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New Madrid Seismotectonic Study

Activities During Fiscal Year 1980

Prepared by T. C. Buschbach

St. Louis University

Prepared for
U.S. Nuclear Regulatory
Commission

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Activities During Fiscal Year 1980

Manuscript Completed: February 1981
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Prepared by
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Division of Health, Siting and Waste Management
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
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ABSTRACT

Parallel linear geophysical trends, similar to those associated with the New Madrid seismic zone, were found to extend from New Madrid northeastward into Indiana and northwestward to St. Louis, Missouri. The origin of the basement structures may be a Precambrian triple junction associated with rifting during a period of continental break-up. Aeromagnetic and gravity data from much of the study area have been integrated, gridded, and contoured. Fault studies in the area this year found no faults that displaced Quaternary deposits. There were 238 earthquakes detected and located by the St. Louis regional microearthquake array in the New Madrid area during annual year 1979. A map has been prepared to show the epicenters of 1190 earthquakes detected and located by that array for the six-year period between July 1, 1974 and June 30, 1980.

SUMMARY

The New Madrid Seismotectonic Study is a coordinated program of geological, geophysical, and seismological investigations of the area within a 200-mile radius of New Madrid, Missouri. The study, funded in part by the U.S. Nuclear Regulatory Commission, is designed to define the structural setting and tectonic history of the area in order to realistically evaluate earthquake risks in the siting of nuclear facilities.

Participants in the study include geologists from the State Geological Surveys of Illinois, Indiana, Kentucky, Tennessee, Alabama, Arkansas, and Missouri; faculty members of earth science departments at Saint Louis University, Vanderbilt University, Purdue University, Memphis State University, the University of Pittsburgh, the University of Kentucky, the University of Wisconsin at Milwaukee, and the University of Texas at El Paso; and staff members of the U.S. Geological Survey, the U.S. Army Corps of Engineers, and the Tennessee Valley Authority.

Fiscal year 1980 was the fourth year of a five-year program. Our research has pursued a working hypothesis that earthquakes in the region are the result of reactivation of zones of weakness along ancient structures associated with a rift complex. Compressive stresses appear to be the principal stresses in the region that are associated with the current seismicity, although the rift complex is interpreted as a tensional feature. Interest during the past year has developed in the potential driving forces of a deep-seated heat source as a cause for renewed tectonism.

Parallel linear geophysical trends, similar to those associated with the Reelfoot Rift, were found to extend from New Madrid northeastward into Indiana and northwestward to St. Louis, Missouri. It has been postulated that the origin of the basement structures may be a Precambrian triple junction associated with rifting during a period of continental break-up.

Gravity and aeromagnetic data from the New Madrid area were integrated, digitized, and contoured. The resulting maps represent a significant contribution by this cooperative study. They will be published at a scale of 1:1,000,000 as NUREG Documents. Tapes containing the digitized data will be available to interested researchers.

A two-year program to acquire deep seismic reflection profiles across the Wabash Valley Fault System and the northeastern extension of the parallel

linear trends of geophysical anomalies in Indiana has been developed and funded. Selection of specific sites for the profiles and contracting for the seismic survey are currently underway.

Detailed studies of faulting in Indiana, Illinois, and Missouri found no faults that offset Quaternary deposits. Only one tectonic fault was identified in northwestern Alabama that displaced rocks as young as the Cretaceous strata. The Illinois and Alabama studies indicated that numerous faults reported to have displaced Cretaceous strata are related to collapse features, the result of solution of underlying Paleozoic carbonate rocks.

The U.S. Geological Survey continued its studies on geophysics, geology, and seismology in the New Madrid area. They have published the results of their seimic reflection studies in the Reelfoot Lake region, and they are planning seismic refraction studies of the middle and lower crust in the area of current seismic activity. The U.S. Army Corps of Engineers, St. Louis, Missouri, has prepared a seismic zoning map for midwestern United States. The map is currently in the editorial process.

At the end of fiscal year 1981 the participating organizations will report on the results of their 1981 activities and will summarize their research efforts thus far; each organization will present its summary as a separate report. The coordinator's report will be an overall review of the research performed during the five-year period of this study.

A new five-year program has been proposed in order to maintain the team effort that has characterized the New Madrid study group during these past few years. This second phase will include geological and geophysical studies aimed at better definition of the east-west trending fault systems--the Rough Creek and Cottage Grove systems--and the northwest-trending Ste. Genevieve faulting. A prime objective will be to determine the nature and history of faulting and to establish the relationship with that faulting and the northeast-trending faults of the Wabash Valley and New Madrid areas. The question to be answered is whether or not the 38th Parallel Lineament decouples the structural features to the north from those south of the lineament.

The studies will also be aimed at improved delineation of the Reelfoot Rift as well as an understanding of what mechanism is causing the current seismic activity in the rift complex. Some high-altitude imagery studies have been proposed for use with geophysical information, geochemical investigations, and surface and subsurface geological studies to determine the presence of major fracture zones in the area.

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INTRODUCTION

During the winter months of 1811-1812 the New Madrid area was the site of the strongest series of earthquakes ever recorded in central United States. The area continues to be seismically active, and there are more than 200 earthquakes recorded and located each year by the New Madrid seismograph network. Evaluating seismic risk for the surrounding region, especially when consideration is given to the siting of nuclear facilities, requires a better understanding of the structure and tectonics of the area and their relationship to the seismicity than is presently available.

To expand our knowledge of the area geologists from the State Geological Surveys of Illinois, Indiana, Kentucky, Tennessee, Alabama, Arkansas, and Missouri; faculty members of earth science departments at Saint Louis University, Vanderbilt University, Purdue University, Memphis State University, the University of Pittsburgh, the University of Wisconsin at Milwaukee, the University of Kentucky, and the University of Texas at El Paso; and staff members of the U.S. Geological Survey, the U.S. Army Corps of Engineers, and the Tennessee Valley Authority have participated in a cooperative geological, geophysical, and seismological study of the area within a 200-mile radius of New Madrid, Missouri (Figure 1). The study, funded in part by the U.S. Nuclear Regulatory Commission, is designed to define the structural setting and tectonic history of the area in order to realistically evaluate earthquake risks in the siting of nuclear facilities.

PROGRAM SCOPE AND HISTORY

The early stages of this study, initiated in fiscal year 1977, were devoted to making an inventory of existing data and supporting research in the area where the needs were obvious. Aeromagnetic, ground magnetic, and gravity surveys were sponsored to complete geophysical coverage in our most critical regions. A tectonic overview of the region was prepared and published, as was a bibliography of selected references on the structure, tectonics, basement, and geophysics of the New Madrid region.

A seismograph array was established in the Wabash Valley, and detailed studies of the faulting have been conducted in that area. Maps have been prepared to show the geologic structure and thicknesses of significant rock units in the region. Quaternary deposits have been studied in the area, and numerous relatively shallow borings have been drilled to determine the age of faulting. In general our efforts within the broad categories of this study have followed the flow chart shown in table 1.

Research performed by State Geological Surveys and universities under contracts with the U.S.N.R.C. are fully coordinated in this cooperative study and reports of research activities by those organizations during the past year are included. In addition, virtually all pertinent geologic research performed in the area by Federal and state agencies, and by the major universities, has been coordinated with the research projects funded through the U.S.N.R.C. Only the general scope and regional significance of research sponsored by the other agencies are reported in this summary.

This report is presented as an annual report by the coordinator. Work accomplished earlier under this coordianted program is summarized in the following U.S. Nuclear Regulatory Commission Documents: NUREG - 0379, "New Madrid Seismotectonic Study - Activities during fiscal year 1977;" CR-0450, "New Madrid Seismotectonic Study - Activities during fiscal year 1978;" and CR-0977, "New Madrid Seismotectonic Study - Activities during fiscal year 1979."

COORDINATED RESEARCH PROGRAMS SUPPORTED BY U.S.N.R.C. CONTRACTS

Ten research proposals were supported by the U.S. Nuclear Regulatory Commission for the cooperative study of geology, geophysics, and seismology in the New Madrid area during fiscal year 1980. The annual reports prepared by the Principal Investigators of the research projects are included here, either in complete or summarized form. Two reports have been submitted to U.S.N.R.C. for their consideration to release them as separate NUREG Documents. Only summaries of those reports are included here. One summary is entitled "An integrated geophysical and geological study of the tectonic framework of the 38th Parallel Lineament in the vicinity of its intersection with the New Madrid Fault Zone;" by L. W. Braile, W. J. Hinze, and J. L. Sexton, Purdue University; G. R. Keller, University of Texas at El Paso; and E. G. Lidiak, University of Pittsburgh; August, 1980. The interested reader is referred to the complete report for many excellent illustrations which could not be included in this summary, and for abstracts of papers presented at scientific meetings. The research efforts of the group are also reported in two significant papers included in an appendix. Only the abstracts of these papers are included here.

The second summary is entitled "Structural framework of the Mississippi Embayment of southern Illinois" by Dennis Kolata, Janis Treworgy, and John Masters, Illinois Geological Survey. The report summarizes the studies performed in southernmost Illinois for three years. The complete report includes descriptions of the stratigraphic units present in the region, and illustrations of the specific areas of field studies which are not included in this summary.

The project titles of the coordinated research programs, the investigators, and the participating organizations are as follows:

A. Coordination of a Cooperative Seismotectonic Study of the New Madrid Area; T. C. Buschbach, Saint Louis University.

B. 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; L. W. Braile, W. J. Hinze, and J. L. Sexton, Purdue University; E. G. Lidiak, University of Pittsburgh; G. R. Keller, University of Texas at El Paso.

C. Structural Framework of the Mississippi Embayment of Southern Illinois; Dennis R. Kolata, Janis D. Treworgy, and John M. Masters, Illinois State Geological Survey.

D. Near Surface Geology of the Reelfoot Lake District of the New Madrid Earthquake Region; R. G. Stearns, Vanderbilt University.

E. General Geology, Geophysics, and Seismicity of Northwest Alabama; Jack T. Kidd, Geological Survey of Alabama.

F. Structural Geologic Study of Southeastern Missouri; Ronald Ward, Division of Geology and Land Survey, Missouri Department of Natural Resources.

G. A Study of Indiana Fault Locations, Displacements, Attitudes and Ages in Southwestern Indiana; Dan F. Sullivan and Curtis H. Ault, Indiana Geological Survey.

H. Paleozoic Geology of the New Madrid Area; H. R. Schwalb, Kentucky Geological Survey.

I. Memphis Area Regional Seismic Network; James Zollweg and Arch Johnston, Tennessee Earthquake Information Center, Memphis State University.

