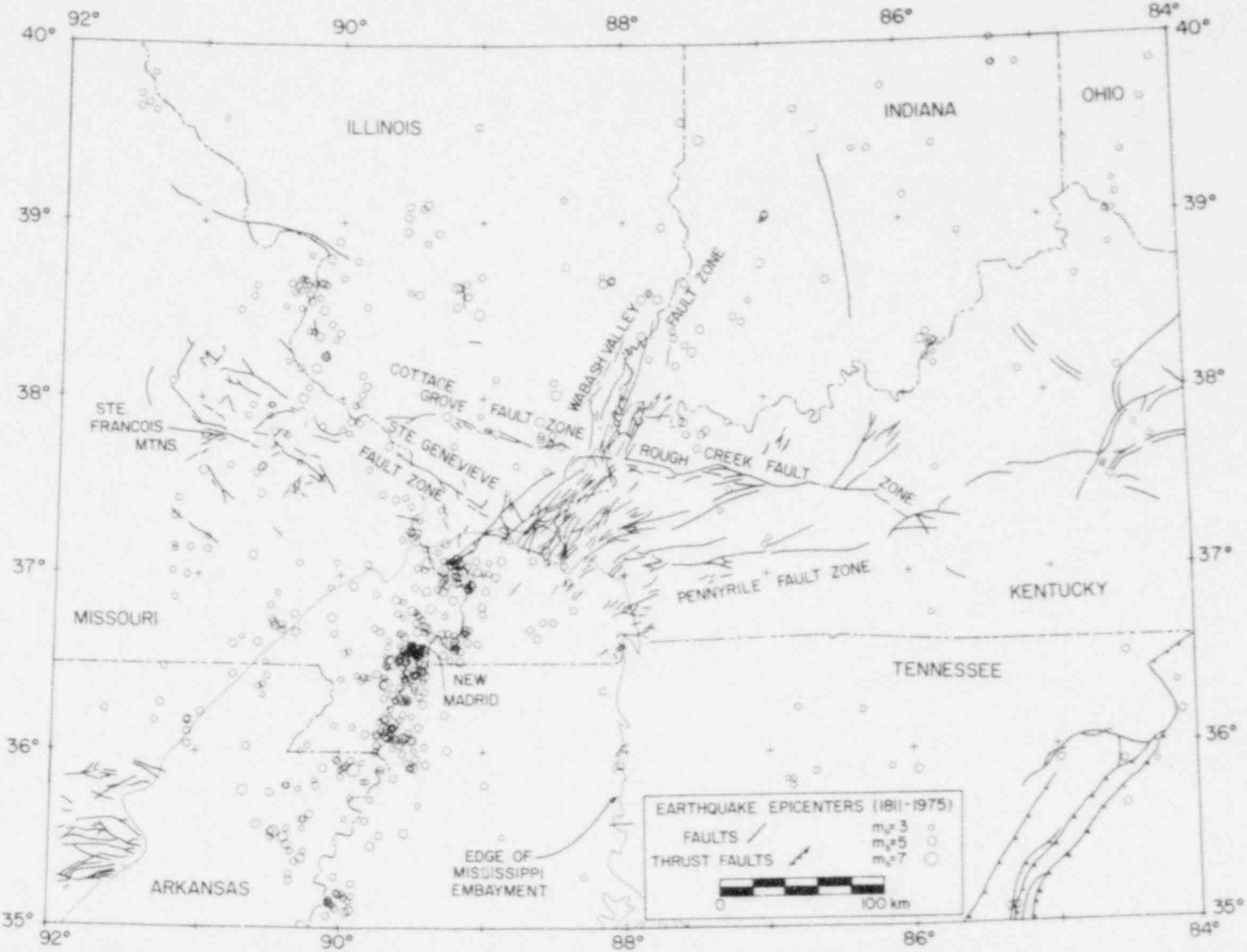


Figure 52. Earthquake epicenters (1811-1975) and mapped faults in the vicinity of the 38th Parallel Lineament and its intersection with the extension of the New Madrid Fault Zone.

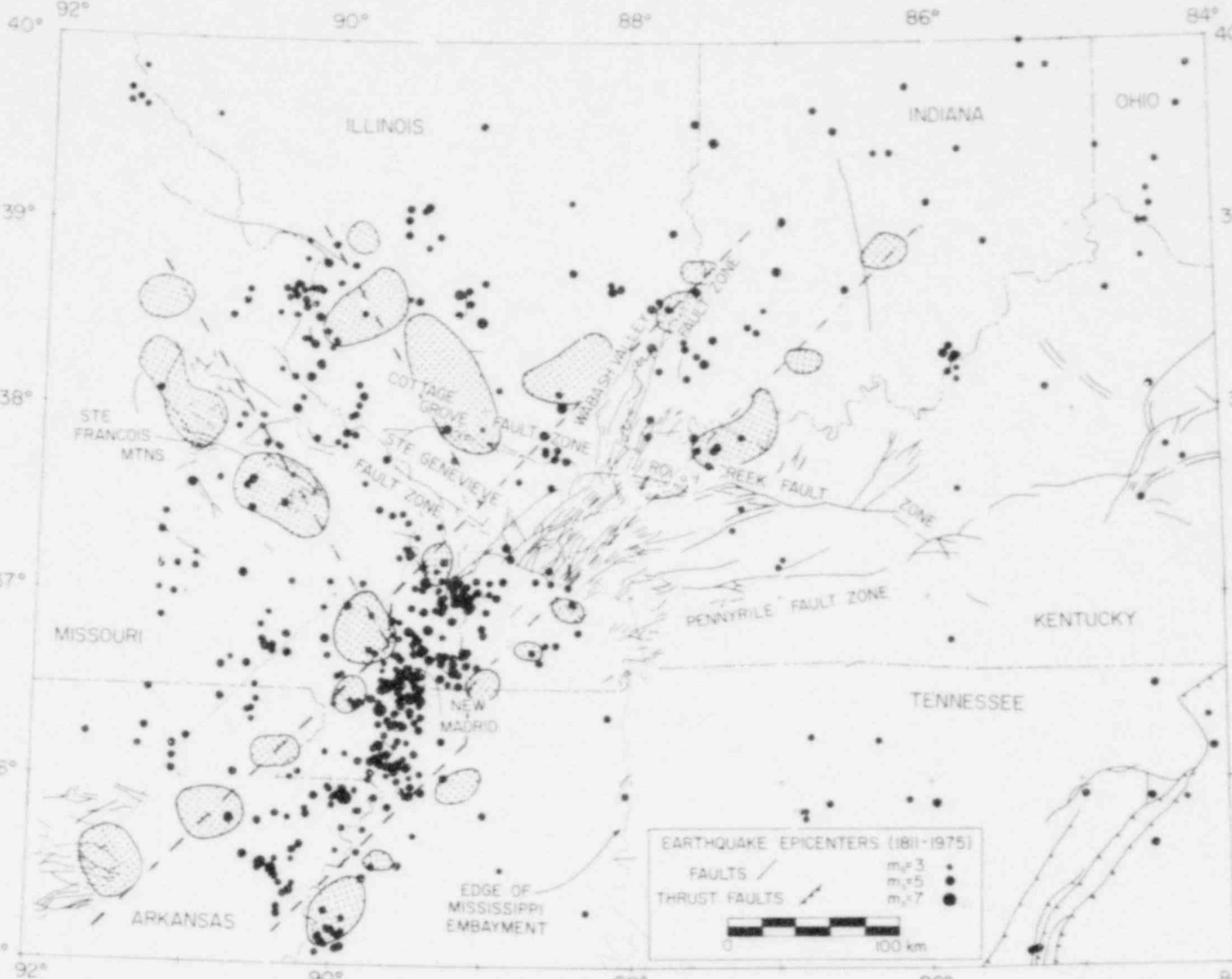


Figure 53. Earthquake epicenters, mapped faults and inferred mafic intrusives (stippled pattern) and boundaries of linear basement features (heavy dashed lines).

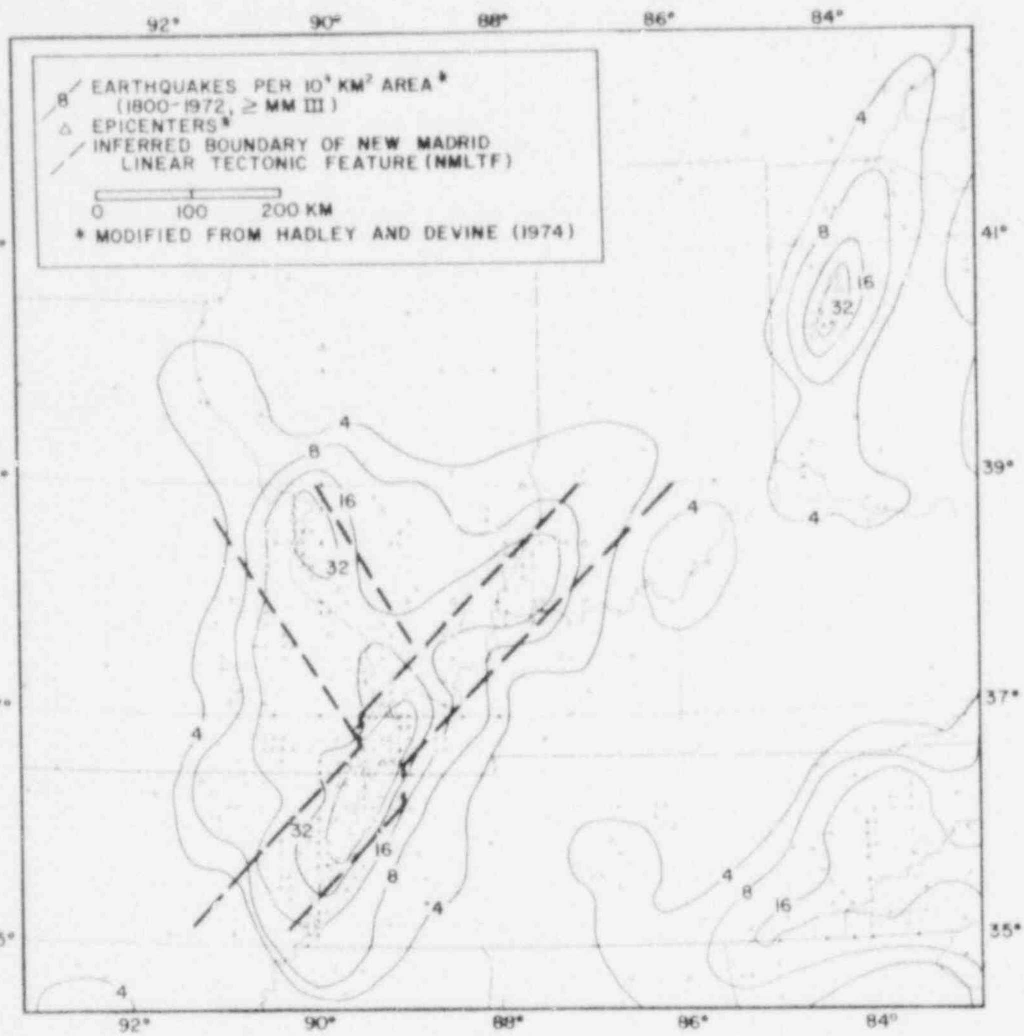


Figure 54. Contour map of number of earthquakes per 10^4 km^2 area (from Hadley and Devine, 1974) and inferred boundaries of linear basement features (heavy dashed lines).

MAJOR PRODUCTS

The major products completed during this contract year include the following:

1) Bouguer gravity anomaly map of southern Indiana to 40°N latitude based on approximately 7200 gravity observations spaced at 2 to 3 km.

2) Bouguer gravity anomaly map and associated 2 km grid data set of the area between 35°-39°N latitude and 82°-92°W longitude including a report on the source, reduction, and compilation of the data.

3) Total magnetic intensity anomaly map and associated 2 km grid data set of the area between 35°-39°N latitude and approximately 82°-91°W longitude including a report on survey parameters, data reduction procedures, and the compilation process.

4) Improved Bouguer gravity anomaly computer codes and improved and modified computer codes for processing large gravity and magnetic anomaly data sets with a variety of frequency domain operators.

5) Vertical magnetic intensity anomaly data set of the ground survey map of Missouri.

6) Plotting of earthquake epicenter data file between 35°-40°N latitude and 84°-92°W longitude for correlation with other studies.

7) Observation, processing, and interpretation of nine seismic refraction lines ranging in length from 6 to 172 km in the vicinity of the northeast extension of the New Madrid Fault Zone.

8) High-resolution seismic reflection profiling in the Ohio River to locate faults on the extension of the New Madrid Fault Zone.

9) Continued study of basement rocks, pre-Mt. Simon sedimentary rocks, and mafic and ultramafic intrusive rocks.

10) Measurement of the natural remanent magnetization and density of approximately 100 basement rock samples.

11) Interpretation and integration of data as presented in ten papers at scientific meetings, publication of one NRC report and one paper in "Continental Tectonics", preparation of two NRC reports on anomaly maps and papers on the tectonic approach to evaluation of earthquake hazards in the midcontinent and the gravity and magnetic modeling of the Mississippi Embayment crustal structure at satellite elevations, and acceptance of three papers for publication in the U.S. Geological Survey professional paper on the New Madrid Fault Zone.