J. A Seismological Study of the Northern Extent of the New Madrid Seismic Zone; R. B. Herrmann, Saint Louis University.

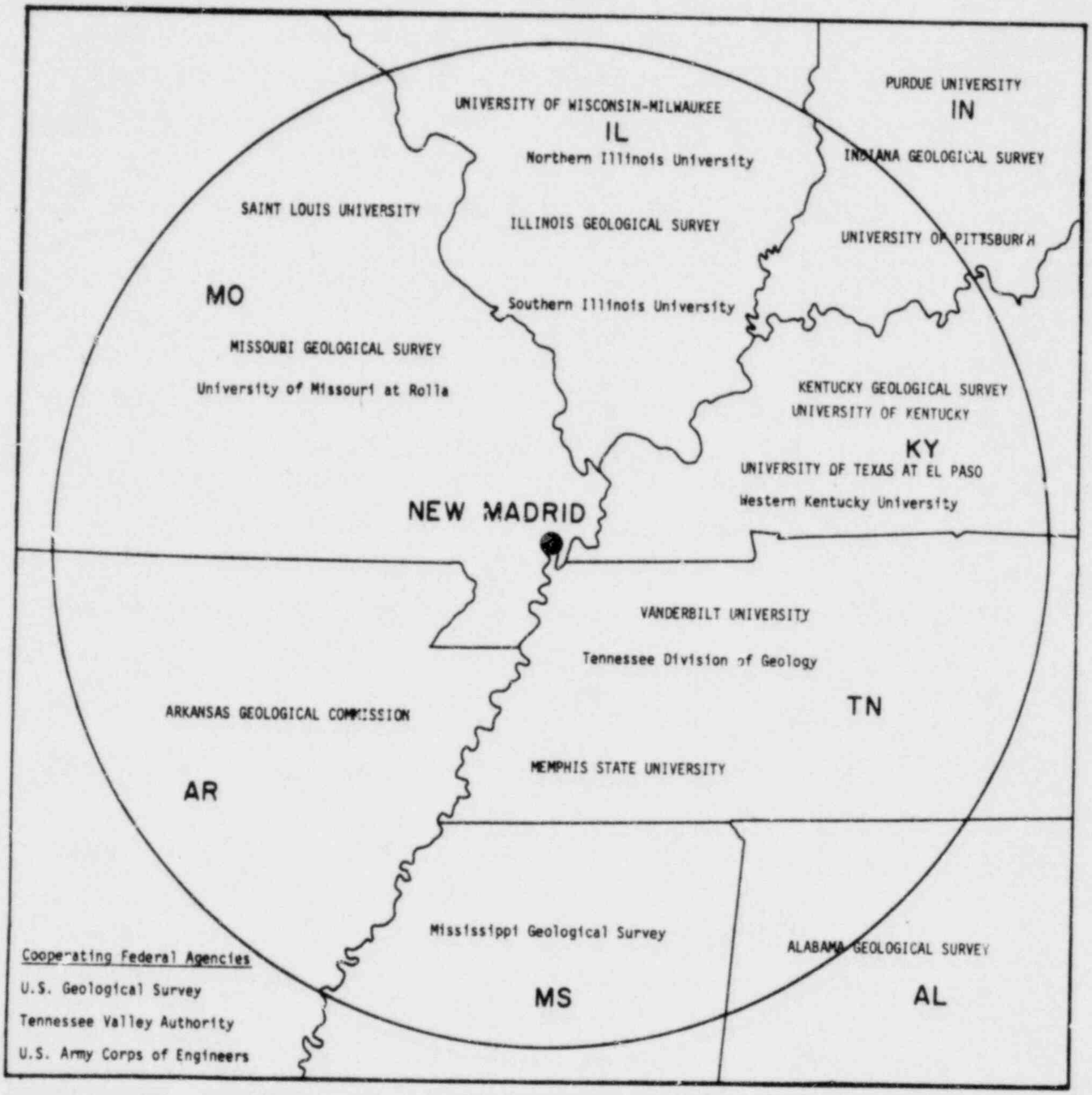
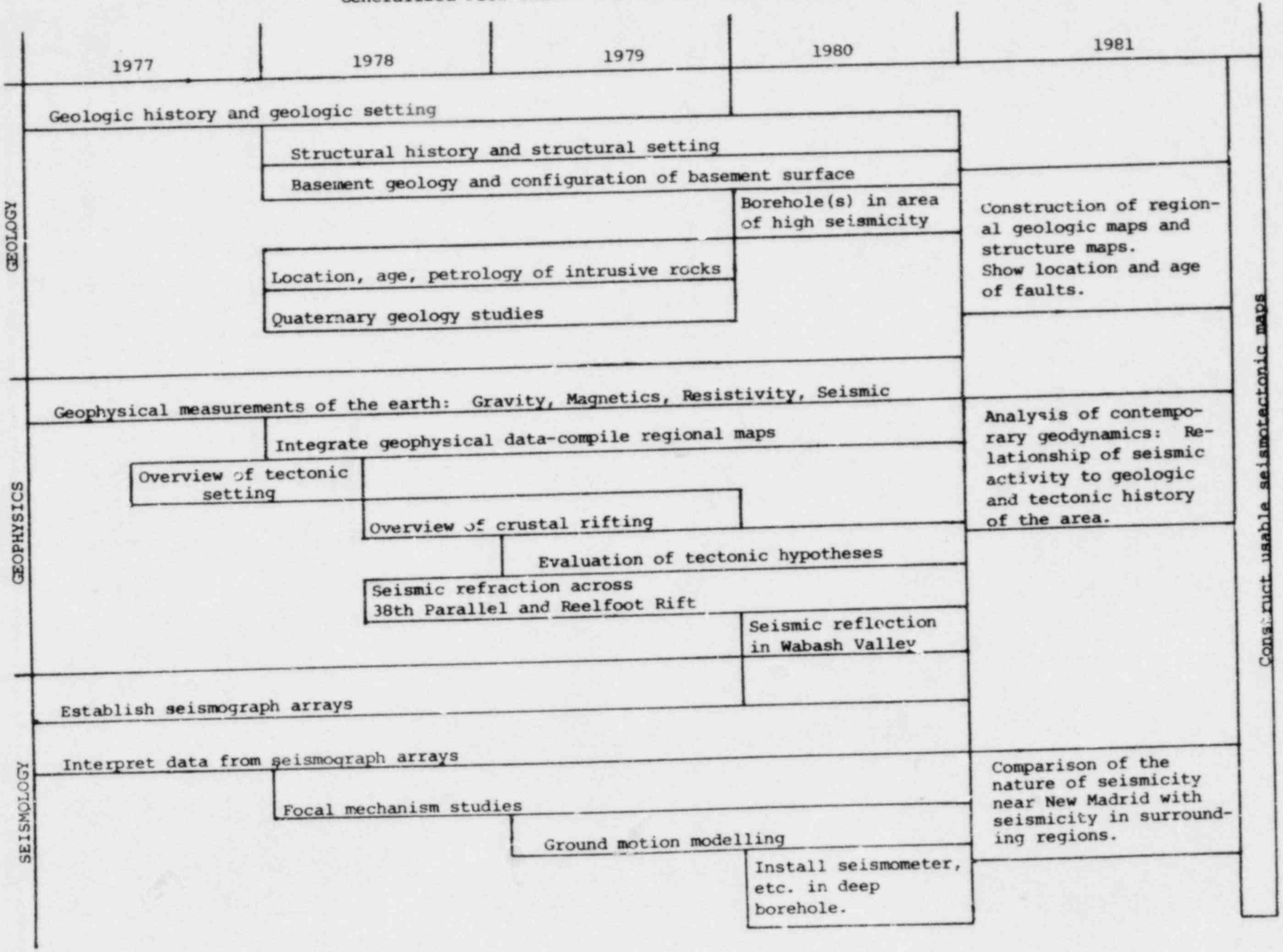


Figure 1 State Geological Surveys, universities, and Federal agencies cooperating in the New Madrid Seismotectonic Study. Names in capital letters indicate organizations involved in research supported by the U.S. Nuclear Regulatory Commission in 1980 and 1981.

Table 1

Generalized Flow Chart - New Madrid Seismotectonic Study



COORDINATION OF A COOPERATIVE SEISMOTECTONIC STUDY OF THE NEW MADRID AREA

Annual Pr_ress Report - Fiscal Year 1980

Contract No. NRC-04-78-251

T.C. Buschbach
Saint Louis University

INTRODUCTION

The objectives of the coordinator's efforts are to encourage, assist, and coordinate the research programs of scientists from organizations participating in significant research on seismotectonics in the New Madrid area. To achieve these objectives the coordinator visited each participating organization once or twice, had coordination meetings with the U.S. Geological Survey at Reston and Denver, and reported on progress of the studies during two trips to the N.R.C. offices in the Washington, D.C. area.

Perhaps the most significant accomplishments of this coordinated study are:

1. A group of about 30 of the most qualified scientists in the region meet together, communicate, and coordinate their research programs.
2. Individual participating organizations continue to maintain their research objectives toward active efforts to better understand the seismic and tectonic processes in the New Madrid area.
3. Currently there are a significant number of meaningful research projects on the geology, geophysics, and seismology of the New Madrid area.

COORDINATION ACTIVITIES

During the fiscal year the coordinator issued three Newsnotes advising participants of forthcoming progress meetings, deadlines for quarterly and annual reports, and significant new publications that reported results of research in the New Madrid area. The coordinator attended the National Academy of Science - Seismology meeting on research in the New Madrid area at Saint Louis University. With several other members of the New Madrid study group, he was invited to attend a U.S.G.S - sponsored "Seismic Zoning Meeting for Central United States" held in Golden, Colorado. The two-day meeting resulted in preparation of a preliminary probabalistic ground-motion map of central United States.

The coordinator maintained communications with researchers in the Nemaha study group, Oak Ridge National Laboratories, Waterways Engineering Station of the Army Corps of Engineers, and N.O.A.A. offices at Boulder, Colorado. He reviewed many of the manuscripts listed in a later section entitled "Significant Publications," and he submitted a proposal for a 3-year contract, with 3 additional years optional to NRC, in response to an NRC Request For Proposal to coordinate seismotectonic studies in the New Madrid area.

Progress Meetings

The Midwest meeting of the American Geophysical Union was held in September, 1979, at Ohio State University. Members of the New Madrid study group reported the results of their research at sessions on "Geology and Geophysics of the Central United States" and on "Seismicity and Geology of the Central United States and the Siting of Nuclear Reactors." Neil Steuer, U.S.N.R.C., was Chairman of the latter session, and T. C. Buschbach presented a paper entitled "Tectonics and Seismicity - Central Mississippi Valley." Other sessions of interest to the New Madrid study group were those entitled "Seismology in the Central United States;" "Geomagnetism and Paleomagnetism of the Mid-Continent"; and "Geodesy and Gravity." It is becoming increasingly obvious that the New Madrid study group has had a distinct influence on the Midwest meetings of A.G.U. by the total attendance, selection of session topics, and by the papers presented. A progress meeting of the New Madrid study group was held in conjunction with the A.G.U. meeting in Columbus. There were 21 participants and invited observers in attendance (Appendix A-1).

The North-Central Section of the Geological Society of America met in April, 1980, at Indiana University. Several members of the New Madrid study group presented papers at sessions entitled "Structural Geology and Tectonics" and "Geophysics". A progress meeting of the New Madrid study group was held at the conference room of the Indiana Geological Survey in conjunction with the G.S.A. meeting in Bloomington. There were 26 participants and invited observers in attendance. (Appendix A-1).

Significant Publications

During the fiscal year 1980 several reports on the research activities in the New Madrid area, supported in part by U.S.N.R.C. funds, were published as NUREG Documents. They are:

1. 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, by L. W. Braile, W. J. Hinze, G. R. Keller, E. G. Lidiak; NUREG CR-1014, 1979.
2. New Madrid seismotectonic study--Activities during fiscal year 1979, by T. C. Buschbach, Coordinator; NUREG CR-0977, 1980.
3. Monoclinal structure and shallow faulting of the Reelfoot Scarp as estimated from drill holes with variable spacings, by R. G. Stearns; NUREG CR-1501, 1980.
4. General geology, geophysics, and seismicity of northwest Alabama, by J. T. Kidd; NUREG CR-1519, 1980.

Some of the results of research performed in the New Madrid area by participants in the study group were published in professional journals or other media. These include:

1. Models for midcontinent tectonism, by W. J. Hinze, L. W. Braile, G. R. Keller, and E. G. Lidiak; in Continental Tectonics - National Research Council, 1980.
2. Faulting in Posey and Gibson Counties, Indiana, by C. H. Ault, D. M. Sullivan, and G. F. Tanner; Proceedings of the Indiana Academy of Science for 1979, 1980.

In October, 1979, the U.S. Geological Survey issued a news release entitled "Discovery of fault zone in Arkansas may solve quake puzzle." The report of a deep-penetrating seismic survey announced that for the first time, New Madrid seismicity could be linked to specific structural features that may have been reactivated through geologic time. The study resulted in publication of a report entitled "Recurrent intraplate tectonism in the New Madrid seismic zone, by M. D. Zoback, R. M. Hamilton, A.J. Crone, D. P. Russ, F. A. McKeown, and S. R. Brockman; Science, v. 209, p. 971-976, 1980.

The U.S. Army Corps of Engineers published a paper that presents correlations between sustained maximum acceleration, velocity, and the product of acceleration and duration versus MM intensity. Earthquakes of western United States are compared with earthquakes in central United States. The report is in the series "State-of-the-Art for Assessing Earthquake Hazards in the United States," Miscellaneous Paper S-73-1. It is Report 16, "The relation of sustained maximum ground acceleration and velocity to earthquake intensity and magnitude," by Otto W. Nuttli, 1979.

At the request of U.S.N.R.C. the coordinator reviewed an Army Corps of Engineers manuscript entitled "Siting of nuclear facilities in karst terrains and other areas susceptible to ground collapse," by A. G. Franklin, D. M. Patrick, D. K. Butler, W. E. Strohm, Jr., and M. E. Hynes - Griffin of the U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi. This will be an extremely useful report when it is published.

A large number of papers have been presented at scientific meetings by participants in the New Madrid study. For this reason no attempt has been made to include the abstracts in this report. The interested reader is referred to: (1) American Geophysical Union - Midwest Meeting, Program and Abstracts, Ohio State University, September 13-14, 1979; (2) Geological Society of America - 14th Annual Meeting of North-Central Section, Abstracts and Programs, Indiana University, Bloomington, Indiana, April 10-11, 1980; and (3) NUREG CR-1878.