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** Available for purchase from the NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission, Washington, D.C. 20555, and the National Technical Information Service, Springfield,Va. 22161

APPENDIX I

SEISMICITY, STRESSES, AND STRUCTURES

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Delineating zones of seismic hazard is dependent on the development of dynamic geologic models which explain paleo - and neo-tectonics and can be used to successfully predict into the future and into presently unknown geologic areas. Significant progress has been made during the past decade in the identification of a model for the New Madrid Seismic Zone - a model in which the present stress pattern reactivates a pre-existing basement structure. Even though this model is still evolving and is under continued testing and evaluation, the process which has lead to its development provides a framework for similar studies and illustrates problems which must be solved before zones of seismic hazard can be successfully mapped in the Midcontinent and eastern North America.

Three principal ingredients have been utilized to develop the New Madrid model - seismicity, stresses and sutures - or pre-existing geologic zones of weakness. Gravity, magnetic and related investigations to map pre-existing, but buried sutures, structures, or other zones of potential weakness which are being reactivated by current stresses are particularly important. Mapping of these features and identifying a model based on seismicity, stresses and sutures permits prediction of the potential seismic hazards from historical seismicity and delineates areas for more intense investigation. This methodology is applicable to developing models for neo-tectonism in eastern North America, but requires intensive and extensive integrated seismic, geophysical, and geologic investigations.

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BASEMENT ROCKS IN THE NEW MADRID REGION

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Detailed aeromagnetic and Bouguer gravity maps and widely spaced wells to basement in the New Madrid region permit a preliminary interpretation of basement geology. The geophysical maps reveal a series of prominent west-northwest-trending anomalies and a less distinct but clearly discernible cross trend to the northeast.

A major west-northwest-trending gradient that separates magnetic and gravity highs on the north from magnetic lows and gravity highs on the south occurs northeast of the Ste. Genevieve Fault Zone. The magnitude of the gradient suggests that it is a major basement boundary. A orogenic granite, rhyolite, and minor trachyte and tholeiitic basalt compose the basement on both sides of the gradient. Pre-Upper Cambrian sandstones and siltstones were also encountered in the Illinois Basin to the south of and along the major geophysical gradient. The presence of old sedimentary rocks in the deeper parts of the Illinois Basin suggests that basin subsidence began in pre-Upper Cambrian time and that sedimentation may have been in part controlled by the basement boundary. The distribution of these rocks is thus important in understanding the early tectonic development of the region.

The previously mentioned cross trend extends to the northeast along a series of circular, positive magnetic and gravity anomalies of high amplitude. The anomalies bound a central zone of magnetic and gravity lows and are associated with the New Madrid Seismic Zone (Braile et al., in press). Good correlation between the anomalies suggest the existence of a linear basement feature along which tectonism and mafic igneous activity occurred. Geologic models that fit the observed data are discussed.

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A MODEL FOR INTRAPLATE SEISMICITY OF EASTERN NORTH AMERICA

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Observation of a basement structural feature which is reflected by prominent, correlative gravity and magnetic anomalies and which delimits the New Madrid Seismic Zone in central North America suggests that contemporary seismicity in this area may be the result of reactivation of ancient geologic structures. Two factors influencing slip along a preexisting zone of weakness are the orientation of the zone of weakness with respect to the principal stress directions and the coefficient of friction for slip along the weakness plane. Analysis of the compressive horizontal stress directions for eastern North America and the orientation of major zones of earthquake activity indicate that most of the seismic zones are oriented within the range of 10^{o}-40^{o} of the maximum horizontal compressive stress direction, whereas most of the major recognized geologic structures which could be susceptible to reactivation but are currently seismically inactive are oriented outside of this range of angles. These observations suggest a model for intraplate earthquake activity in eastern North America in which contemporary earthquake activity is due to slip along appropriately oriented pre-existing zones of weakness.

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MAGNETIC ANOMALY MAP OF THE GREATER NEW MADRID SEISMIC ZONE

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An aeromagnetic anomaly map covering nearly 300,000 km^2 in the eastern midcontinent of the U.S. has been assembled from 26 separate surveys. The airborne surveys were conducted under cooperative agreements involving the Tennessee Valley Authority, U.S. Geological Survey, Nuclear Regulatory Commission, and State geological surveys. The combined effort is in support of the multidisciplinary investigation of the New Madrid Seismic Zone.

The combined survey area, lying between 82^o-91^oW. longitude, and between 35^o-39^o N. latitude has been organized into a gridded data base with a 2 km interval. A magnetic contour interval of 100 nT has been adopted for map construction The appropriate IGRF values have been removed from each aeromagnetic survey unit.

The magnetic anomaly map presents a regional view of a complex basement beneath the eastern midcontinent, containing a number of highly magnetic units, especially in the eastern part of the map coverage. Magnetic values of more than 3000 nT occur locally. In general, few of the basement features are directly reflected in observed surface geologic structure. The magnetic field must be viewed with the effect of basement in mind. Paleozoic, and locally Mesozoic cover rocks range in thickness from about 760 m near the northern part of the Lexington Dome in Kentucky to more than 4600 m in the Moorman Syncline of Kentucky and more than 6700 m near the western margin of the Blue Ridge in Eastern Tennessee.

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A BOUGUER GRAVITY MAP OF A PORTION OF THE CENTRAL MIDCONTINENT

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As part of research efforts funded by the Nuclear Regulatory commission, a Bouguer gravity map of a large portion of the Midcontinent area has been constructed. This map is based on approximately 70,000 gravity readings and covers the area from 35^{o} to 39^{o}N latitude and from 82^{o} to 92^{o}W longitude. There is a strong correlation between observed gravity anomalies and the major tectonic units present. A large north-south trending anomaly dominates the eastern portion of the map and the positive anomaly associated with the northern Mississippi Embayment dominates the western portion of the map. Prominent east-west trending (mostly negative) anomalies are associated with the 38th Parallel Lineament. These anomalies are distrupted when this lineament intersects the northeast trending New Madrid Linear Tectonic Feature in southern Illinois and Western Kentucky. A prominent northwest trend of anomalies is evident west of this intersection.

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SEISMO-TECTONICS OF THE NEW MADRID SEISMIC ZONE AND ITS EXTENSION-AN OVERVIEW

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During the past half decade, significant progress has been made in delineating and understanding the geologic source of the New Madrid Seismic Zone. Microseismicity, focal plane solutions and regional gravity, magnetic, and seismic investigations suggest that the major seismicity occurs in linear zones within a northeast-trending structure that has been interpreted as a paleo-rift dating back to the late Precambrian. Reactivations of this zone of weakness by the comtemporary stress pattern is manifested in the current seismicity. Recent compilations of regional geophysical data suggest that this structural feature extends northeasterly across the 38th Parallel structural features into Indiana where the Wabash River Valley Fault Zone occurs along, but at an angle to the northwestern margin of this geophysically mapped feature. The southwestern extent of the structure is unmapped, but the New Madrid Seismic Zone terminates abruptly to the southwest in contrast to the situation along the northeast extension. Another major zone of seismicity extends north-northwesterly from New Madrid to St. Louis along the Mississippi River. This zone correlates with gravity and magnetic anomalies in much the same manner observed along the New Madrid Seismic Zone suggesting a similar relationship between basement structural feature and seismicity. The correlation of trends of epicenters and basement geologic structures suggests a model for these intraplate earthquakes in which the earthquake activity is the result of failure along appropriately oriented pre-existing zones of weakness in the presence of a regional compressive stress field.

Abstract of paper presented at the 1980 North-Central Section Meetings of the Geological Society of America, April 10-11, Bloomington, Indiana

THE MAGNETIC ANOMALY ASSOCIATED WITH THE STRUCTURE OF OMAHA OIL FIELD, ILLINOIS

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A positive local closure in the aeromagnetic anomaly map of southern Illinois was found to coincide with the Omaha oil field in Gallitin County, southeastern Illinois. A ground magnetic survey confirmed the 145 gamma magnetic high anomaly and also provided the data base for preparation of a residual total intensity magnetic anomaly map. Computer modeling, which utilized available structural information and measured magnetic susceptibilities of well cuttings indicate that the observed anomaly can be attributed to the presence of two superposed mica-peridotite sills which have been intruded below the producing formations of the oil field. The Mississippian Tar Springs and Palestine formations, from which most production has been taken, are domed and exhibit structural closure (256 feet) equal to the combined thickness of the two sills. A Devonian horizon which occurs only 144 feet below the base of the lower sill is not domed and therefore it is concluded that the structural closure of the Tar Springs and Palestine formations was caused by intrusion of the mica-peridotite sills. Thus, in a geological environment where intrusives are encountered within the sedimentary section, magnetic surveys can provide useful information for delineation of structures which are potential hydrocarbon reservoir.

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ENHANCED GRAVITY AND MAGNETIC ANOMALY MAPS OF THE EAST-CENTRAL MID-CONTINENT

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Bouguer gravity and total magnetic anomaly data within the east-central Midcontinent which have been composited and gridded at a 2 km interval are subjected to a variety of enhancement and isolation processes to facilitate interpretation of basement structure and lithology. These processes lead to a suite of derived maps obtained by, where appropriate, reduction to magnetic pole, continuation, and bandpass, derivative, and strikepass filtering schemes encompassing the area between $39^{o}N - 36^{o}N$, $90^{o}W - 84^{o}W$. To filter such large data sets, without developing edge effects from the compositing of smaller data subsets, an out-of-core storage technique was adapted to processing in the frequency domain. Utilization of this and other comparable regional data sets with these enhancement techniques will allow for improved geological studies of continental tectonism.

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A NEW GRAVITY ANOMALY MAP OF SOUTHERN INDIANA

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Regional Bouguer gravity anomaly maps are useful in delineating basement structure and lithology and, therefore, have a significant role in seismo-tectonic studies in the Midcontinent. As part of an intensive study of the northeast extension of the New Madrid Seismic Zone, a gravity survey has been conducted in southern Indiana to acquire regional control to supplement the basement geology, aeromagnetic, and crustal seismic studies. Approximately 7250 observations have been made at road intersection elevations in Indiana from the Ohio River to 40^{o}N. latitude. The stations are located on a 2 mile or smaller grid. Reduction of the data have been conducted by standard techniques used in the Midcontinent. The new Bouguer gravity anomaly map prepared from these observations delineates minor anomalies and improves the definition of the location, amplitude, and gradient of the major, more areally-extensive, anomalies. This map is particular valuable when interpreted in light of the total magnetic intensity anomaly map of the area.

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CRUSTAL SEISMIC STUDIES RELATED TO THE NORTHEAST EXTENSION OF THE NEW MADRID SEISMIC ZONE

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During 1978 and 1979, seismic refraction experiments were carried out in southeastern Illinois and southwestern Indiana as part of an integrated geological-geophysical research program directed toward understanding the seismo-tectonics of the New Madrid Seismic Zone and its extension to the northeast. Recent geophysical results from this program suggest that a basement structural feature extends from the New Madrid Area northeast across the 38th parallel structural features and northeasterly into Indiana. The Wabash River Valley Fault Zone occurs along the northwestern margin of the feature, but at an angle to it. Nine refraction profiles varying in length from 6 to 172 kilometers have been designed and data collected such that two of the lines lie within the feature margins and parallel to its northeast trend. Several lines cross the inferred boundaries of the feature while other lines lie wholly outside. Data from the nine refraction profiles have been collected, processed, and compared to synthetic seismograms calculated for models of the area. Analysis of the records to date indicate that the Paleozoic sedimentary rocks in the Illinois Basin have an average velocity of about 5.4 km/sec. The upper crustal velcoity is about 6.1 km/sec. and a lower crustal layer has a velocity of approximately 6.8 km/sec. Further results of interpretation of the records will be presented and comparison of observations to synthetic seismograms will be discussed.

Abstract of paper presented at the 1980 North-Central Section Meetings of the Geological Society of America, April 10-11, Bloomington, Indiana

APPENDIX II

THE TECTONIC APPROACH TO EVALUATION OF EARTHQUAKE HAZARDS IN THE MIDCONTINENT

by

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THE TECTONIC APPROACH TO EVALUATION OF EARTHQUAKE HAZARDS IN THE MIDCONTINENT

by

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ABSTRACT

Experience in the New Madrid Seismic Zone and its extensions suggests that deficiencies in the historical seismic record and insufficient knowledge of neotectonic structures in the midcontinent require that earthquake hazard evaluation be based not only on the conventional seismicity approach, but also on the definition and evaluation of tectonic models. This supplementary tectonic approach to the evaluation of earthquake hazards utilizes information derived from seismicity and microseismicity studies in combination with the mapping of stresses and existing geologic structures to define tectonic models which are used to predict the origin and extent of seismicity. The postulated models are then verified and revised if necessary on the basis of the results of detailed microseismicity and geologic investigations.

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INTRODUCTION

Seismic hazard evaluation in the midcontinent is a complex problem relating to the prediction of earthquake type and the occurrence of quakes in time and space. Prediction of the type earthquake and the occurrence of earthquakes in time is difficult under the best of conditions, but is particularly difficult in the central U.S. because of limited earthquake statistics. Thus, our attention is focused on the problem of the spatial prediction of earthquakes. It is the purpose of this paper to review the case for a tectonic approach to the solution of this problem, show how it is being used in the New Madrid Seismic Zone and its extensions, and, finally, to present recommendations for improvement of the tectonic approach to seismic hazard evaluation in the midcontinent.