RESEARCH HIGHLIGHTS

Parallel linear trends of correlative gravity and magnetic anomalies, which previously had been related to the New Madrid Seismic Zone, were found to extend northeastward into Indiana. During continued investigation of these anomalies an additional pair of parallel trends of anomalies was identified extending northwestward from New Madrid to St. Louis, Missouri. It is postulated that a possible origin for the basement structures is a Precambrian triple junction associated with rifting during a period of continental break-up. The New Madrid study group will be evaluating this as well as other hypotheses which have been proposed. Some of the most significant developments during fiscal year 1980 are:

1. Gravity and aeromagnetic data from the New Madrid area which had been integrated and gridded on a 2-km grid were contoured and submitted to the U.S. Nuclear Regulatory Commission for release as NUREG Documents. The gravity and aeromagnetic maps will be published at a scale of 1:1,000,000 and will be available before the end of 1980.

2. A two-year program to acquire deep seismic reflection profiles across the Wabash Valley Fault System and the northeastern extension of the parallel linear trends of geophysical anomalies has been developed and funded. Selection of specific sites for the profiles and contracting for the seismic surveys are currently underway at Purdue University.
3. A three-year study of the structural framework of southernmost Illinois was completed during the past year. The results indicate that the northeast-trending faults that cut the Paleozoic bedrock to the north continue southward beneath the Cretaceous and Tertiary sediments of the Mississippi Embayment. Essentially all displacement on these faults appears to have occurred before Cretaceous deposits overlapped the southern tip of Illinois. The present relief on the sub-Cretaceous surface in the area was shown to be the result of pre-Late Cretaceous erosion, post-Lake Cretaceous solution of the underlying Paleozoic carbonates, and possibly minor deformation during or after Cretaceous time.
4. Faulting at the eastern edge of Crowleys Ridge in the Missouri Bootheel was investigated by field studies and by the drilling of 15 test holes. The faulting strikes northwest-southeast and the main fault has about 16 feet of displacement. The faults appear to be normal faults with no evidence of strike-slip movement. The investigation showed that faulting has not disturbed the overlying Pleistocene colluvial silts and gravels, nor the Pleistocene loess above them. The age of latest faulting is therefore established as post-Paleocene and pre-Pleistocene. It is postulated that the faulting may have a temporal relationship to the emplacement or renewed activity of the nearby Bloomfield pluton.
5. Faulting in southern Indiana was investigated by using subsurface data from petroleum test holes and extensive surface field surveys. The detailed studies showed the faults to be high angle, normal, and in the case of the Mt. Carmel Fault, more complex than previously believed. Rather than a single fault, four or more associated faults are present in some areas, and drag-fold structures, small horsts and grabens, and jointing were mapped.
6. Structural geologic studies of reported faulting that displaces Cretaceous rocks were completed in northwestern Alabama. Only one "tectonic" fault was identified as displacing Cretaceous rocks. Numerous faults in the area appear to be related to collapse features; the result of solution

of the underlying Mississippian-age carbonates. Four major structural features were identified in the area from subsurface mapping. They include a major fault zone and an associated fault splay, an anticline, and a structural high in Madison and Limestone Counties that appears to reflect the southern extension of the Nashville Dome.

7. Regional subsurface studies have resulted in the construction of hypothetical cross sections through the New Madrid area.
8. Maps have been constructed to show the locations of felt earthquakes prior to 1975 and the epicenters of 1190 earthquakes located by the Saint Louis University microearthquake array during the period between July 1, 1974 and June 30, 1980. Free-depth hypocenter solutions indicate that the hypocenters of well-located earthquakes in the New Madrid area occur at depths between 5 and 15 km. However, the hypocentral depths of the few earthquakes recorded to the northeast by the Wabash Valley array have previously been reported to occur at depths of 15 to 22 km.
9. The soutnern extent of New Madrid seismicity appears to end rather abruptly at about 35.5° North Latitude, although geophysical indications are that a rift structure in the magnetic basement extends at least as far south as 34.5° North Latitude.
10. Detailed gravity surveys in northwestern Tennessee have recognized a distinct narrow, linear trend that is interpreted as a fault that could be related to the eastern edge of the Reelfoot Rift. Ground magnetic studies in the same area show what appear to be shallow plutons that reach as close as 700 feet to the present land surface.

A map showing the interpreted configuration of the top of Precambrian igneous rocks was prepared by the coordinator in 1977. Since that time it has been revised to reflect new data and new concepts. The current map (Figure A-1) has been modified only slightly from the map presented last year. Faulting in northwestern Mississippi is shown to be somewhat more complicated based on new subsurface data, including a borehole that reached quartzite below 10,000 feet in Quitman County. The Big Chief - Taylor well in Gibson County, Tennessee, is once again considered to have an anomalously high elevation on Precambrian rocks. The Paleozoic-age dates obtained from igneous rock samples of that well appear to have been collected from a sill present near the top of the Precambrian granite (H.R. Schwalb, personal communication).

The contours in western Illinois and eastern Missouri have been modified to better depict the structure on the Waterloo-Dupo Anticline and the Cap au Grés Faulted Flexure. Other changes include a slight tightening of the western end of the Rough Creek Graben and the local deepening of the basement just east of the Wabash Valley Fault System. The latter area is especially critical because of the anticipated seismic surveys to be conducted there during the next year. Mapping of the Precambrian surface in that area will doubtless be modified again as a result of those studies.

APPENDIX A-1

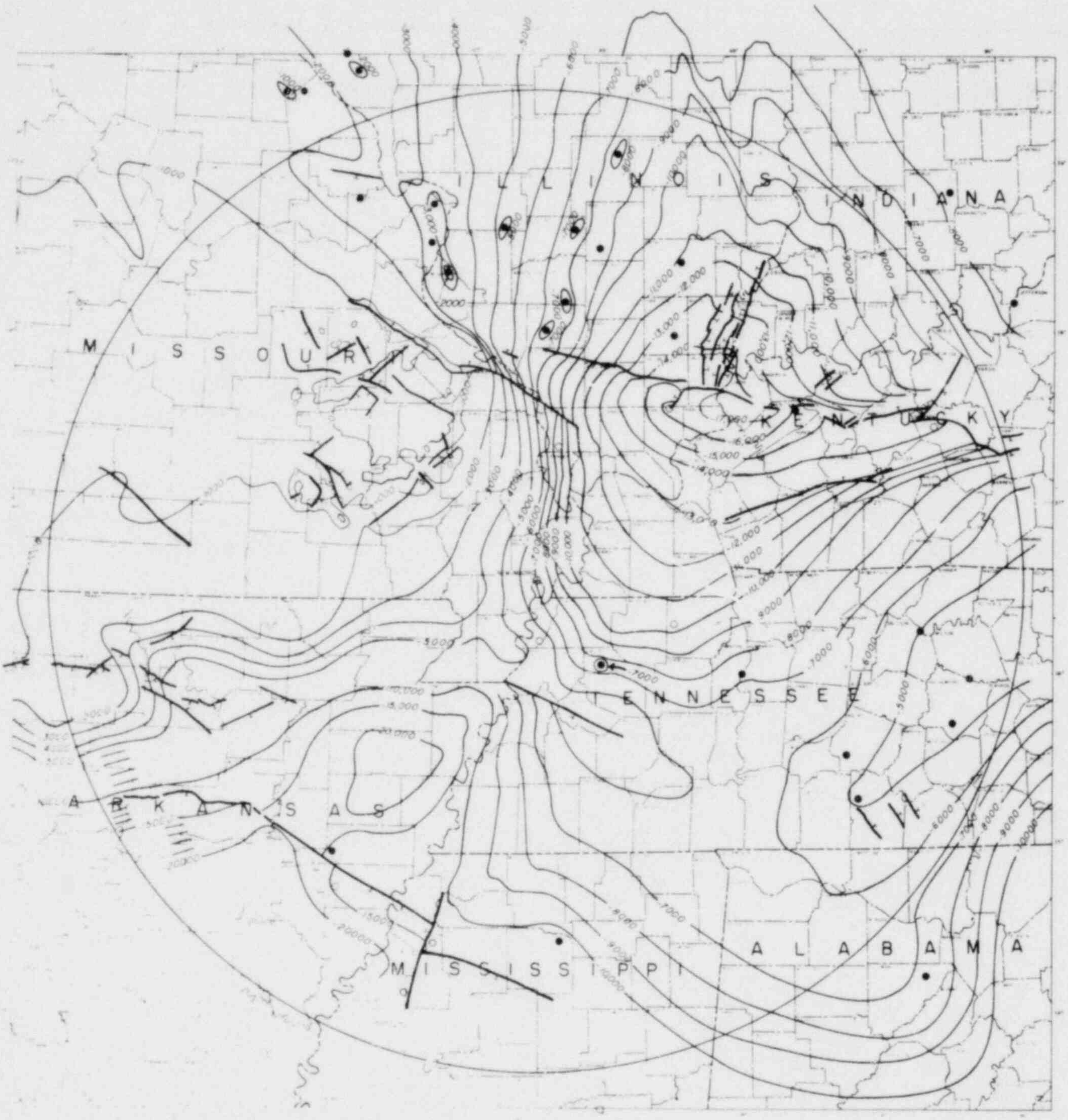
Attendance at Progress Meetings

NEW MADRID STUDY GROUP
Progress Meeting - Columbus, Ohio
September 13, 1979

NAME	ORGANIZATION
Pat Barosh	Weston Observatory
Larry Braile	Purdue University
Tom Buschbach	Saint Louis University
Bob Carmichael	University of Iowa, for Iowa Geol. Survey
Greg Hempen	USAED - St. Louis
Bill Hinze	Purdue University
Randy Keller	University of Texas at El Paso
Edward G. Lidiak	University of Pittsburgh
Kenneth V. Luza	Oklahoma Geological Survey
Edward O'Donnell	U.S. N.R.C.
Eric J. Rinehart	University of Missouri - Columbia
David Russ	U.S.G.S
Howard Schwalb	Illinois State Geological Survey
John Sexton	Purdue University
Dick Stearns	Vanderbilt University - Nashville, TN
Sheila Steele	Earth Sci. Res. - Carbondale, IL
Robert Taylor	University of Wisconsin - Milwaukee
John S. Trapp	Dames & Moore
S. A. Vincenz	Saint Louis University
Ralph von Frese	Purdue University
Ron Ward	Mo. DNR, Div. of Geology & Land Survey

NEW MADRID STUDY GROUP
Progress Meeting - Bloomington, Indiana
April 9, 1980

NAME	ORGANIZATION
Ina Alterman	U.S.N.R.C.
Curtis Ault	Indiana Geological Survey
James Baldwin	Purdue
Patrick J. Barosh	Weston Observatory
Barbara Beeman	Indiana Geological Survey
Larry Braile	Purdue
Tom Buschbach	Saint Louis University
Abraham Dolgoff	Sargent & Lundy
Norman Hester	Kentucky Geological Survey
Bill Hinze	Purdue
Jim Howe	University of Oklahoma
Mark Jaworsko	Indiana Geological Survey
Arch Johnston	Tennessee Earthquake Information Center
Andrew J. Murphy	U.S.N.R.C.
Keith Peregrine	Purdue
Tom Schmitt	U.S.N.R.C.
Howard Schwalg	Illinois State Geological Survey
C. Ronald Seeger	Western Kentucky University
John Sexton	Purdue
Dick Stearns	Vanderbilt University
Neil B. Steuer	U.S.N.R.C.
Dan M. Sullivan	Indiana Geological Survey
George Tanner	Indiana Geological Survey
Janis D. Treworgy	Illinois State Geological Survey
Ron Ward	Missouri Geological Survey
Alan K. Yonk	Sargent & Lundy



TOP OF PRECAMBRIAN IGNEOUS ROCKS

● Borehole reaching Precambrian igneous rocks
○ Other significant deep borehole

Work map by T.C. Buschbach
Dec., 1980

Figure A-1

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

Summary of
Annual Progress Report - Fiscal Year 1980

Contract No. NRC-04-76-323

L.W. Braile, W.J. Hinze, and J.L. Sexton
Purdue University

G.R. Keller
University of Texas at El Paso

E.G. Lidiak
University of Pittsburgh

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 structures, 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.