The tectonic approach is intended to supplement rather than displace the more specific seismic approach to spatial earthquake prediction which is based on the historical seismicity record. The tectonic method of seismic hazard evaluation is based on three ingredients - the seismic record, the state of stress within the earth, and geologic structures or zones of weakness with the crust.

As illustrated in the flow chart of Figure 1, where historical seismicity can be directly related to neotectonic geologic features, the spatial prediction problem is greatly simplified. The three-dimensional extent of the geologic feature plus the surface geology, and available seismological data can be used to define the type earthquake and recurrence pattern over the extent of the geologic feature. Examples of this situation occur in the western U.S., for example, the earthquake activity along the San Andreas fault. Of course, this definition of the characteristics of seismicity can only be adequate if the historical seismicity record is long compared to recurrence intervals of large earthquakes and if non-stationarity in the seismicity patterns is negligible.

However, where seismicity is not related to known structure or geologic attributes and the historical record is limited, the problem is much more complex. Whitham (1975) states that the lack of understanding of the tectonic framework is the key factor inhibiting a better expression of seismic risk in Canada. This is the situation in much of central and eastern U.S., for example, the St. Lawrence River Valley;

Charleston, South Carolina; and the New Madrid areas. In these regions delineating zones of seismic hazard is dependent on the development of models which explain paleo- and neotectonics and can be used to successfully predict into the future and into presently unknown geologic areas.

Most tectonic models which have been cited as possible explanations for central and eastern U.S. seismicity (Hinze et al., 1980) can be grouped into three general categories - isostatic warping, thermal expansion and contraction, and resurgent tectonics associated with crustal rifting, zones of weakness and crustal boundaries, and local basement inhomogenities. Although all of these may be important locally, most studies and interest have focused upon resurgent tectonics or reactivation of pre-existing structures by contemporary stress patterns whose origins are unrelated to the structures.

THE NEW MADRID SEISMIC ZONE HAZARD EVALUATION PROBLEM

The history of development of seismic hazard evaluation in the New Madrid Seismic Zone and its extensions provides an excellent illustration of the manner in which the tectonic approach can be applied to studies of other areas in central and eastern U.S. The New Madrid Seismic Zone, a region of intense seismic activity and the site of several destructive earthquakes (Nuttli, 1973), has been subjected to a broadly-based study program which has led in a short span of time to significant progress in developing a tectonic model to explain the seismic activity. In simple terms, the zone of earthquake activity has been found to be associated with an ancient zone of weakness which can be traced by surface geophysical methods. Even though this model is still evolving and is under continued testing and evaluation, the process which has led to its development provides a framework for similar studies and illustrates problems which need to be solved before zones of seismic hazard can be successfully mapped in central and eastern U.S.

The history of development of the New Madrid tectonic model is shown schematically in the series of simplified diagrams of Figure 2. In the pre-1970 era (Figure 2a) the historical seismicity record showed several major and many minor earthquakes in the New Madrid area and portions of adjacent states. Most explanations for the seismicity focused on the correlation with various Phanerozoic geologic structures and surface attributes. There was no well defined pattern of seismicity except for the general northeast trend in the New Madrid area. Then around 1977, the St. Louis University seismological group (Figure 2b) delineated a northeast trending microseismicity zone and determined right lateral fault movement from a fault plane solutions (Stauder, 1977; Herrmann and Canas, 1978). At about that same time, Haimson (1976), Sbar and Sykes (1973) and others were measuring a prevailing horizontal, approximately east-west trending, maximum compressive stress over much of central and eastern U.S.

Then around 1978, Hildenbrand and Kane (Hildenbrand et al., 1977) studied the gravity and magnetic anomaly data of southeastern Missouri and adjacent area with the aid of sophisticated processing techniques and Stauder's microseismicity results. They identified a series of isolated gravity and magnetic positive anomalies which bound a northeast striking zone of long wavelength anomalies which contain the microseismicity trend (Figure 2c). They interpreted this trend as originating from a rift expressed in the basement rocks with bordering mafic intrusives. More recently, Braile et al. (1980) assembled additional gravity and magnetic anomaly data and suggested from this compilation that the New Madrid basement feature extends northeastward across Illinois into Indiana as far north as 39°N latitude (Figure 2d). This trend can be traced northeastward utilizing the bounding, local gravity and magnetic anomalies as shown in Figure 3 plus other evidence (Braile et al., 1980). Studies are continuing to determine the extent of the trend, its geological origin and relationship to paleo- and neotectonics.

THE TECTONIC APPROACH

Three principal ingredients have been employed in the evolution of the New Madrid tectonic model which has been used in the tectonic approach to seismic hazard evaluation. Historical seismicity has focused attention on the region, but recent microseismicity studies have been particularly important. The definition of the stress pattern and focal plane solutions also have made significant contributions. And finally, crustal structures identified largely from regional geophysical measurements have had an important role in establishing the model and predicting the potential spatial pattern of the seismicity in the New Madrid area.

Similar general studies indicate that these three ingredients may be important in developing related models over much of central and eastern U.S. Figure 4 illustrates the results of mapping the trend of the major geologic structures, stresses, and seismicity zones of this area. Analysis of these trends reveal that roughly 75% of the structures are consistent with a model in which contemporary earthquake activity results from strike or dip slip movement appropriately oriented pre-existing zones of weakness by prevailing maximum compressive stress.

Thus it is indicated that seismicity, stresses, and structures are important in defining models for intraplate seismicity and specifically the spatial occurrence of earthquakes where earthquakes are not directly attributable to neotectonic elements. A strategy for the tectonic approach to seismic hazard prediction built around these components is presented in Figure 5. Several of the specific items of this flow chart require special consideration.

A knowledge of microseismicity is critical to the tectonic approach, but this information is limited because of the restricted number of microseismicity nets, widely spaced seismograph stations and the short historical record. The effect of widely spaced seismographs is graphically illustrated on Figure 6 which shows the minimum earthquake magnitude for 100% probability of detection by at least 5 stations. Although this map is now out of date since it dates back to the mid-60's, the situation has not changed greatly in many areas of central and eastern U.S. except where detailed arrays have been deployed in critical locations such as the New Madrid area. The implication of Figure 6 is that over vast areas of the midcontinent, earthquakes of magnitude of less than 4 will not be detected or at least will be poorly located.

In analyzing the spatial distribution of epicenters, special care must be taken to avoid the tendency to connect earthquake epicenters into lineaments or linear segments where the data are sparse. Figure 7 shows three possible patterns of epicenters. Clustered epicenters may occur around a rigidity perturbation in the crust caused by an intrusive or similar lithologic variation. Randomly located epicenters may occur within a basement province because of homogeneity in zones of weakness or geometry. Linear trends of epicenters will occur along a dominant linear zone of weakness which is oriented correctly with respect to the stress pattern, but evidence for the validity of interpreted epicenter lineaments must be pursued. One approach to this problem is to seek corroboration by mapping the other two critical ingredients of the strategy - stress patterns and geologic zones of weakness.

Definition of the contemporary stress pattern is also very important to this strategy. Many stress studies have been made, but numerous additional measurements are needed especially at depth and in critical areas. Furthermore, coefficient of friction and general rock strength characteristics are poorly known. These are essential to relating the stress pattern to new fractures or reactivation of old lines of weakness and the orientation of fractures favorable to movement.

Finally, it is important to define the crustal structures and because many of these will be covered by younger sedimentary rocks, geophysical studies constrained by available geologic data from deep drill holes are particularly useful. Furthermore, it is important that we are not blinded by major features of the geophysical results. In particular, we must direct our attention to more subtle gravity and magnetic anomalies that have limited areal size and amplitude, but may reveal zones of weakness that are especially prone to reactivation. This is illustrated in the aeromagnetic map of the greater New Madrid area (Figure 8) in which the subtle isolated magnetic highs are apparently more important to seismicity investigations than the dominant west-northwest magnetic trend.

With the definition of the seismicity, stresses, and structures, a tectonic model is defined which will explain the origin and geographic extent of the observed seismicity. The validity of this model can be checked by determining its ability to predict the paleo- and neotectonics. It can be anticipated that this procedure as shown in the flow chart (Figure 5) will undergo several iterations. Along with related seismological data, this strategy based predominately on the tectonic approach may be used to define the seismic hazard of the region supplementing the more obvious seismic approach.

SUMMARY AND RECOMMENDATIONS

In summary, experience with the evaluation of seismic hazards in the New Madrid area suggests that deficiencies in the historical seismic record and insufficient knowledge of neotectonic structures require that seismicity studies in the midcontinent be based not only on seismicity, but also on the evaluation of tectonic models. As a result, a strategy for developing tectonic models and evaluating earthquake activity should be based on seismicity and microseismicity investigations and mapping of stresses and existing geologic structures. The tectonic models that are postulated should be verified by microseismicity studies.

Many improvements are needed to achieve the goal of seismic evaluation through the tectonic approach in the midcontinent. They include:

1) Inexpensive, high-sensitivity microearthquake monitoring so that large number of networks of stations can be deployed in areas based on predictive models.

2) Number and methods of stress analysis particularly at depth.

3) Investigation of subtle gravity and magnetic anomalies utilizing digital processing techniques.

4) Definition of the basement geologic provinces of the midcontinent.

5) Investigation of the importance of the coefficient of friction of rocks.

6) Mapping and recognition of neotectonism in surface geology.

7) Methods of testing geodynamic models and role of plate tectonics in intraplate seismicity.

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FIGURE CAPTIONS

Figure

1. Earthquake hazard evaluation strategy where historical seismicity can be related to geologic features.

2. History of the development of the New Madrid tectonic model.

3. Selected profiles of gravity (dashed lines) and magnetic (solid lines) anomaly data across the New Madrid tectonic feature (heavy dashed lines) (after Braile et al., 1980).

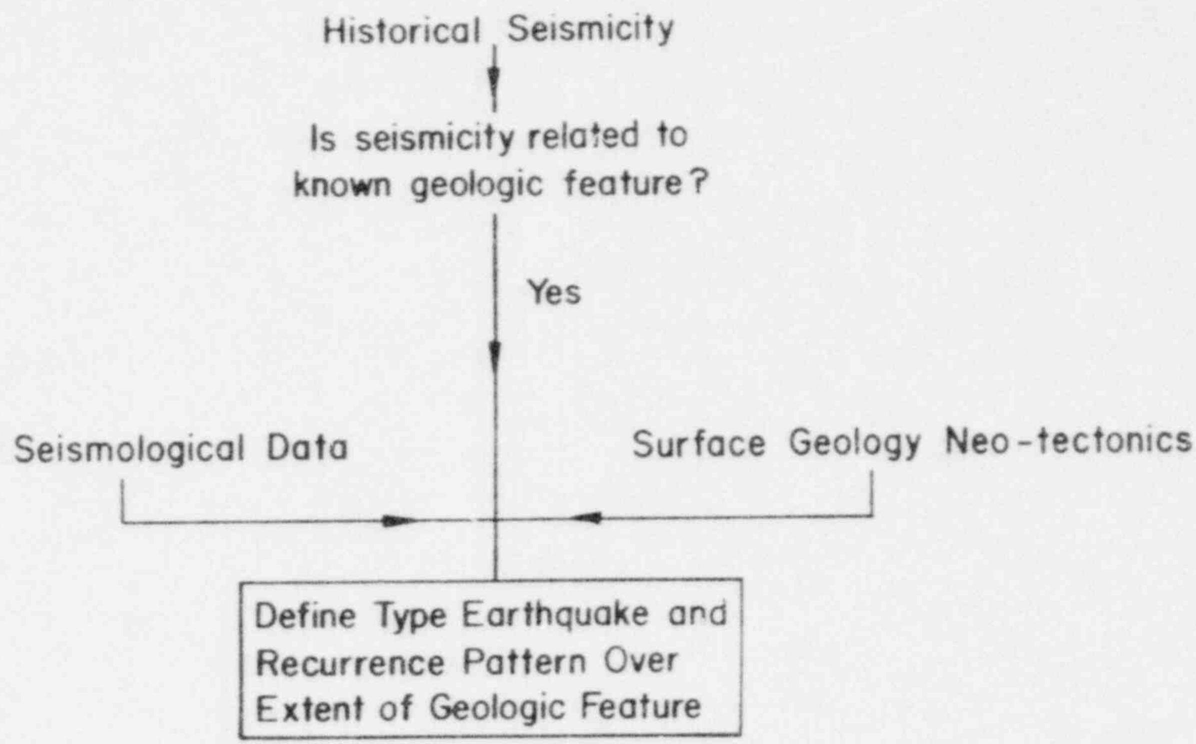
4. Trends of stresses, major structures, and seismicity in central and eastern U.S.

5. Earthquake hazard evaluation strategy where historical seismicity is unrelated to known geologic feature.

6. Magnitude for 100 percent probability of detection by at least five stations of the total set of all U.S. seismograph stations (after Stepp et al., 1965).

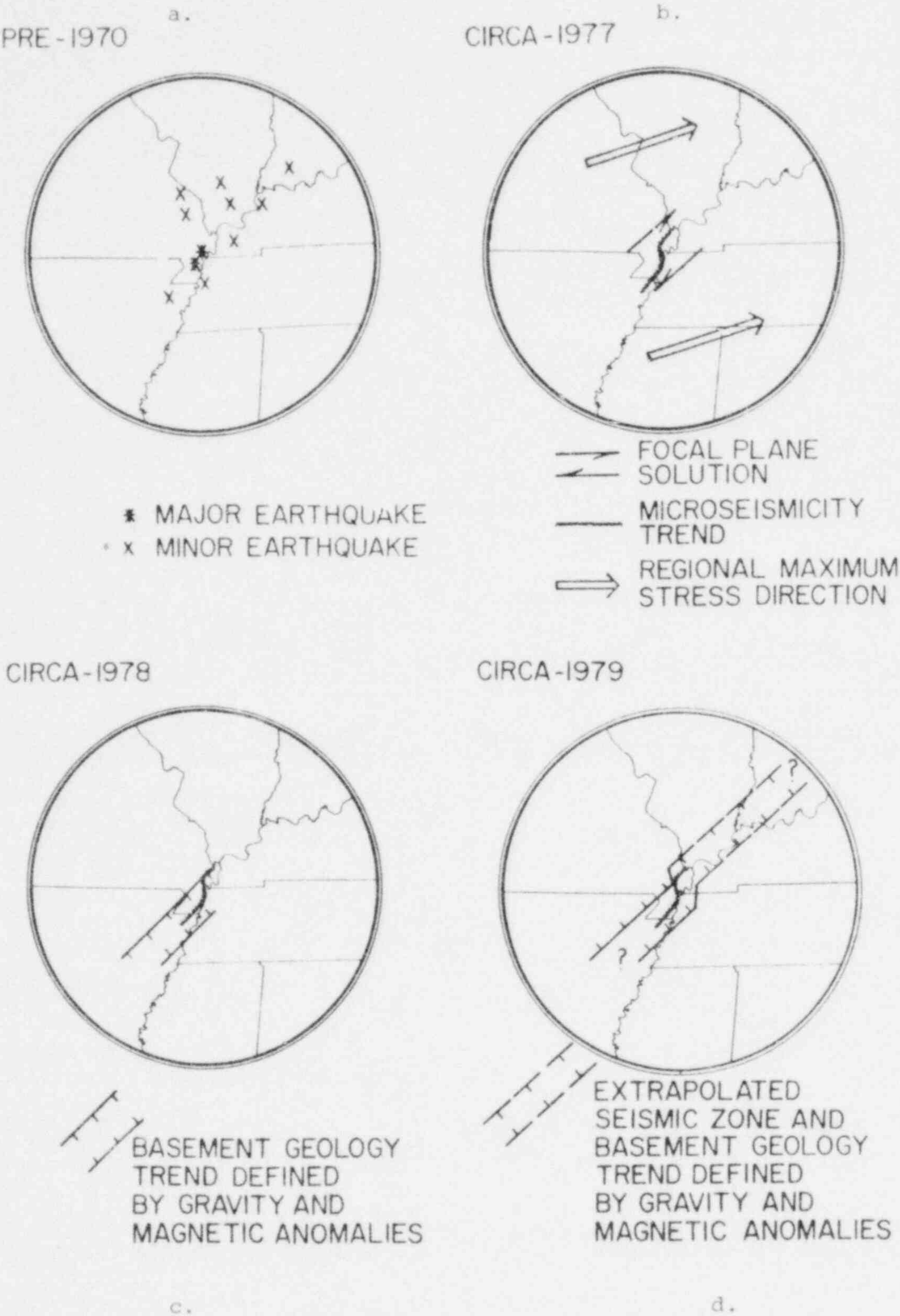
7. Schematic spatial distribution of earthquake epicenters.

8. Shaded magnetic anomaly contour map with inferred boundaries of the New Madrid Linear Tectonic Feature shown by the heavy dashed lines. South of $36^{\circ}N$ latitude the boundaries are identical to those inferred by Hildenbrand et al., 1977 (after Braile et al., 1980).



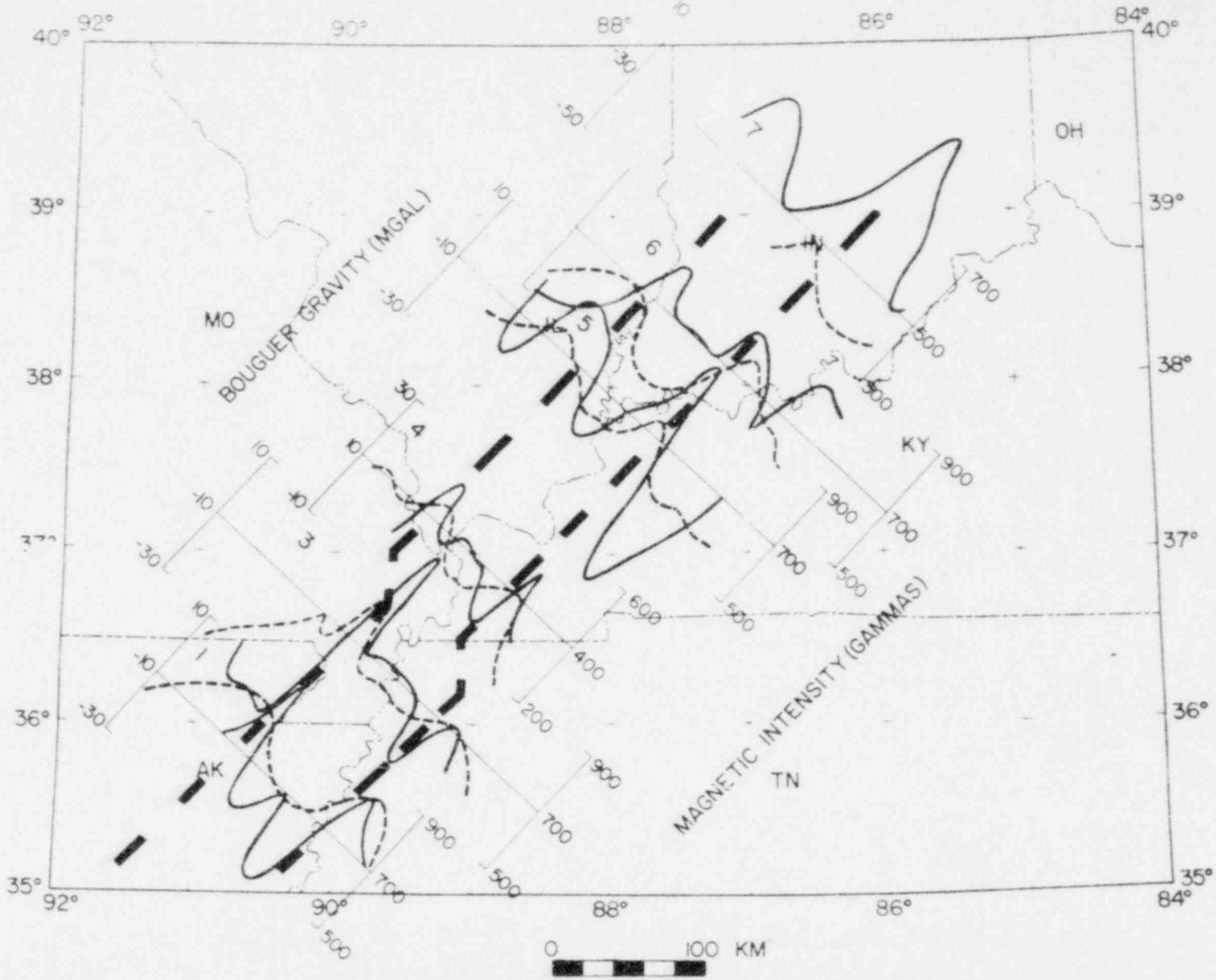
Earthquake hazard evaluation strategy where historical seismicity can be related to geologic features.

Figure 1



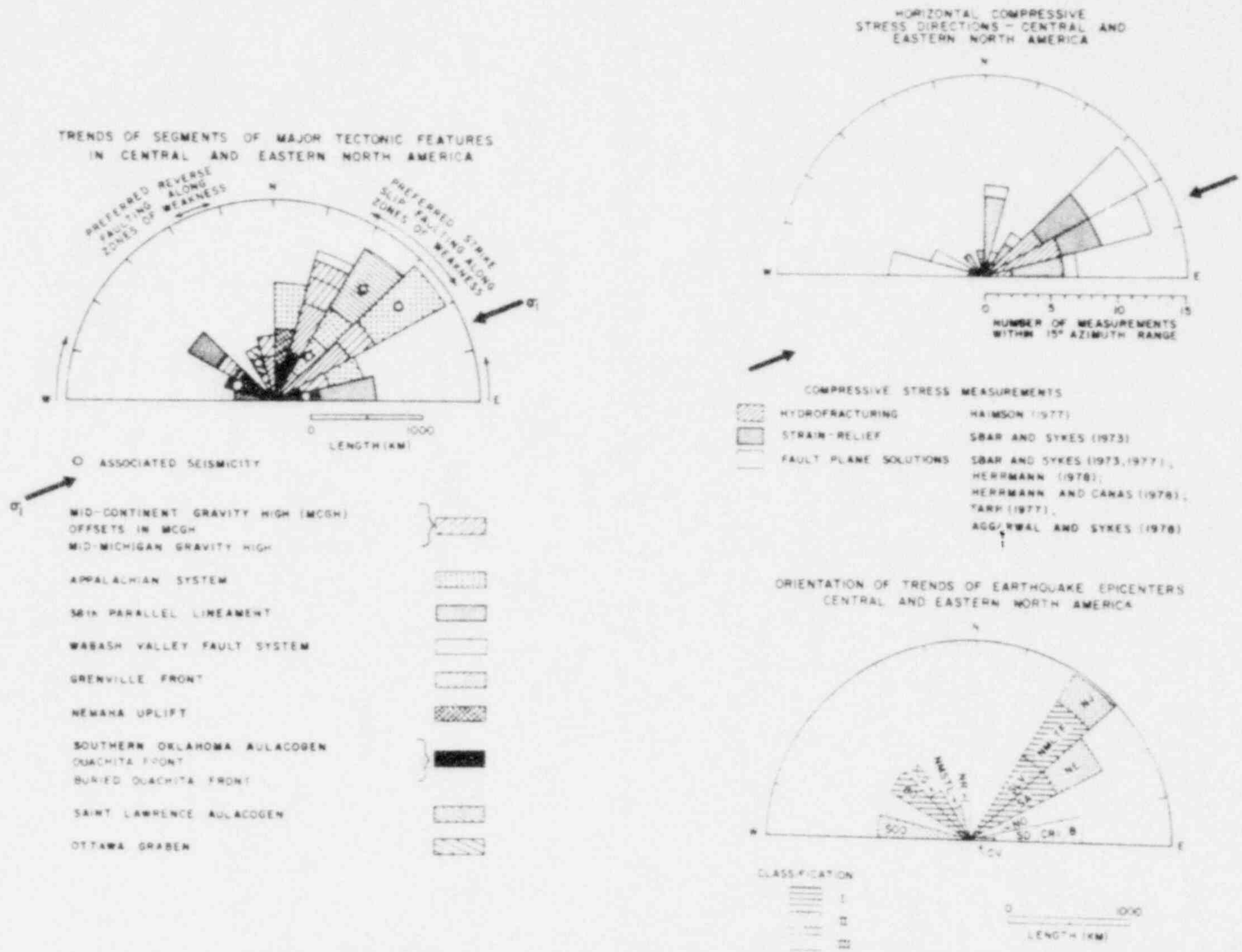
History of the development of the New Madrid tectonic model.