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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 United States 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° W. and 90° W. longitude and 36° 30' N. and 39° 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° W. and 92° W. longitude and 35° N. and 40° 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 investigations 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. These papers are 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. Five additional papers were presented at the North-Central Section Meetings of the Geological Society of America on 10 April, 1980 in Bloomington, Indiana. These papers are 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.

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 "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 the abstract is presented in Appendix B-1.

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, the abstract of which is presented in Appendix B-2, 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 (Figure B-1) extends from 35° to 39° N. latitude and approximately 82° to 91° 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 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 Om.na 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 B-2).

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. In lieu of better data, this map has been employed in our preliminary analyses which extend into Missouri.

GRAVITY ANOMALY INVESTIGATIONS

The original study area has been completely gravity surveyed, and 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, and approximately 3500 additional stations were established. Consideration of repeat observations over the three years of surveying indicates a standard deviation of the order of 0.07 mgals. The gravity stations are referenced to the national gravity datum through a network of base stations. Comparison of the previous gravity anomaly map of Indiana with the Bouguer gravity anomaly map prepared from reduction of the data collected over the past three years shows good correlation between the major maxima and minima.

Approximately 50,000 stations within the area bounded by 35° and 39° N. latitude and 82° and 92° W. longitude 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 (Figure B-3) 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 B-4. 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. Figures B-5a and B-5b summarize graphically the results of natural remanent magnetization (NRM) intensity measurements 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 B-6. 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 of the mafic and ultramafic intrusions are also continuing. Figure B-7 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 latitute 37° 30' N., longitude 88° 22' 30" W., (Figure B-7). 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.

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 B-1 and their geographic location is shown on Figure B-8. Profiles 2 and 6 were analyzed together and profile 9 is too short to obtain meaningful results.

Record sections for the profiles are based upon a reducing velocities of 6.0 km/sec for compressional wave analysis and 3.5 km/sec for shear wave analysis. A significant aspect of the data is the relatively strong energy

Table B-1. 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	72	1979
7	Wright	WE	50	1979
8	Wright	SE	25	1979
9	Wright	NW	6	1979

of the shear waves--direct, reflected and refracted—probably as a result of the ripple-fired areal patterns of the explosive sources. 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 are largely derived from models which best fit the observed data. The results of this analysis are presented on Table B-2. Figures B-9 to B-15 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 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 B-16 and B-17). The potential-field anomalies probably are caused 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 ess within the New Madrid Fault Zone. At the northeastern end of the , 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 B-2) 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

Table B-2. Results of Wabash River Valley crustal seismic study.

Profile	Refractor	Shear Intercept sec	Shear Velocity km/sec	Shear Thickness km	Compressional Intercept sec	Compressional Velocity km/sec	Compressional 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
	2	.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

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 B-18. 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.
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 B-18) 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 B-18. 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 following observations are made concerning the new crustal model:

1) Compressional velocity of the basement rocks is essentially the same as for the other two models 6.14 km/sec (average), 6.1? km/sec (normal), 6.20 km/sec (anomalous).
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, Missouri. 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 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, Illinois (Figure B-19). Preliminary tests were conducted in August, 1979 using a 40 cubic inch capacity air-gun source. 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 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 and data follows:

I. Data from August, 1979
   A. Air-gun survey from Douglas' landing (near Post Creek Cutoff) to Joppa. Air-gun firing rate was 1 shot every eight seconds. Boat speed 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
   A. Metropolis launch area to 1 mile upstream - sparker.
   B. Metropolis launch area to 1.5 miles upstream - 1 cubic inch air-gun.
   C. From 1.5 miles downstream of Post Creek Cutoff to 1.5 miles upstream of Joppa - sparker.
   D. 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.

E. Boat speed was 2 miles/hour.

F. Sparker firing rate was 1 shot every 2 seconds giving a shotpoint approximately every 6 feet.

G. Air-gun firing rate was 1 shot every 8 seconds giving a shotpoint approximately every 23 feet.

H. 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.

I. Useable record length from the sparker source appears to be 150 milliseconds two way time.

J. Useable record length from the air-gun source is difficult to determine due to the presence of multiples, but may be 250-500 milliseconds.

K. 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.

L. Water depth in the area is approximately 40 feet deep.

M. Data were recorded on magnetic tape at 3.5 inches per second recording tape speed.

N. Records of the water bottom channel were obtained from a sonartype 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 B-20 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 recored section crosses the location which corresponds to the straight-line extrapolation of the Dixon Springs Graben (Figure B-19). 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 6500ft/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 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 ± 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 B-21). The epicenter 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 Ste. 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 Ste. 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). 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 B-22. 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 B-23.

One of the primary areas of investigation remaining is the northern extension of these basement structures. Recent gravity studies in Indiana 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 B-22) 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 B-23. 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.

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) Bouger 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, DC 20555 and/or the National Technical Information Service, Springfield, VA 22161.

APPENDIX B-1

Abstract of Paper Submitted with Annual Report

THE TECTONIC APPROACH TO EVALUATION OF EARTHQUAKE HAZARDS IN THE MIDCONTINENT

by

W.J. Hinze[1], L.W. Braile[1], G.R. Keller[2], and E.G. Lidiak[3]

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 (Figure BA1-1) 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.

Presented at the special session of the Midwest American Geophysical Union Meeting, October, 1979, Columbus, Ohio, entitled "Seismicity and Geology of the Central United States and the Siting of Nuclear Reactors".

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APPENDIX B-2

Abstract of Paper Submitted with Annual Report

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 (Figure BA2-1). 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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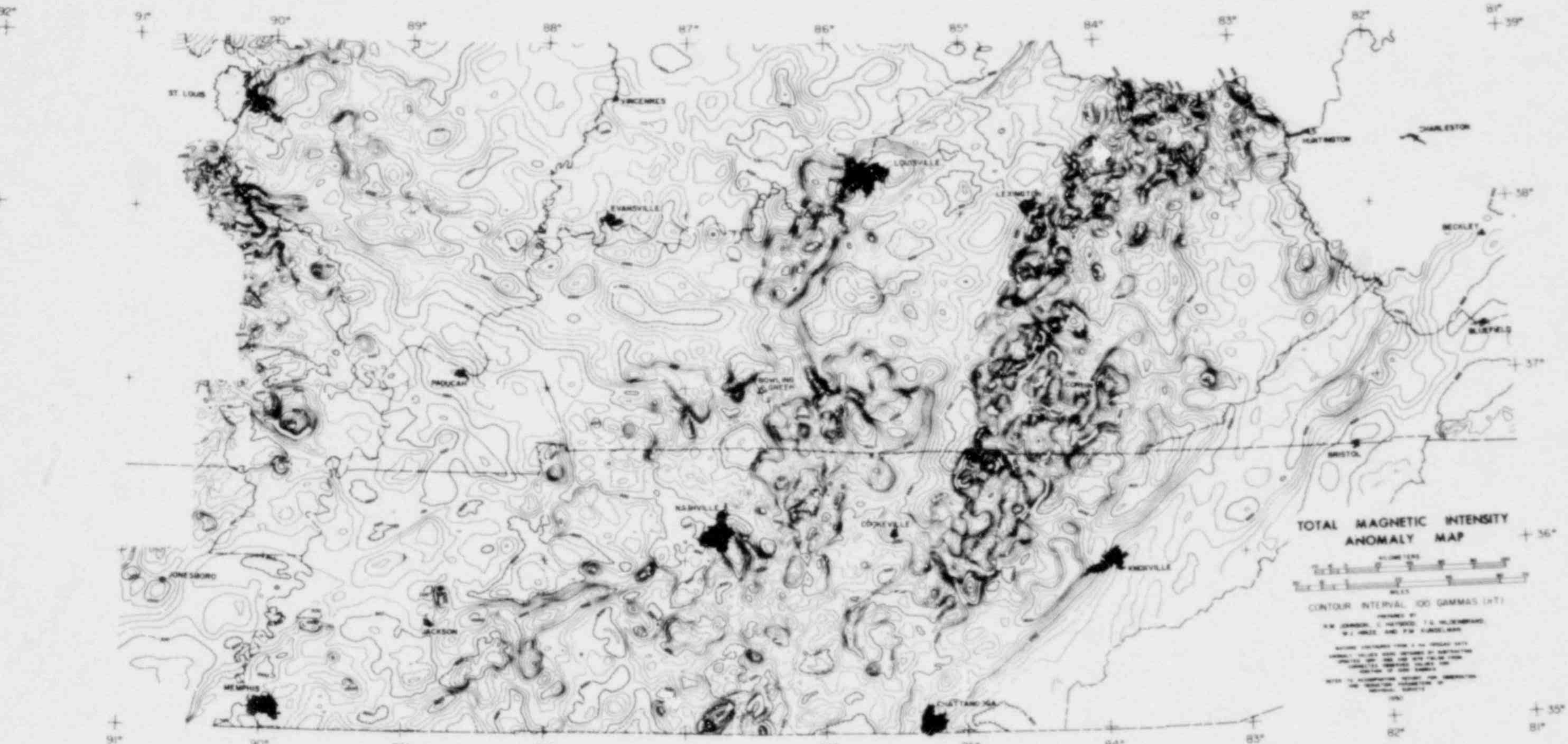


Figure B-1. Total magnetic intensity anomaly map of the east-central midcontinent.

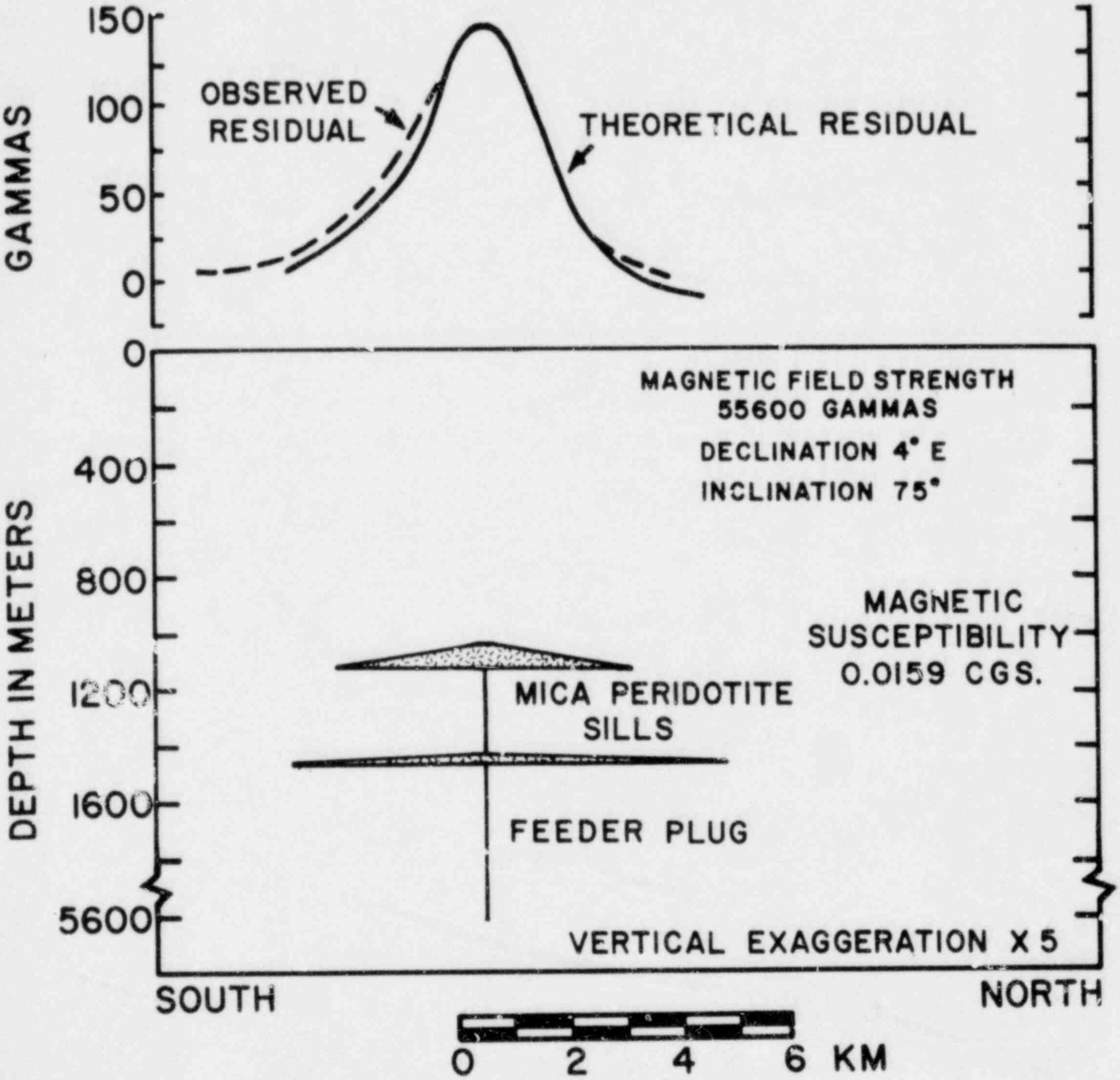


Figure B-2. Observed and theoretical residual magnetic anomalies over the Omaha Oil Field, Illinois.