Figure 2



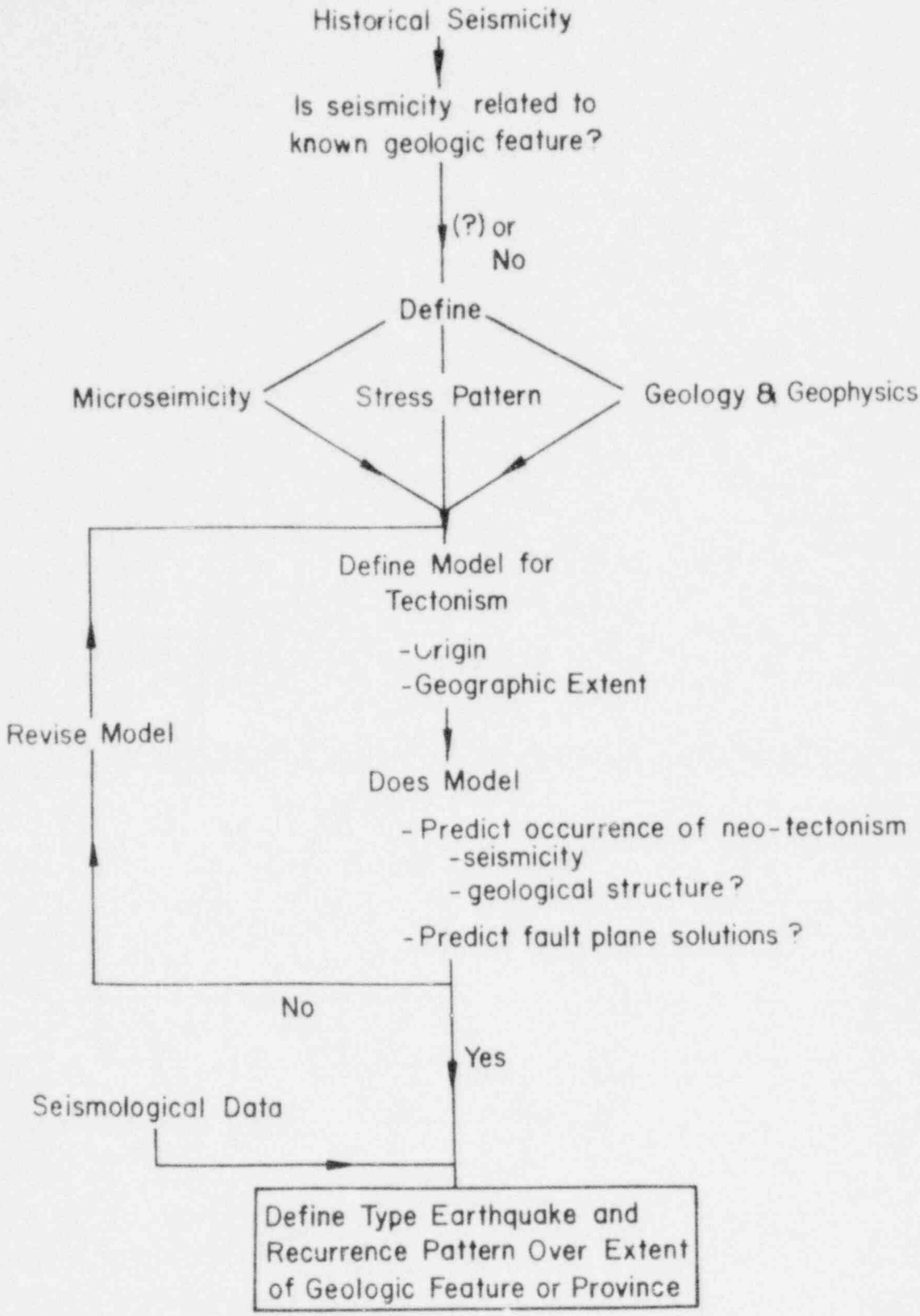
Selected profiles of gravity (dashed lines) and magnetic (solid lines) anomaly data across the New Madrid tectonic feature (heavy dashed lines) (after Braile et al., 1980).

Figure 3



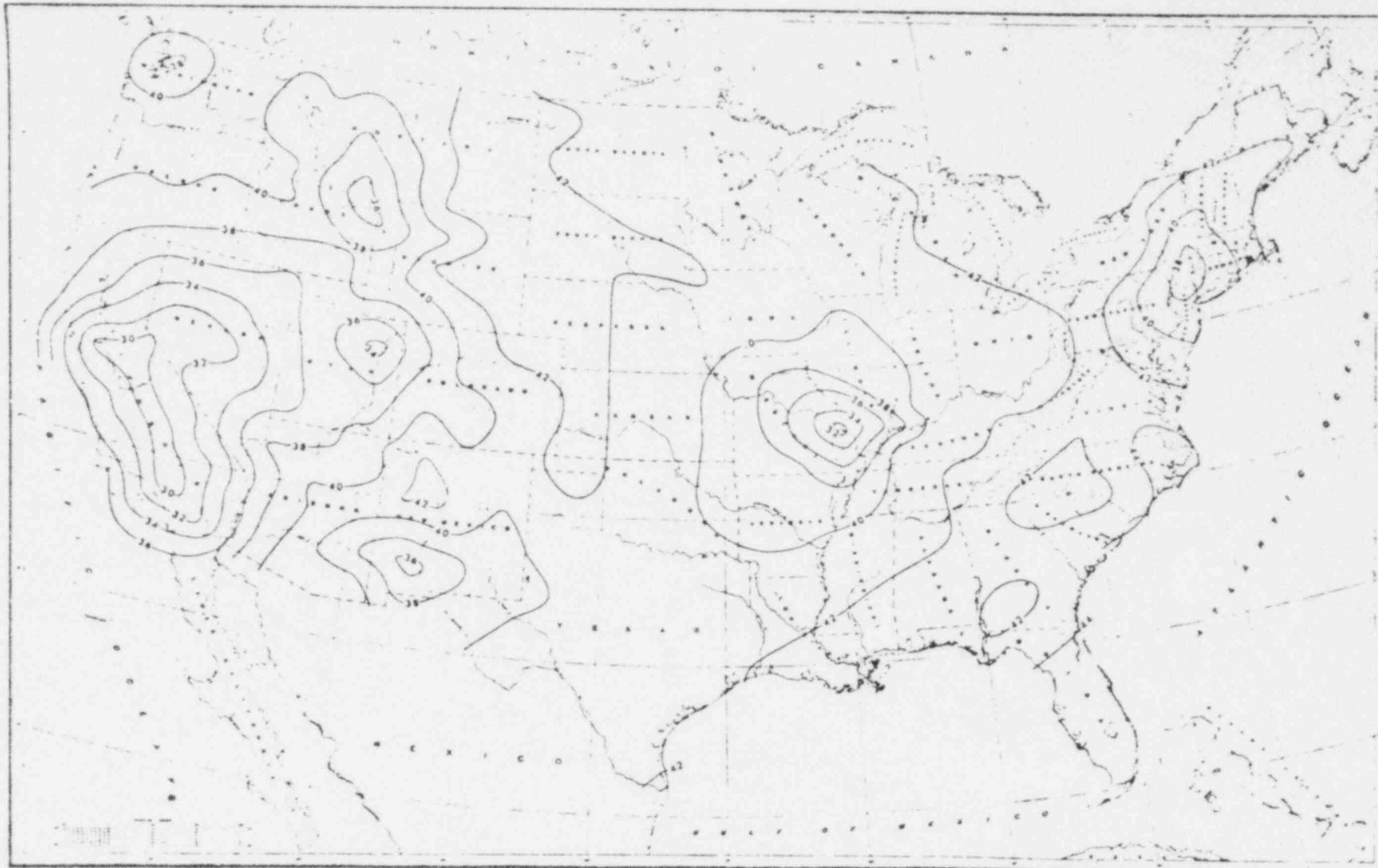
Trends of stresses, major structures, and seismicity in central and eastern U.S.

Figure 4



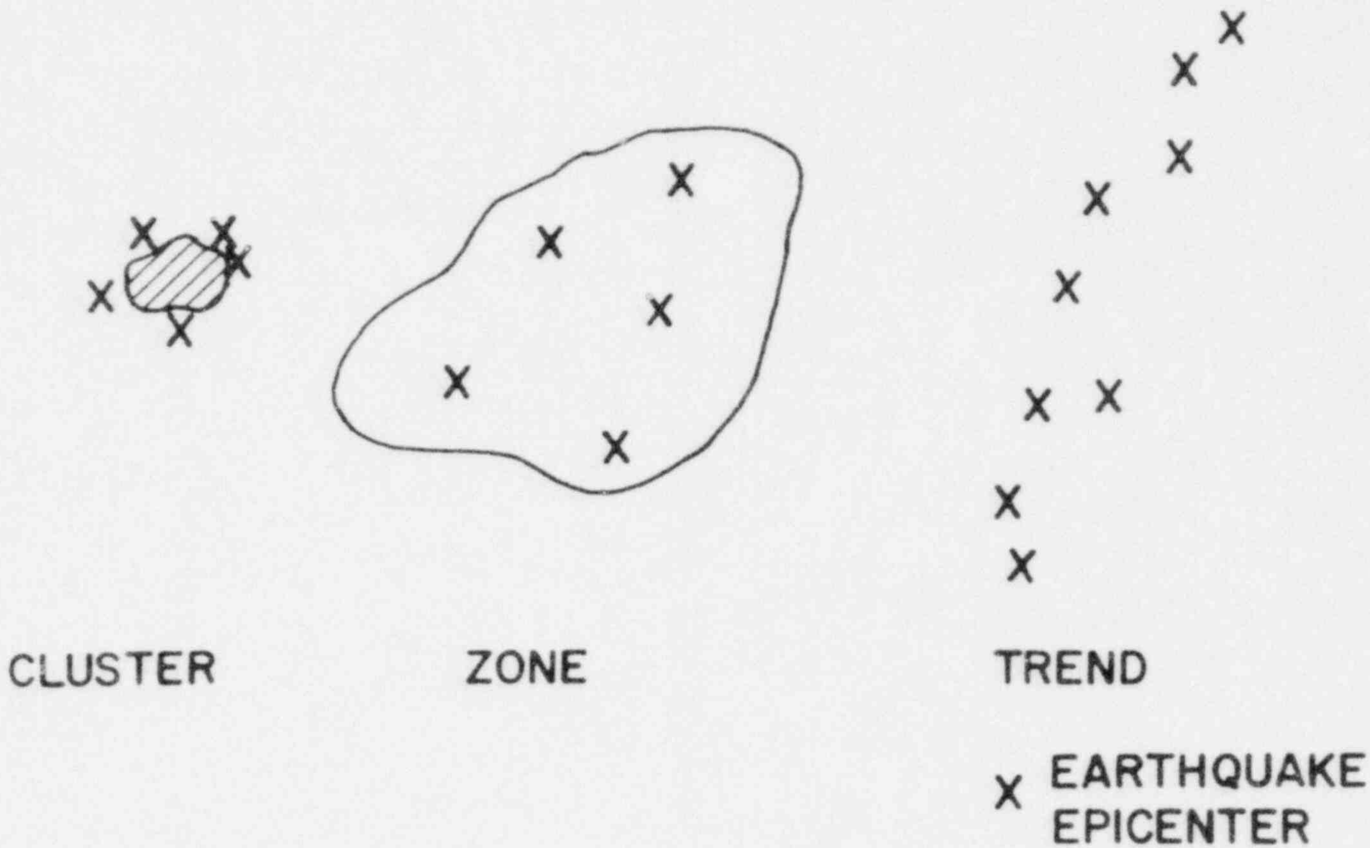
Earthquake hazard evaluation strategy where historical seismicity is unrelated to known geologic feature.

Figure 5



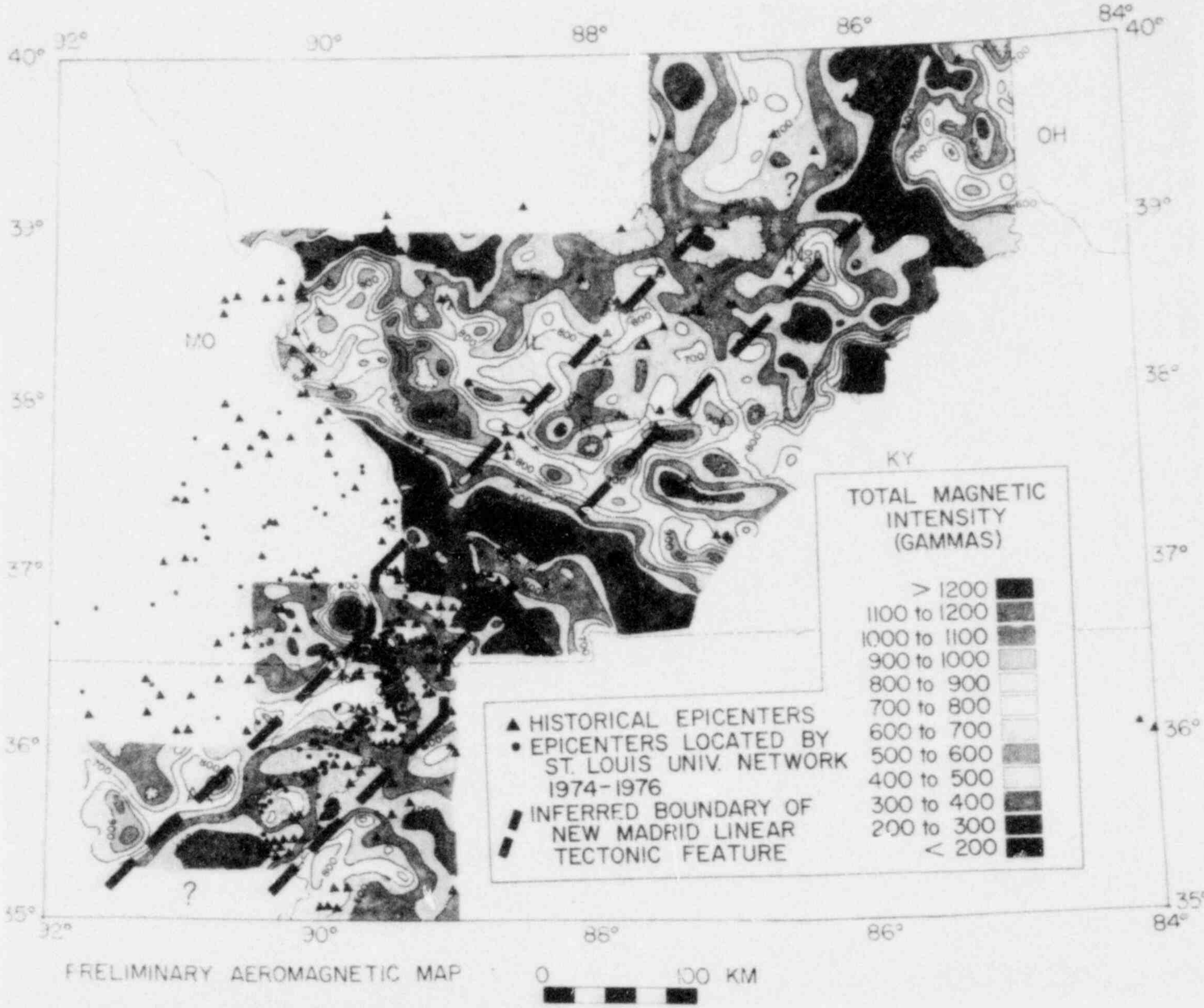
Magnitude for 100 percent probability of detection by at least five stations of the total set of all U.S. seismograph stations (after Stepp *et al.*, 1965).