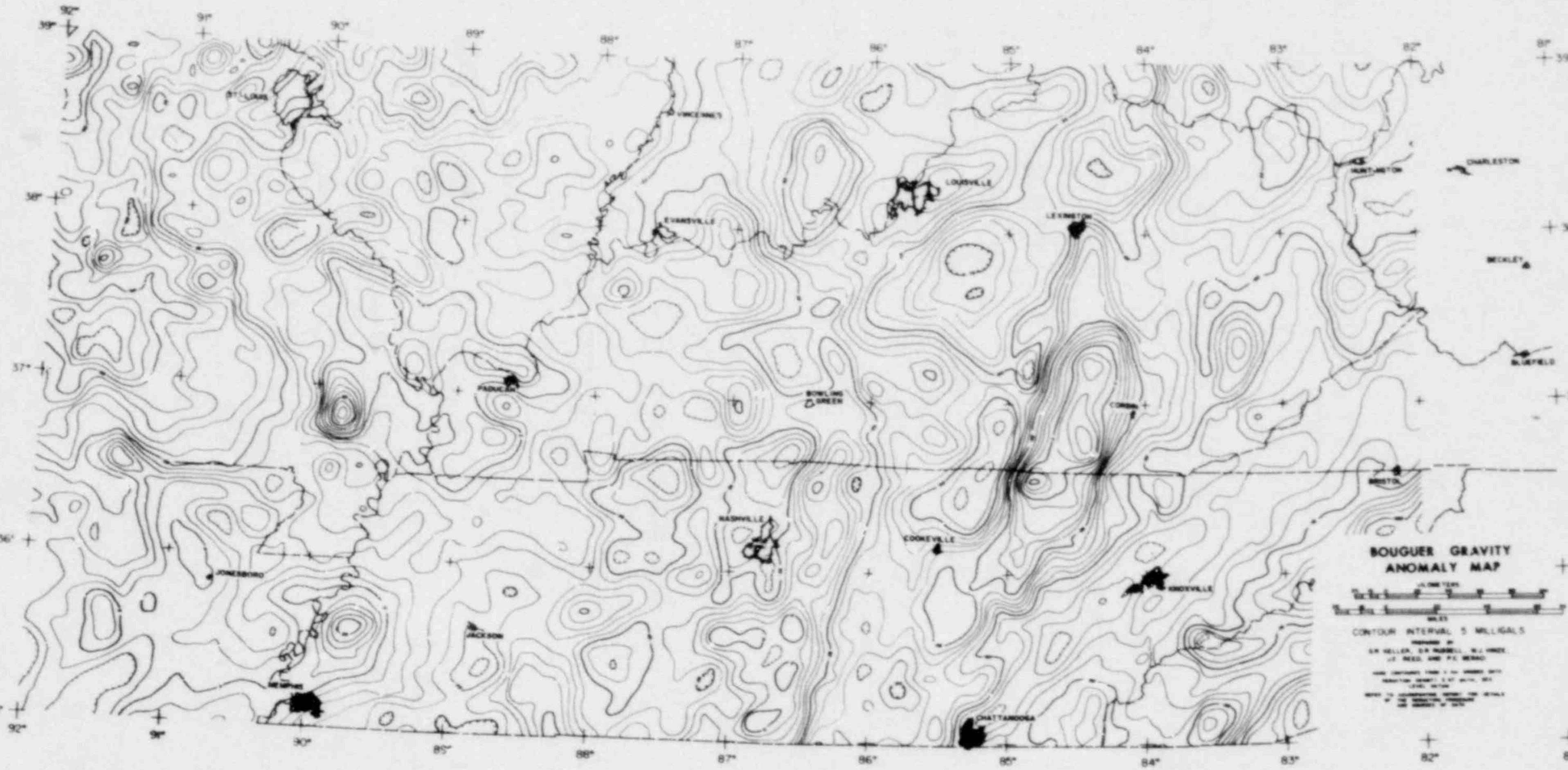


Figure B-3. Bouguer gravity anomaly map of the east-ˇentral midcontinent.

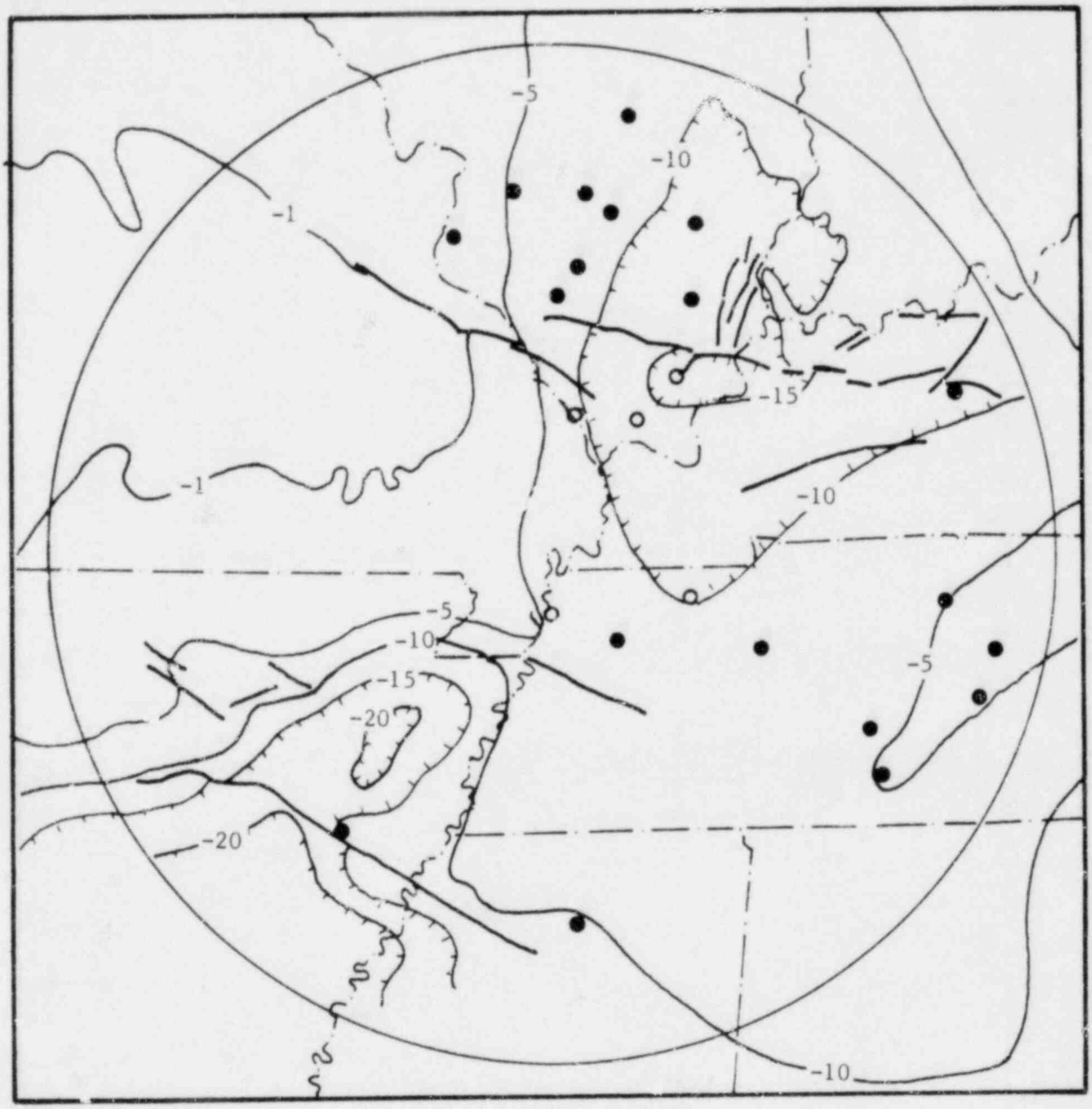


Figure B-4. Distribution of pre-Mt. Simon sedimentary rocks in study area. Open circles, drill holes to pre-Mt. Simon sedimentary rocks; closed circles, drill holes to Precambrian basement rocks. Thick lines are faults. Contour interval is in kilofeet on the basement rocks.

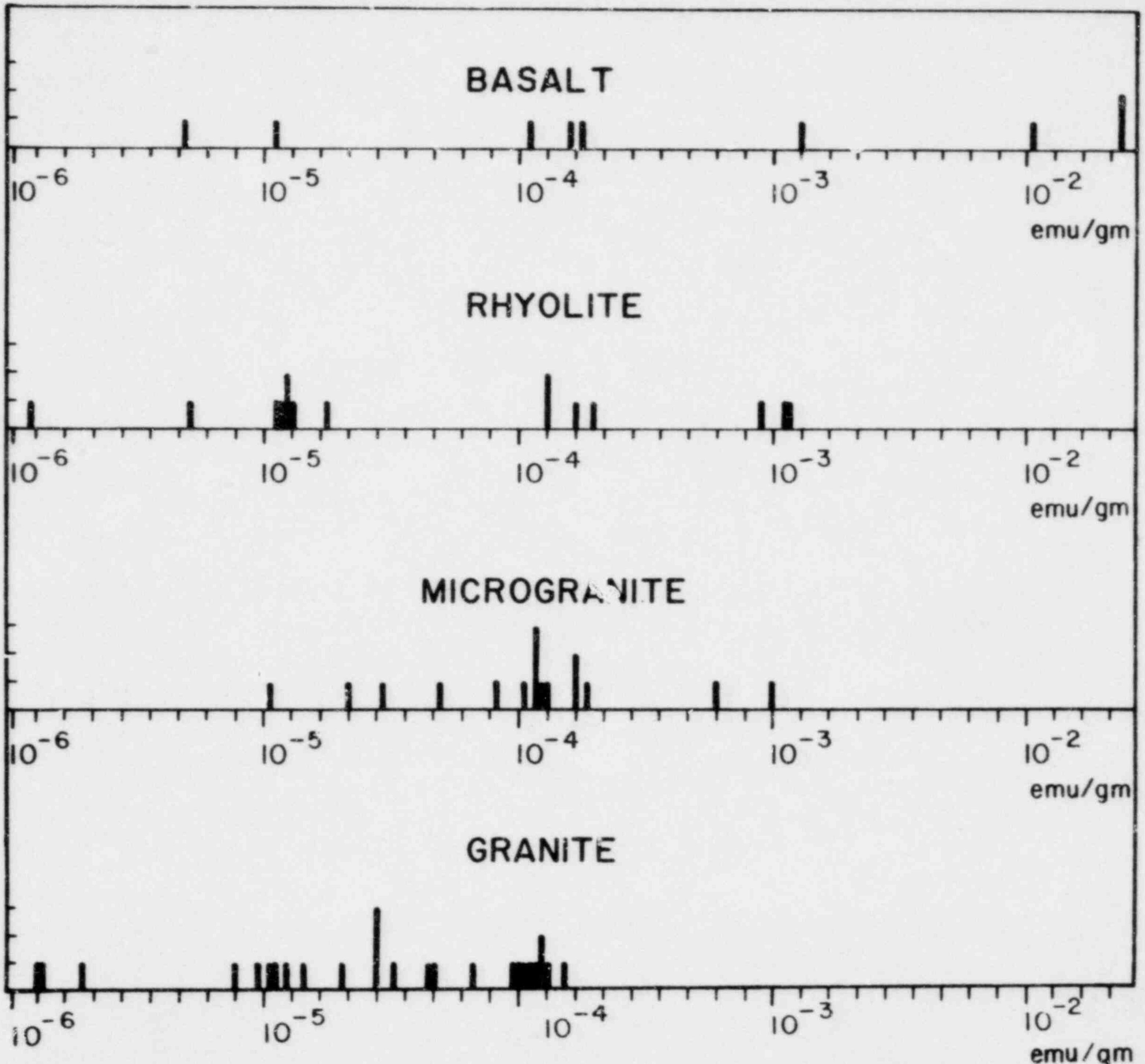


Figure B-5a. NRM intensities of basement rocks in the east-central midcontinent.

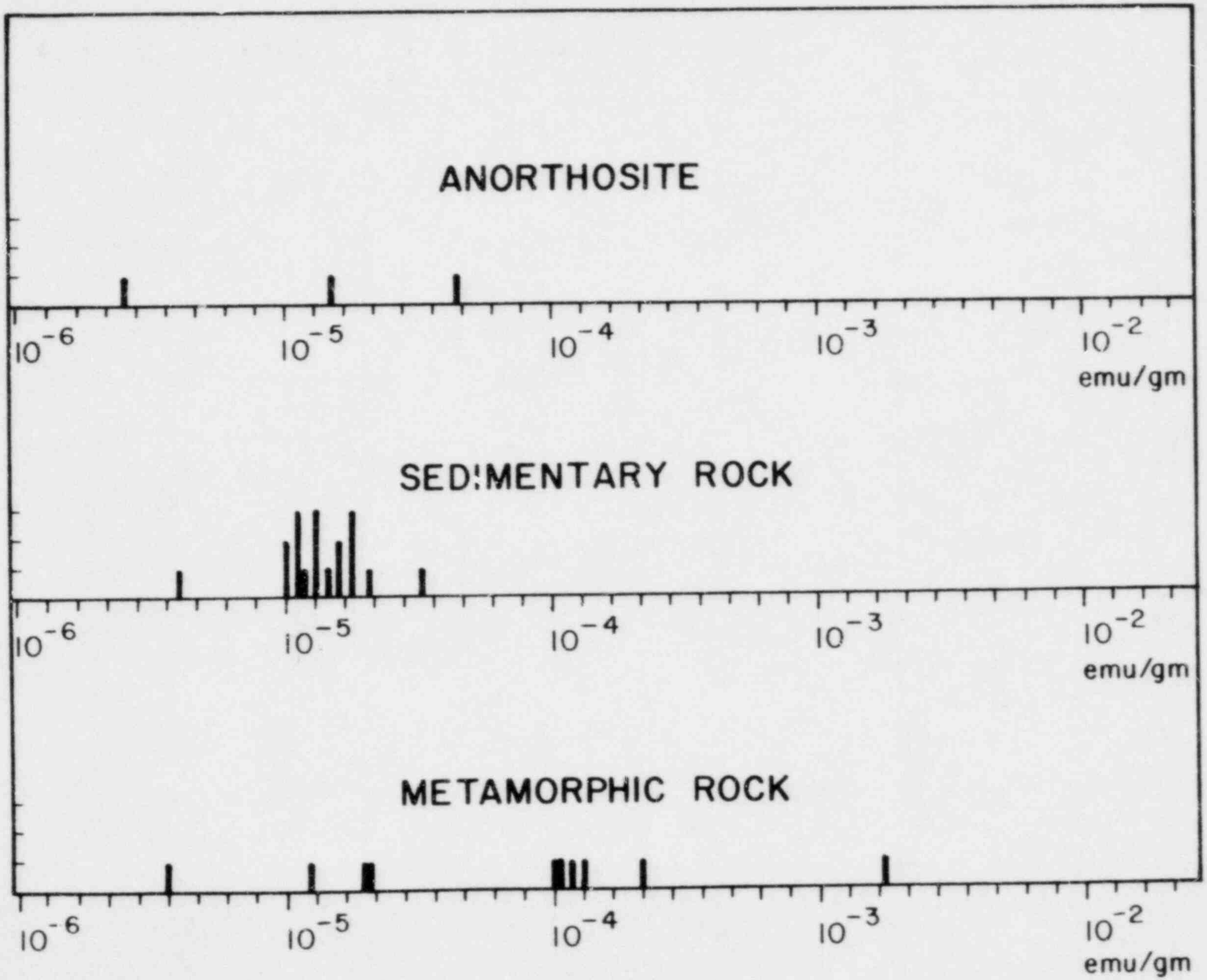


Figure B-5b. NRM intensities of basement rocks in the east-central midcontinent.

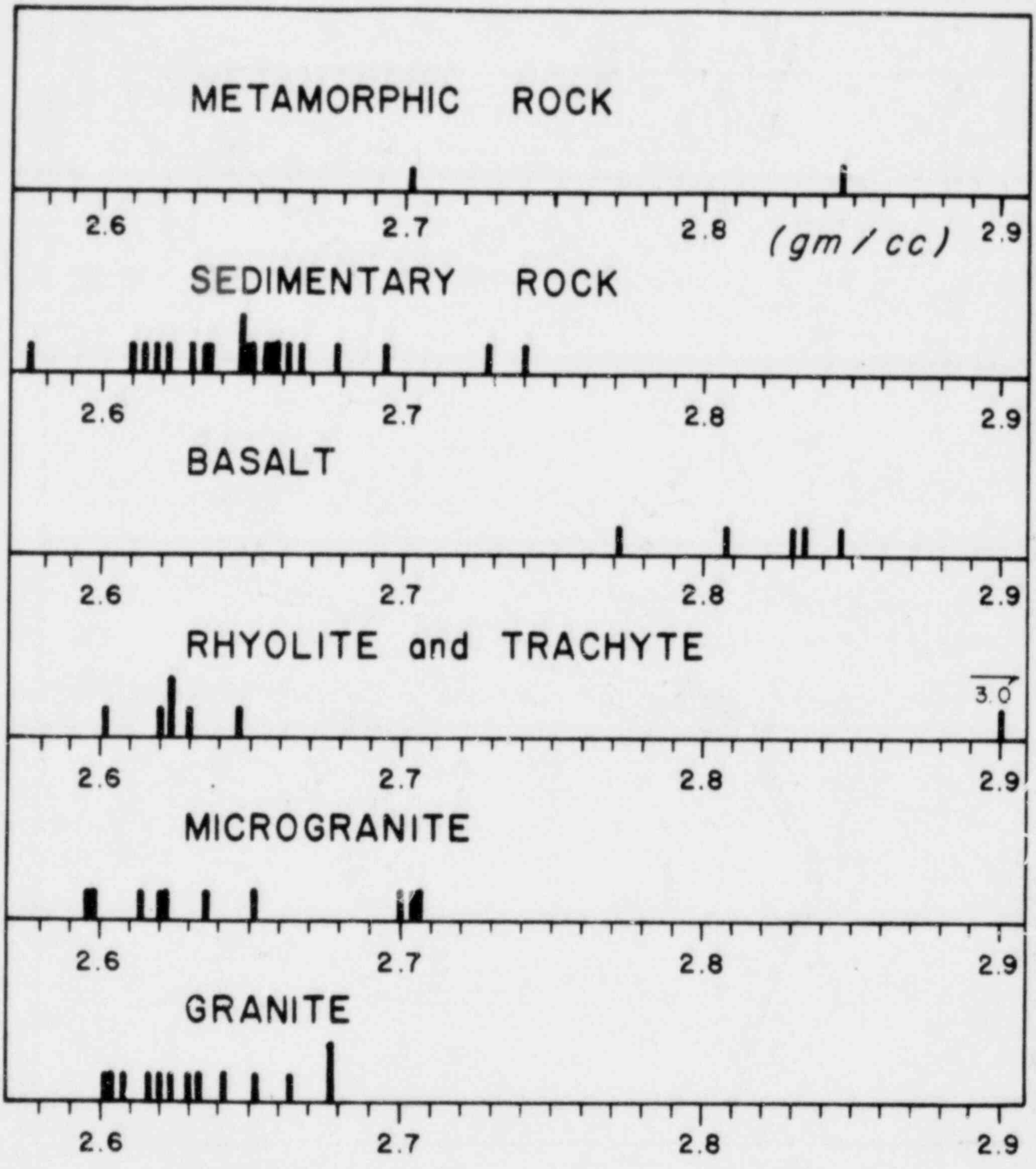


Figure B-6. Density (gm/cc) of basement rocks from Illinois and Indiana.

Figure B-7. 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.

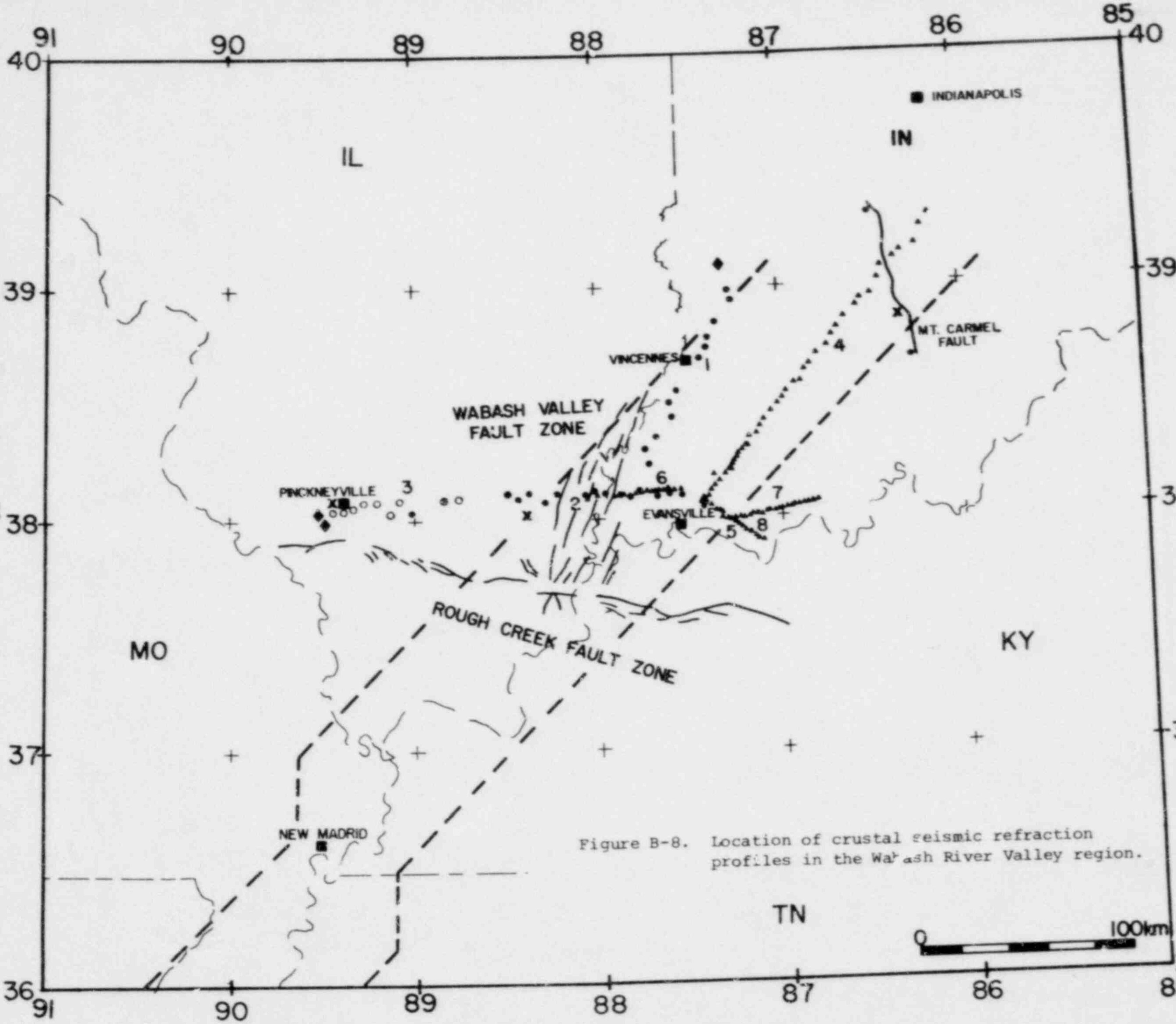


Figure B-8. Location of crustal seismic refraction profiles in the Wabash River Valley region.