Figure 6



Schematic spatial distribution of earthquake epicenters.

Figure 7



Shaded magnetic anomaly contour map with inferred boundaries of the New Madrid Linear Tectonic Feature shown by the heavy dashed lines. South of 36°N latitude the boundaries are identical to those inferred by Hildenbrand et al., 1977. (after Braile et al., 1980).

Figure 8

APPENDIX III

GRAVITY AND MAGNETIC ANOMALY MODELING OF MISSISSIPPI EMBAYMENT CRUSTAL STRUCTURE AT SATELLITE ELEVATIONS

by

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GRAVITY AND MAGNETIC ANOMALY MODELING OF MISSISSIPPI EMBAYMENT CRUSTAL STRUCTURE AT SATELLITE ELEVATIONS

by

R.R.B. von Frese[1], W.J. Hinze[1], and L.W. Braile[1]

ABSTRACT

A model for the three-dimensional crustal structure of the northern Mississippi Embayment is generalized from published surface wave dispersion, and seismic refraction studies. The gravity and magnetic anomaly signatures of this model are computed at 450 km elevation by Gauss-Legendre quadrature integration for comparison with observed anomalies at satellite elevations. The computed positive gravity anomaly compares well with upward continued free-air gravity data suggesting that the generalized model is representative of the crustal structure of the Embayment. Magnetic anomaly calculations show that the pronounced minimum observed over the Embayment in the POGO satellite magnetometer data can be accounted for by a decrease in the magnetization of the lower crust which corresponds to the major gravity source of the region. The results of this investigation support the failed-rift hypothesis for the origin of the Mississippi Embayment. Accordingly, these results suggest that observable gravity and magnetic anomalies characterize failed rifts (aulacogens) at satellite elevations, where the primary source of both anomalies is a high density rift component of non-magnetic lower crustal material.

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INTRODUCTION

Satellite-level magnetic and gravity anomaly interpretational methods largely have been limited to visual spatial correlation of anomalies with known geological features and simple flat earth modeling approximations. However, the full importance of satellite-level anomalies, which map the anomalies of large scale geologic features that are difficult to recognize and isolate in low-level data, will not be achieved until direct modeling of large-scale structural features is accomplished utilizing the spherical earth condition. Modeling of geologic features incorporating available geologic and geophysical data as constraints can be employed as an interpretive technique by altering the model until the computed anomalies match the observed anomalies. Furthermore, spectral analysis of the calculated satellite-level magnetic and gravity anomalies of geologic models provides critical information for designing filters to isolate the observed anomalies of these features.

A technique is described and demonstrated by von Frese et al., (1980) for numerically modeling potential field characteristics due to regional-scale geologic sources by Gauss-Legendre quadrature integration. Herein, the method is used to study the gravity and magnetic anomaly characteristics of the Mississippi Embayment crustal model derived from seismic methods at 450 km elevation. This information, in turn, is pertinent to evaluating the feasibility of using satellite gravity and magnetic surveys for detecting anomaly signatures due to failed rifts. The Mississippi Embayment is particularly suited for this application because a number of geophysical constraints are available for developing a first-order model of its crustal structure.

MODEL DESCRIPTION

The Mississippi Embayment represents a broad, spoon-shaped reentrant of Mesozoic and Cenozoic sedimentary rocks which extends into the Paleozoic terrane of the North American craton from the south. As shown in Figure 1.D, the axis of this feature roughly coincides with the Mississippi River tapering northward into the tectonically active region of the New Madrid seismic zone and beyond.

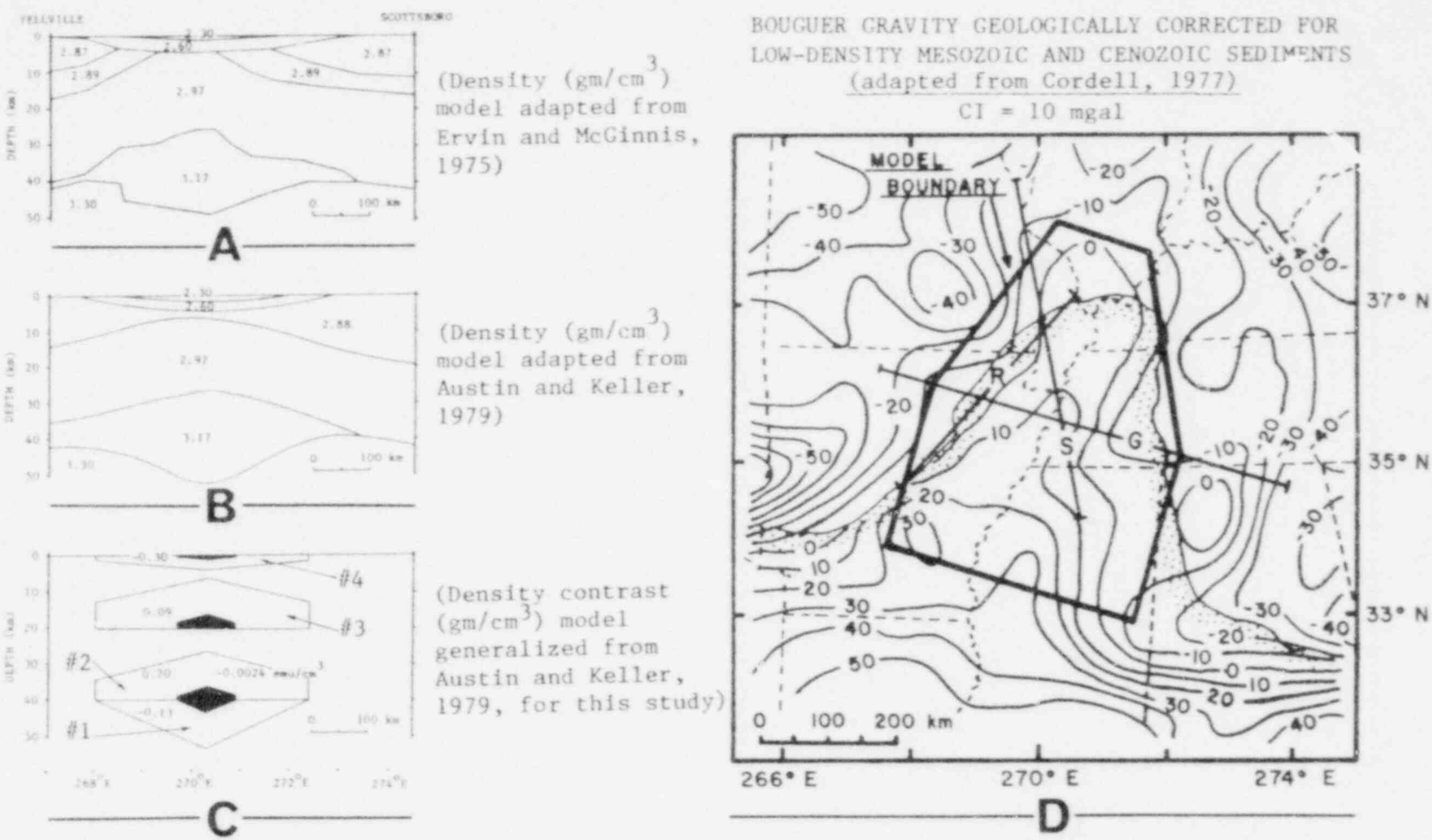

Figure 1 Development of Mississippi Embayment density and magnetization models. Also shown in D is an index map of the Embayment (shaded contour) where G is the gravity profile studied by Ervin and McGinnis (1975), R is the seismic refraction line studied by McCamy and Meyer (1965), and S is the surface wave propagation path studied by Austin and Keller (1979).

Based on the regional geology, Burke and Dewey (1973) suggested the embayment is a Mesozoic aulacogen developed from a triple junction located in the vicinity of Jackson, Mississippi. However, an integrated analysis of gravity, seismic, stratigraphic and petrologic data by Ervin and McGinnis (1975) suggests the Embayment is a late Precambrian aulacogen which was reactivated most recently in the late Cretaceous by tensional forces initiated during the formation of the present Atlantic Ocean basin by subsidence of the Gulf Coastal Plain.

Figure 1.A is a cross-section of the density structure of the Mississippi Embayment given by Ervin and McGinnis (1975) along a profile between Yellville, Arkansas and Scottsboro, Alabama (hereafter called Y-S profile). This density model was synthesized from regional gravity data derived from the U.S. Bouguer gravity anomaly map of Woollard and Joesting (1964) and the results of a reversed seismic refraction profile between Little Rock, Arkansas and Cape Girardeau, Missouri as described by McCamy and Meyer (1966). Austin and Keller (1979) integrated the work of McCamy and Meyer (1966) with an analysis of Rayleigh wave dispersion along a propagation path between Oxford, Mississippi and Florissant, Missouri to obtain a similar density model for the Y-S profile which is illustrated in Figure 1.B. An index map for locating these various studies is given in Figure 1.D. In general, the crustal cross-sections shown in Figures 1.A and B support the failed-rift model for the origin of the Mississippi Embayment.

The agreement of surface wave, seismic refraction, and gravity data in the region of the Embayment suggests that the crustal cross-section given in Figure 1.B can be useful for developing a reasonably valid three-dimensional model of the Embayment. Accordingly, the crustal cross-section that was generalized from Figure 1.B for the purpose of this study is given as the 4-body model shown in Figure 1.C. The gravity analysis due to Cordell (1977) was used to project the characteristics of this generalized crustal cross-section north and south of the Y-S profile.

Cordell (1977) corrected the smoothed positive Bouguer anomaly of the Embayment for the low-density sediments and observed the long continuous positive anomaly with an amplitude of 15 to 45 mgal increasing southward that is illustrated in Figure 1.D. The axis of this anomaly follows closely the Mississippi River northward beyond its confluence with the Ohio River into southern Illinois. The anomaly exhibits fairly uniform behavior south of the Y-S profile until about 33^{o}N where it increases sharply, thus, suggesting that the crustal cross-section may be uniformly projected southward along the Mississippi River to approximately 33^{o}N. Northward decreasing gravity anomaly values in conjunction with the northward tapering surface configuration of the Embayment suggest a commensurate northward tapering projection of the crustal cross-section along the Mississippi River onto southern Illinois. Hence, to obtain the first-order, three-dimensional generalization of the crustal structure of the Embayment used in this investigation, the crustal cross-section of Figure 1.C was projected uniformly south of the Y-S profile and tapered uniformly northward as indicated in Figure 1.D. The northern ends of the 4 bodies of this generalized model as projected onto the cross-section along the Y-S profile are given by the shaded regions of Figure 1.C.

To compute the potential field anomalies at 450 km elevation, each of the 4 bodies of this generalized model was represented by a Gauss-Legendre quadrature formula consisting of 128 equivalent point sources. The latitude and longitude limits of each body were represented each by 8 point sources and the radial limits by 2 point sources. Pertinent body volume limits were interpolated from a set of body points that sampled the coordinates of the surface envelope for each body. The quadrature formulae were next evaluated and summed over a (21,13) observation grid spanning the region $(260\text{-}280)^{o}$E, $(33\text{-}45)^{o}$N and compared to observed gravity and magnetic anomaly data at 450 km elevation.