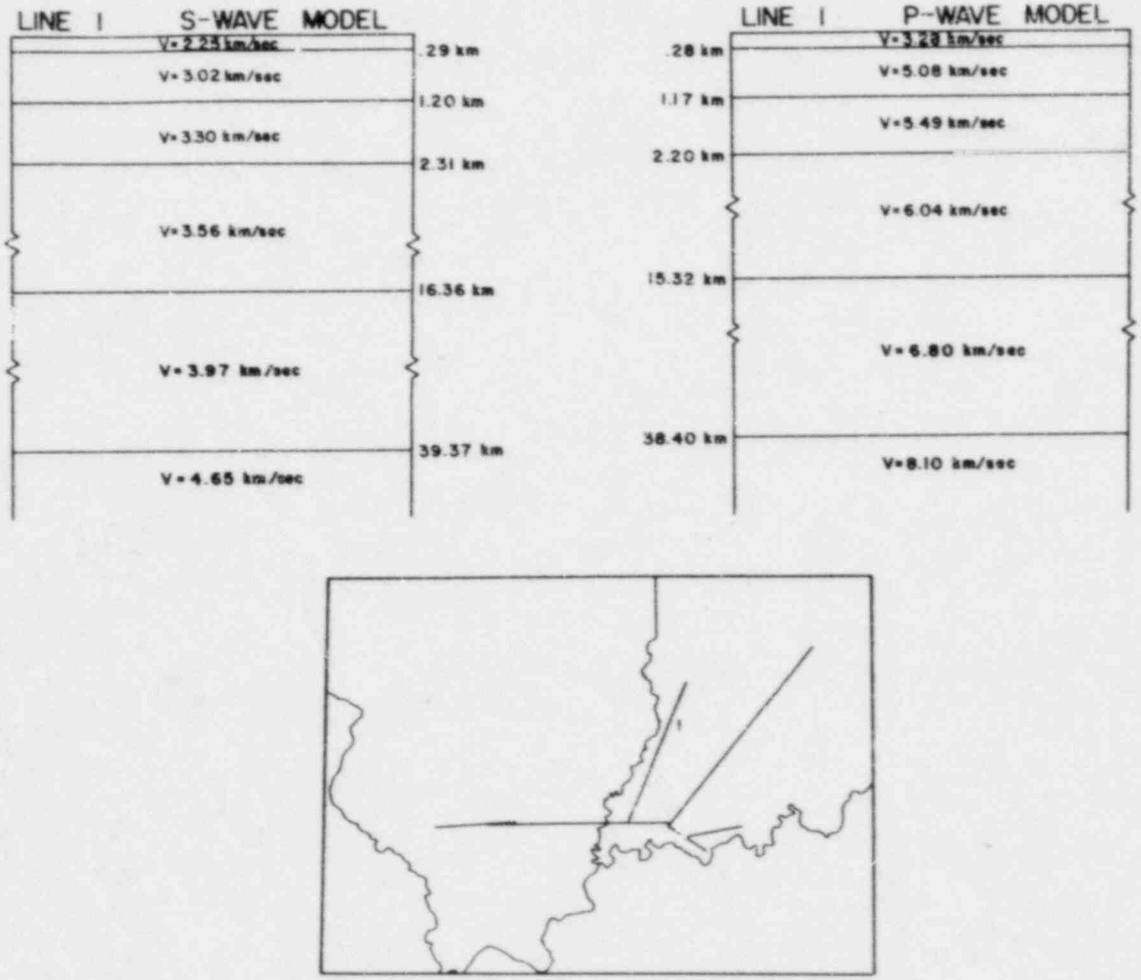


Figure B-9. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 1.

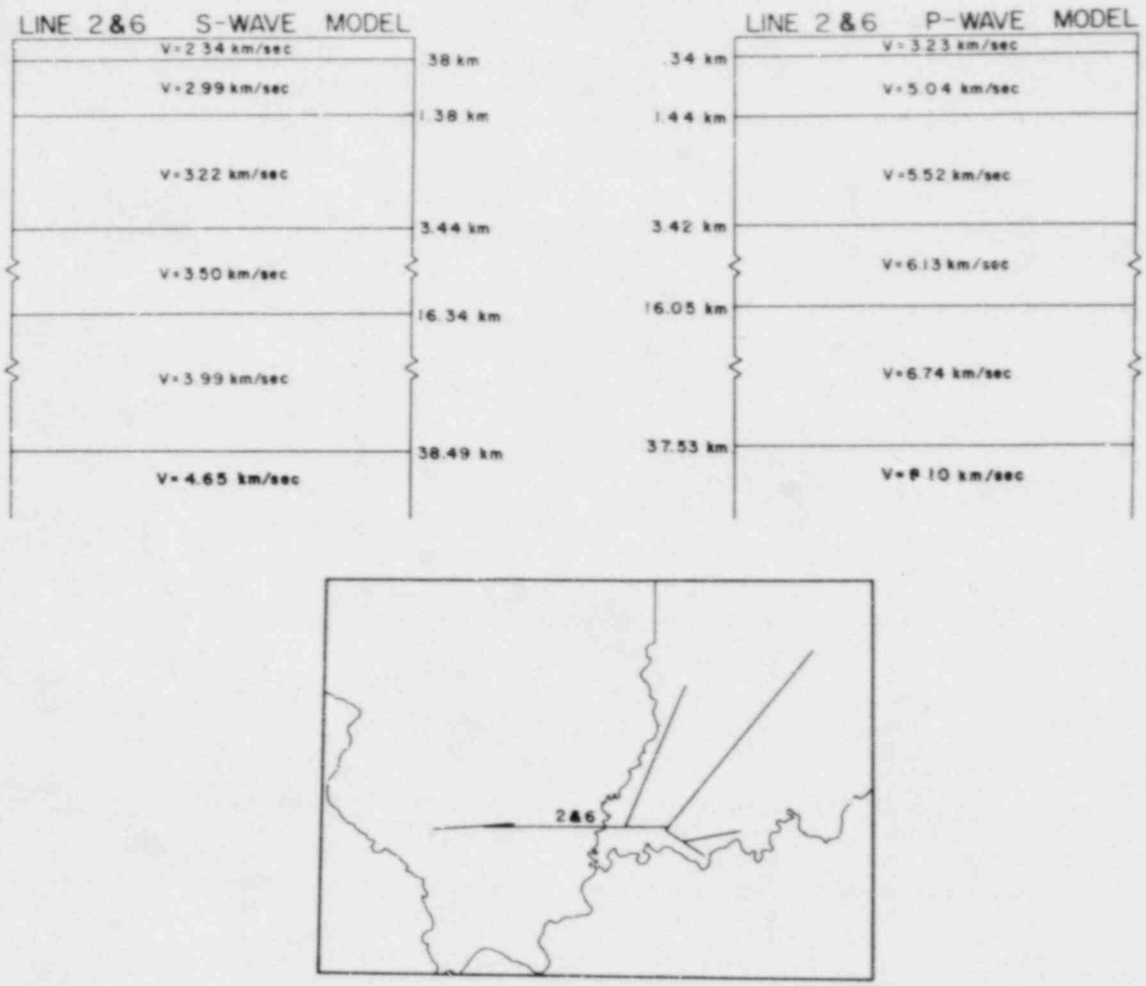


Figure B-10. Crustal models derived from compressional (P) wave and shear (S) wave data of Profiles 2 & 6.

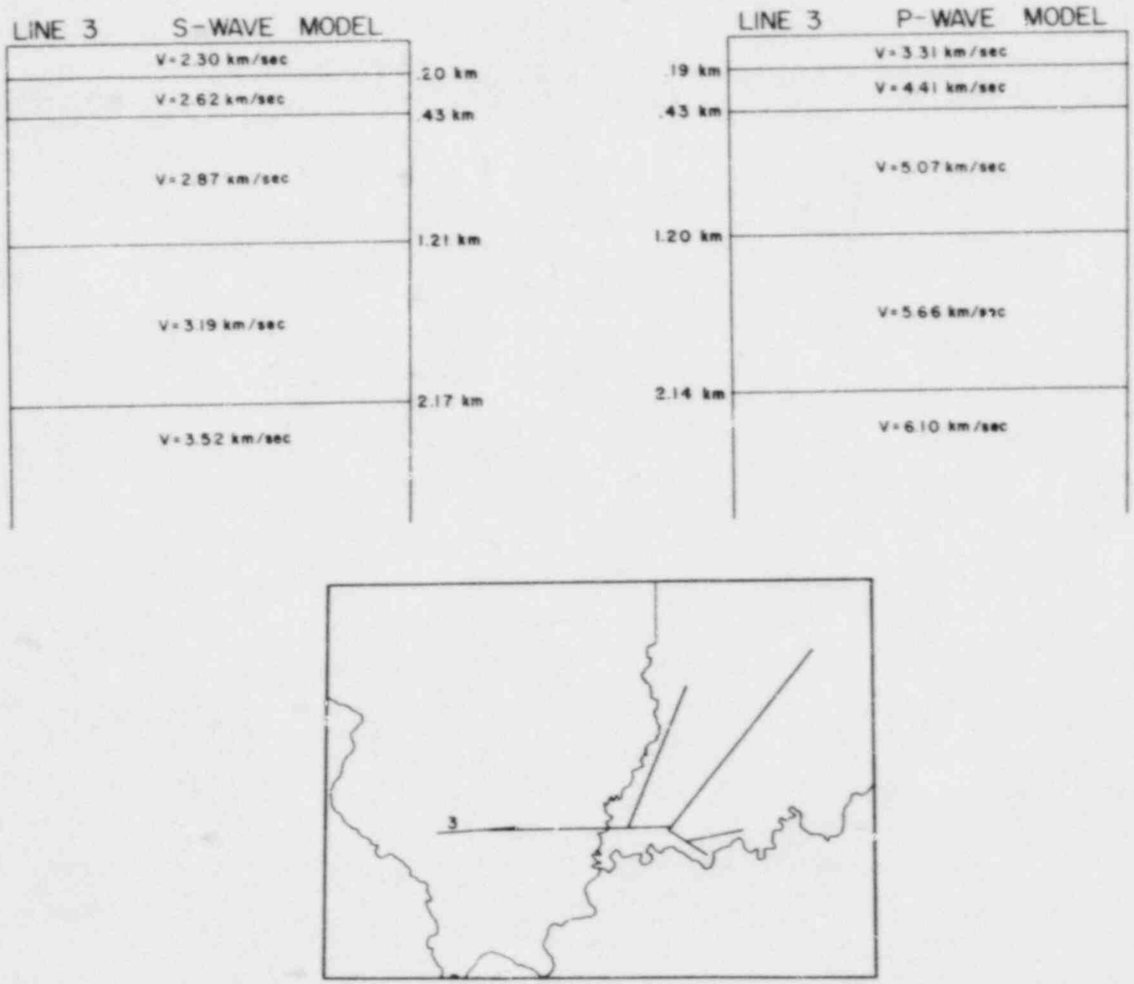


Figure B-11. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 3.

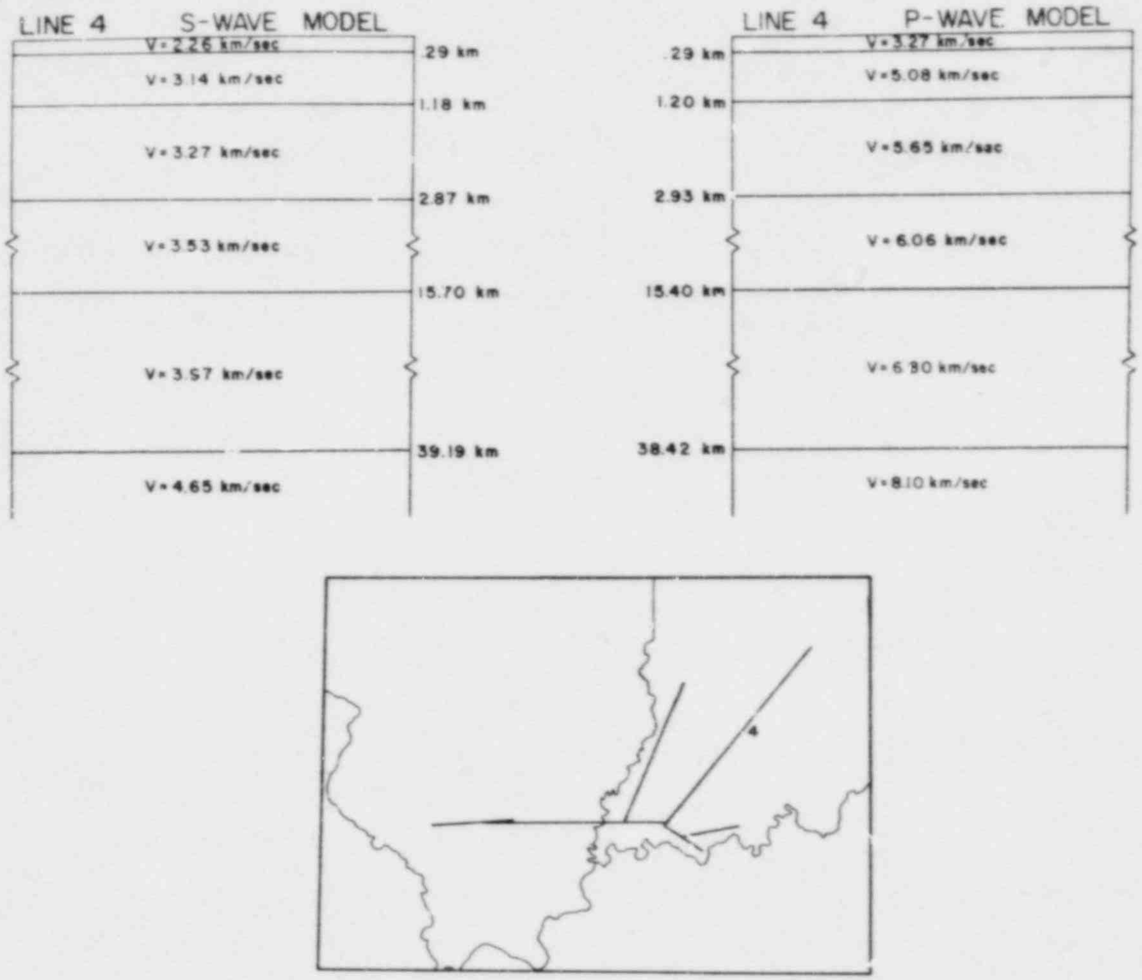


Figure B-12. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 4.