RESULTS AND DISCUSSION

Free-air gravity anomaly values upward continued from the surface of the earth to an elevation (Z) of 450 km by equivalent point source inversion are illustrated for the study area in the stereographic equal-area polar (SEAP) projection in Figure 2.A. The amplitude range (AR) of

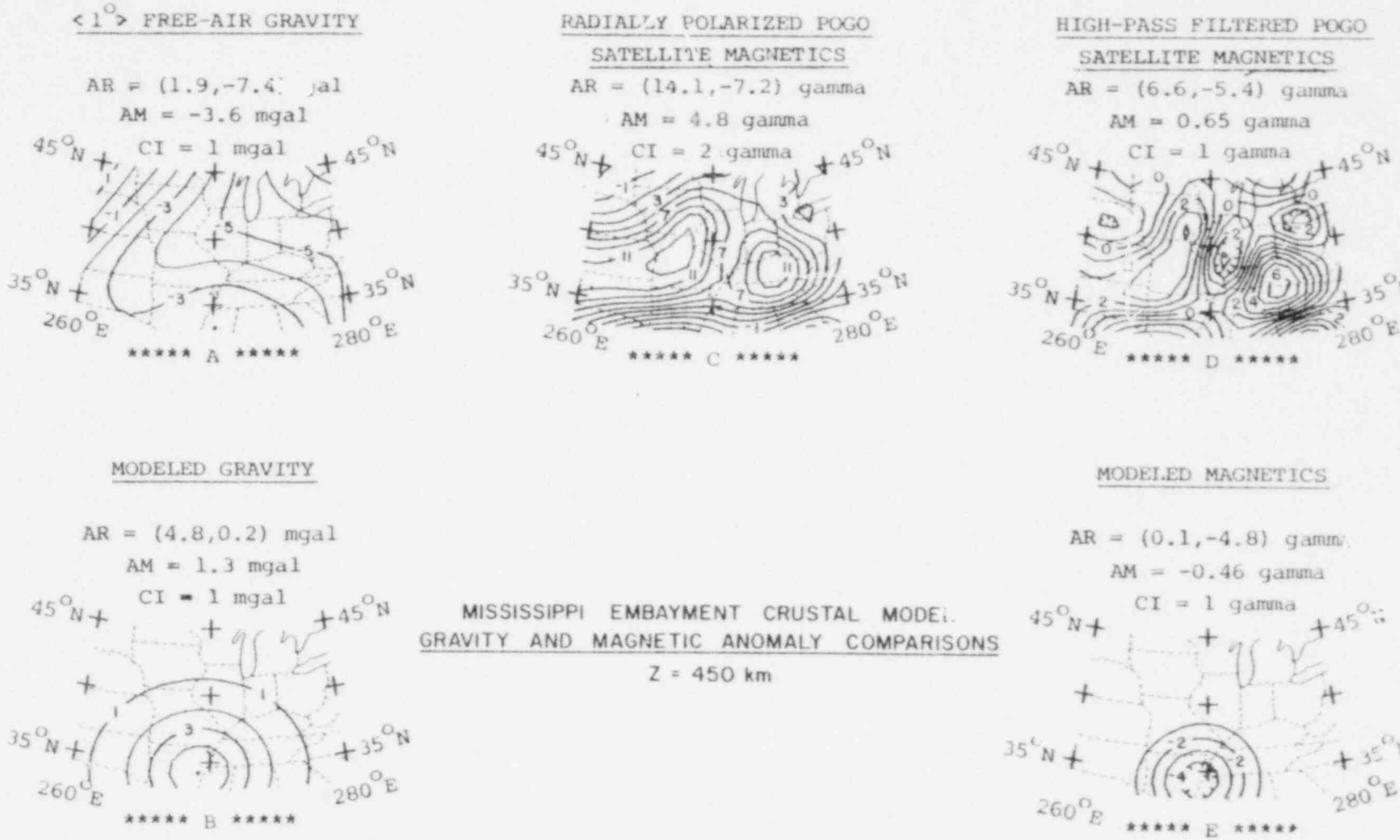

Figure 2 Mississippi Embayment satellite-level comparisons between Gauss-Legendre quadrature modeled gravity and magnetic anomalies and upward continued 1°-averaged free-air gra ity and reduced to the pole POGO satellite magnetic anomaly data. Each anomaly field is plotted on a stereographic equal-area polar projection.

the data set is between 1.9 and -7.4 mgal and the amplitude mean (AM) is -3.6 mgal. These data exhibit a pronounced relative positive anomaly with slightly greater than 3 mgal of relative amplitude in the region of the Embayment. The gravity effect (Figure 2.B) of the generalized 4-body model described above is roughly a 4 mgal anomaly that, in general, corresponds to the observed data. The general degree of this correspondence for profiles along 35^{O}N and 37^{O}N is illustrated in Figures 3 and 4, respectively. Here, the profile peaks of the modeled gravity anomaly have been adjusted to the respective peak values of the observed profiles over the Embayment model to facilitate the comparison.

A study of the profile comparisons shows increasing disparity between the modeled and observed data along the anomaly flanks away from the model. This may reflect contributions to the observed data from sources outside the study area that have not been modeled. Nonetheless, the general agreement between the modeled and observed data over the Embayment suggests that the observed gravity anomaly can be accounted for reasonably well at 450 km elevation by the 4-body model of Figure 1.

POGO satellite magnetometer observations reduced to radial polarization using a normalization amplitude of 60,000 gamma by equivalent point source inversion are given for the study area in Figure 2.C. These data show a prominent east-west magnetic high that is breached in the vicinity of the Embayment by a magnetic low. Inverse correlations of positive gravity and negative magnetic anomalies that characterize the Embayment also have been observed at satellite elevations for features such as the Yellowstone geothermal area where it is proposed that the net negative magnetization may be due to upward deflection of the Curie isotherm (von Frese et al., 1979). In this regard, Mitchell et al., (1977) using travel time residuals of teleseismic P-waves also have speculated that the New Madrid seismic zone may be underlain by a mantle hot spot such as suggested for the Yellowstone region.

To better resolve the characteristics of the magnetic anomaly for the Embayment region, the radially polarized data were high-pass filtered for anomaly wavelengths smaller than about 10^{O}. The high-pass

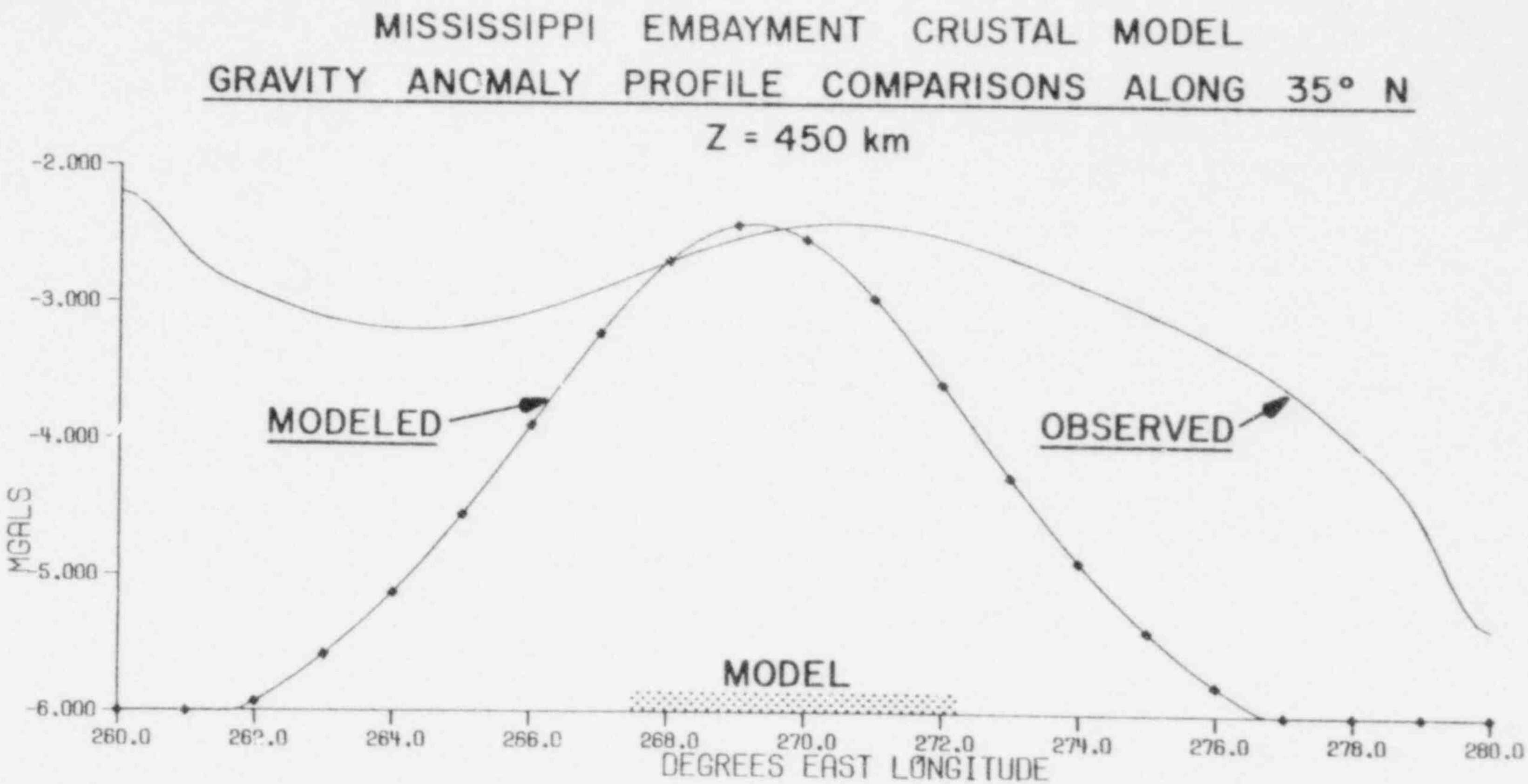

Figure 3 Mississippi Embayment satellite-level profile comparisons between Gauss-Legendre quadrature modeled gravity anomaly and observed upward continued 1^{o}-averaged free-air gravity anomaly data along 35^{o}N latitude. The shaded region indicates the location of the generalized Mississippi Embayment crustal model along the profile.

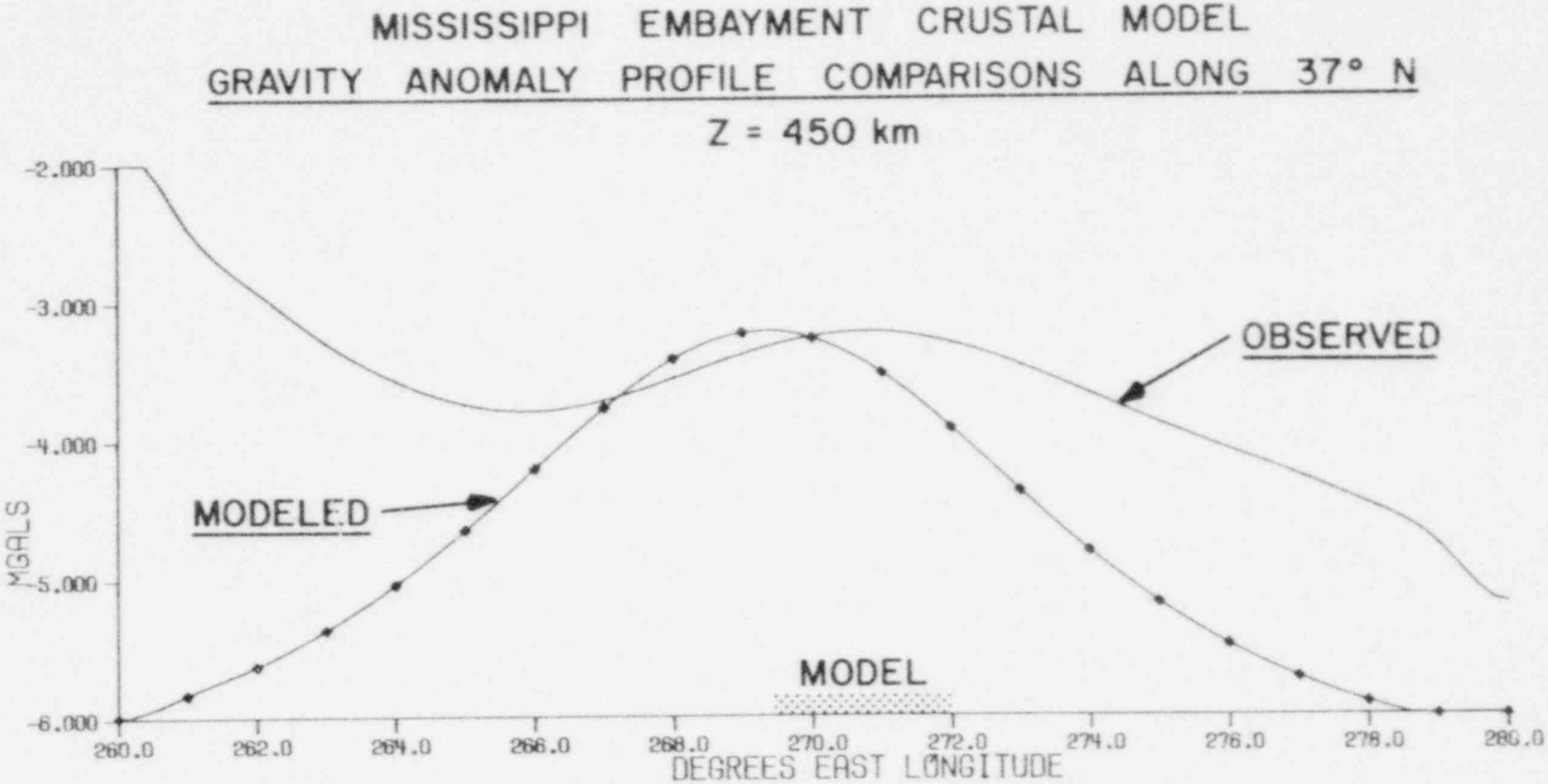

Figure 4 Mississippi Embayment satellite-level profile comparisons between Gauss-Legendre quadrature modeled gravity anomaly and observed upward continued 1°-averaged free-air gravity anomaly data along 37°N latitude. The shaded region indicates the location of the generalized Mississippi Embayment crustal model along the profile.

filtered data are illustrated in Figure 2.D and show a negative anomaly of roughly -3 gamma over the Embayment. Wasilewski et al., (1979) found that all of the information from analysis of medium to long-wavelength magnetic anomalies indicates that the sources probably are contained in the lower crust which, in general, may be substantially more magnetic than the upper crust. Typical estimates of deep crustal magnetization are on the order of 5×10^{-3} emu/cm^3 (e.g., Hall, 1974; Shuey et al., 1973). Wasilewski et al., (1979) propose that conditions for coherent regional magnetization are enhanced as crustal depth increases. Remanence and thermal overprints are diminished, and viscous magnetization and initial susceptibility are enhanced with increasing temperature especially within 100^{o}C-150^{o}C of the Curie point. The thickness of the crust within this thermal regime of the Curie point may be 5 to 20 km depending on the steepness of the geothermal gradient. Accordingly, they suggest that deep crustal magnetic sources probably are related to lateral variations of petrologic factors or Curie isotherm topography.

Consideration of the foregoing remarks indicates that the most obvious deep crustal source for the observed magnetic anomaly is body #2 which also represents the major gravity source of the Embayment model. Austin and Keller (1979) propose that the combination of bodies #1 and #2 was formed as a manifestation of a mantle upwarp beneath the Embayment comprising of a mixture of crust and upper mantle material that cooled subsequently to form a block of high density material. Magnetic hypotheses which are consistent with this view include body #2 as a zone of negative magnetization contrast with respect to the lower crust due to depletion of magnetic minerals. Negative magnetization for body #2 also can result from temperatures which exceed the Curie point, although present heat flow data (Sass et al., 1976) do not appear to warrant this hypothesis for the Embayment.

Body #3 may represent an additional magnetic source for the Embayment assuming crustal magnetization increases with depth. However, the positive magnetic contribution of body #3 will be relatively weak if the Curie isotherm depth is about 40 km or more. Arguments for including bodies #1 and #4 in a magnetic model of the Embayment appear to be lacking, so that body #2 probably represents the primary source for the observed magnetic anomaly data if the Curie isotherm is at about 40 km of depth in the region of the Embayment.

Accordingly, the magnetic anomaly due to body #2 was calculated in Figure 2.E using a magnetization contrast of -2.4×10^{-3} emu/cm^3. These results show that the anomaly amplitude observed for the region of the the Embayment at 450 km elevation can be well matched by a source such as body #2 located near the base of the crust with magnetic properties which correspond with the magnetization characteristics anticipated for the lower crust. Hence, body #2 as determined for gravity modeling considerations represents at least a preliminary magnetic model for the Embayment.

Substantial differences are apparent, however, between the spatial characteristics of the observed and modeled magnetic anomalies. Profile comparisons between Figures 2.D and 2.E along 35^{o}N and 37^{o}N are given in Figures 5 and 6, respectively, which illustrate this disparity. Here again, the modeled profile peaks are adjusted to the observed anomaly peaks over the Embayment model to facilitate comparison. In general, these comparisons indicate that body #2 is magnetically more extensive to the north and more restricted in longitude than it is gravitationally, although care must be taken with this interpretation because the observed data obviously contain the magnetic effects from sources outside the Embayment. Further refinements of the magnetic model are necessary and will be particularly warranted when the data are available from the current Magsat program (Langel, 1979) to verify and further upgrade the POGO satellite magnetic anomalies for lithospheric applications.

CONCLUSIONS

A preliminary three-dimensional model of crustal structure for the Mississippi Embayment was generalized from analyses of surface wave dispersion (Austin and Keller, 1979), seismic refraction data (McCamy and Meyer, 1966) and gravity data (Ervin and McGinnis, 1975; Cordell, 1977). The

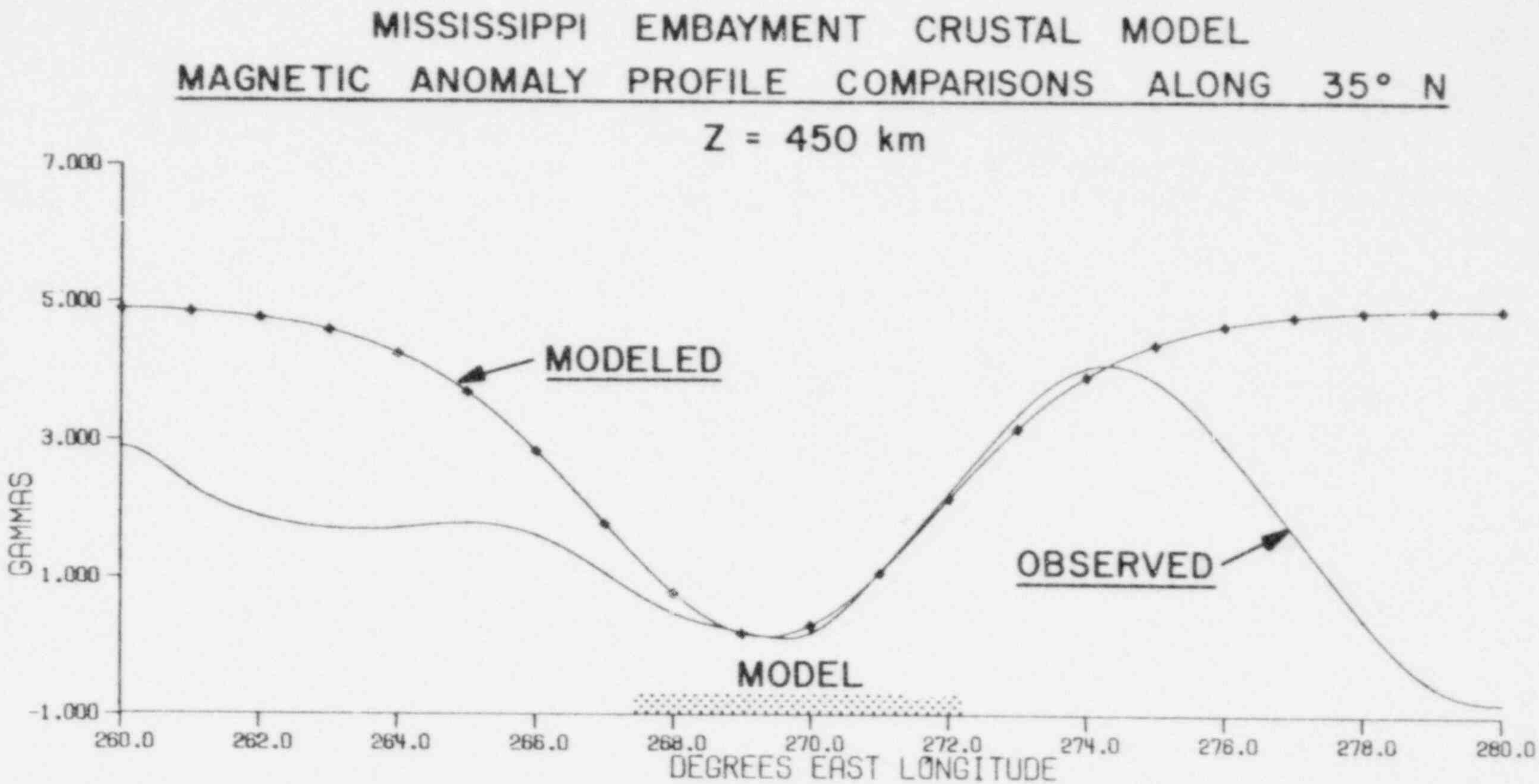

Figure 5 Mississippi Embayment satellite-level profile comparisons between Gauss-Legendre quadrature modeled magnetic anomaly and high-pass ($\lambda \leq 10^{o}$) filtered reduced to the pole POGO satellite observed magnetic anomaly data along 35^{o}N latitude. The shaded region indicates the location of the generalized Mississippi Embayment crustal model along the profile.

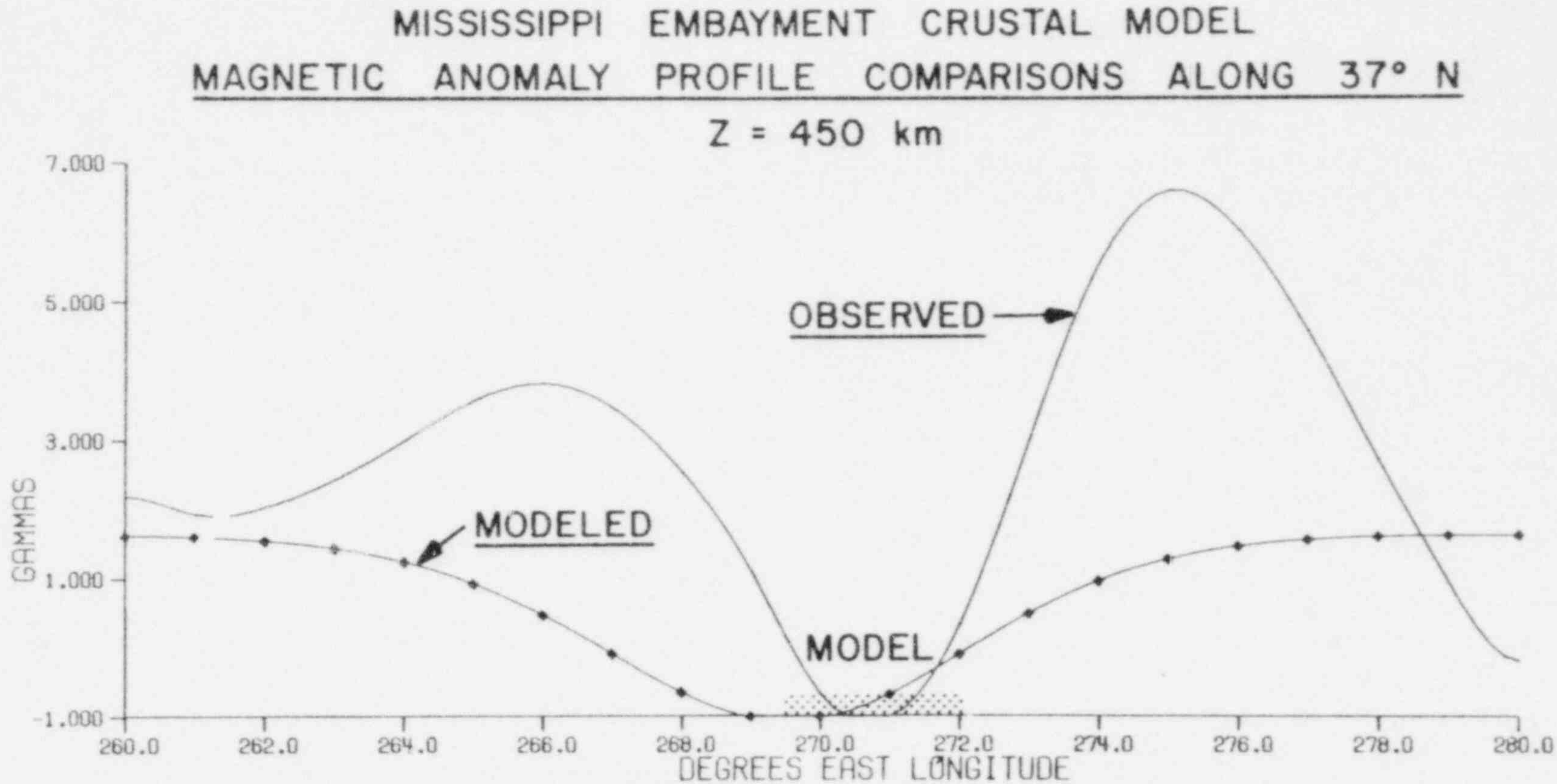

Figure 6 Mississippi Embayment satellite-level profile comparisons between Gauss-Legendre quadrature modeled magnetic anomaly and high-pass ($\lambda \leq 10^{o}$) filtered reduced to the pole POGO satellite observed magnetic anomaly data along 37^{o}N latitude. The shaded region indicates the location of the generalized Mississippi Embayment crustal model along the profile.

agreement between the gravity anomaly calculated for the 4-body model and the gravity data observed at 450 km elevation suggests that this model represents a reasonably valid generalization of the crustal density structure of the Embayment. The magnetic anomaly calculations show that the magnetic data observed at 450 km elevation can be modeled by a non-magnetic portion of the lower crust located along the axis of the Embayment that also corresponds to the major gravity source of the region. These results are consistent with the failed-rift hypothesis for the origin of the Mississippi Embayment.

This investigation further indicates that an aulacogen may be characterized at satellite elevations by observable positive gravity and negative magnetic anomalies. The primary source of both anomalies is the portion of the rift that defines a lateral variation in the physical properties of the lower crust. Finally, these results demonstrate the basic difficulty of separating pertinent anomalies at satellite elevations which perhaps is a major limitation to interpretation of satellite observed gravity and magnetic anomaly data. However, the application of the modeling capacity demonstrated in this investigation will help to alleviate this problem.

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Gravity, magnetic, seismic refraction and reflection, and basement geology are being used to investigate the northeastern extension of the New Madrid Fault Zone. Parallel, linear trends of correlative gravity and magnetic anomalies, previously related to the New Madrid Fault Zone and its associated structure, extend to the northeast into Indiana to approximately 39.5°N latitude. This feature also is suggested in the historical seismicity pattern and perhaps the basement geology and the crustal seismic model. The crustal seismic model is somewhat anomalous in comparison to the "normal" crust adjacent to the Mississippi Embayment. An additional pair of parallel trends of geophysical anomalies has been identified extending from New Madrid to St. Louis on either side of the Mississippi River. One possible origin for the basement structures is a Precambrian triple junction associated with continental rifting during break-up of the continents.

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