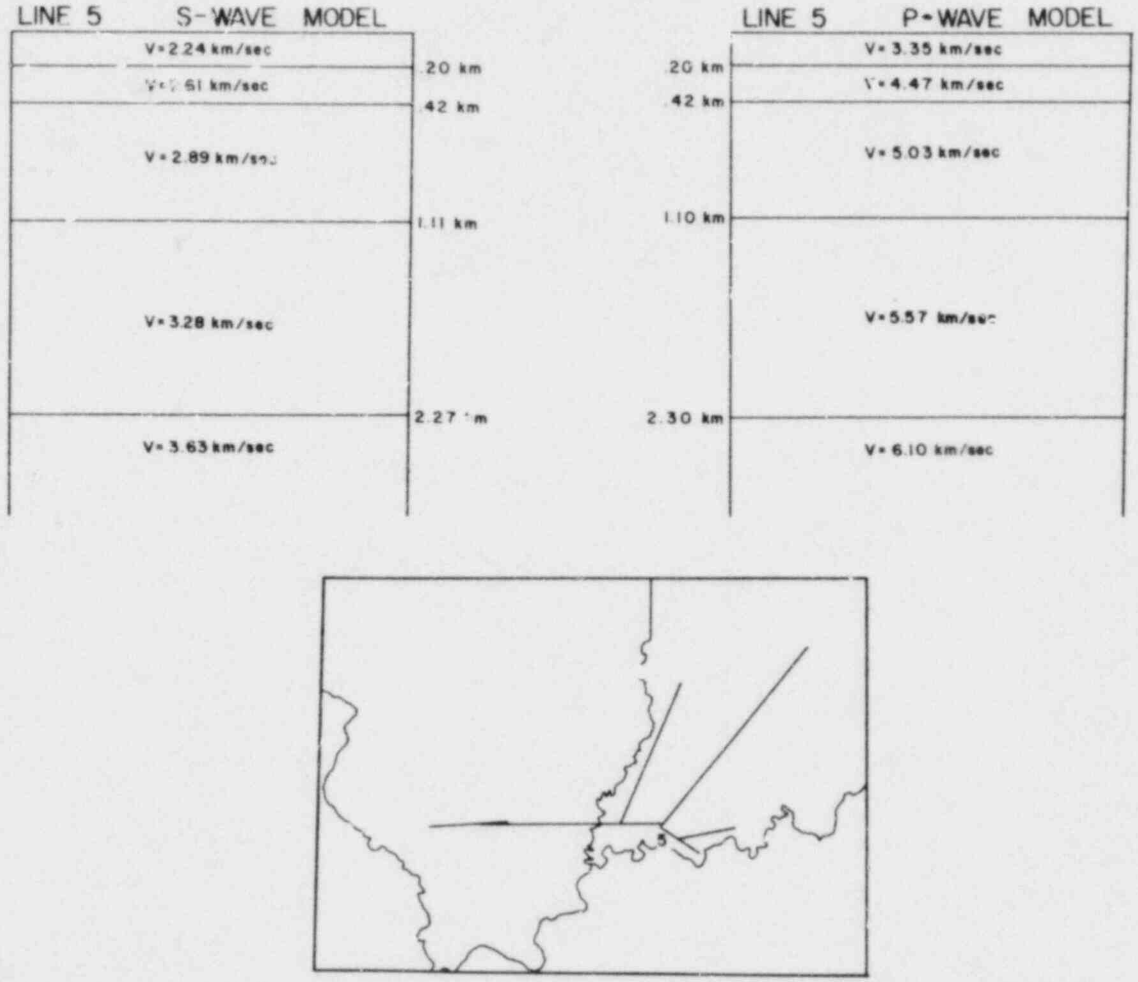


Figure B-13. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 5.

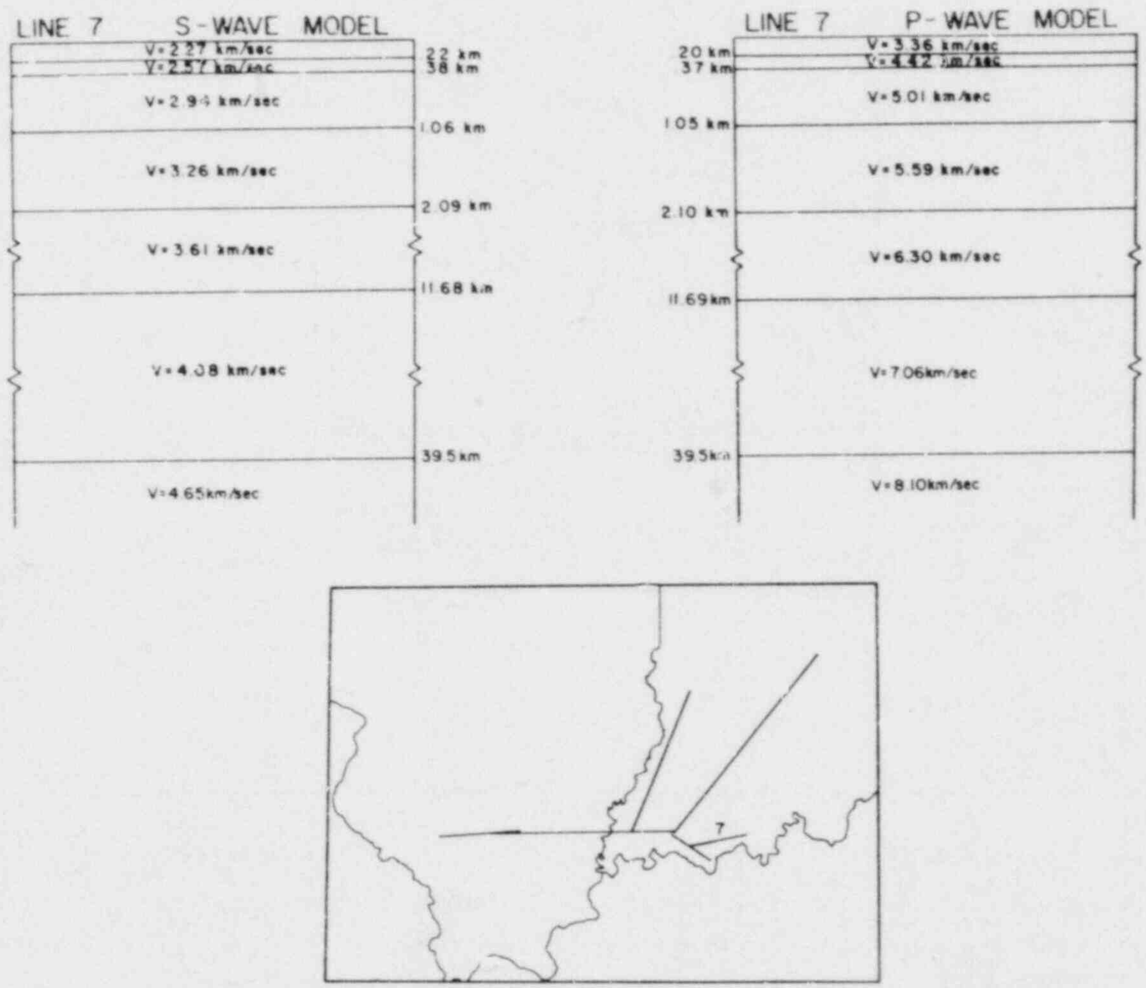


Figure B-14. Crustal models derived from compressional (P) wave and shear (S) wave data of Profile 7.

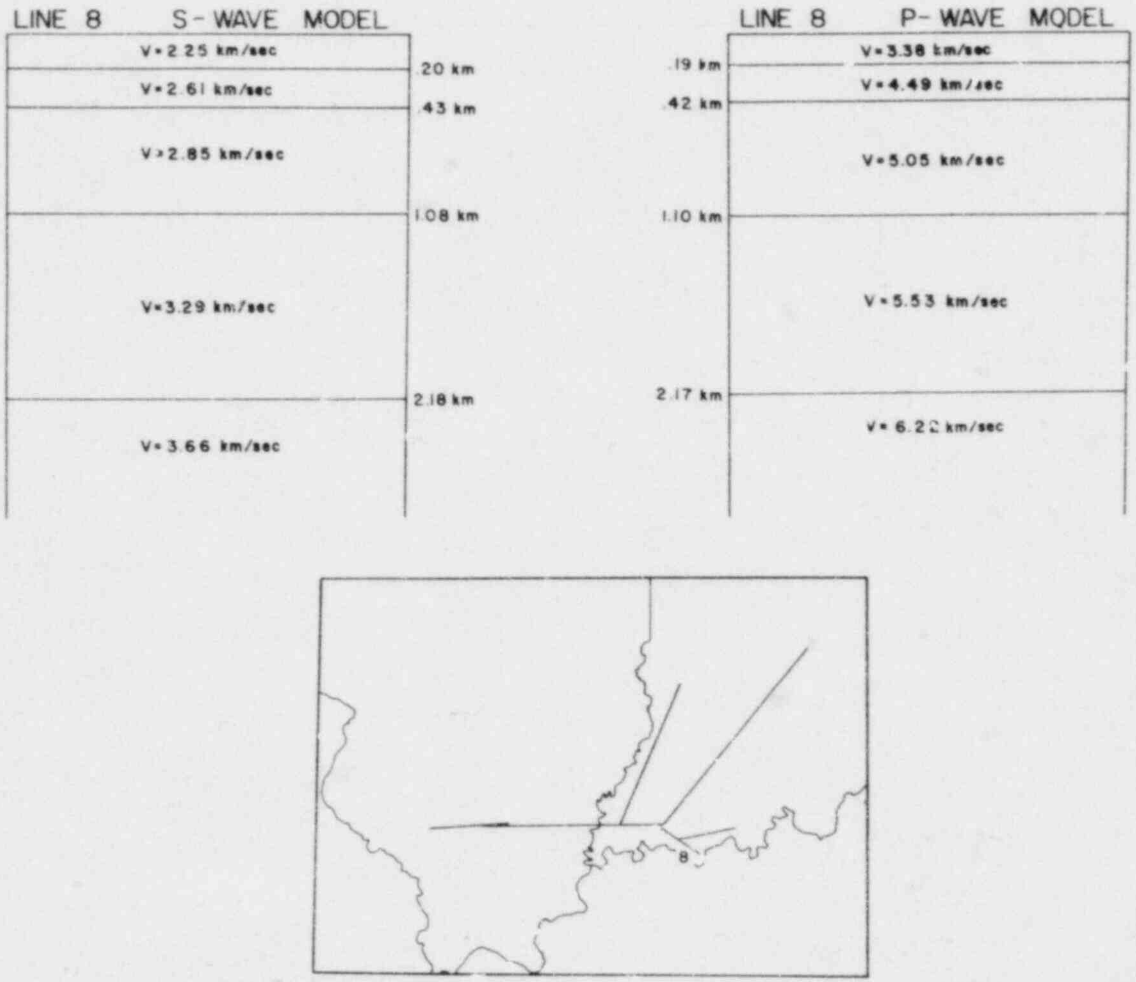


Figure B-15. Crustal models derived from compressional (P) wave and shear(S) wave data of Profile 8.

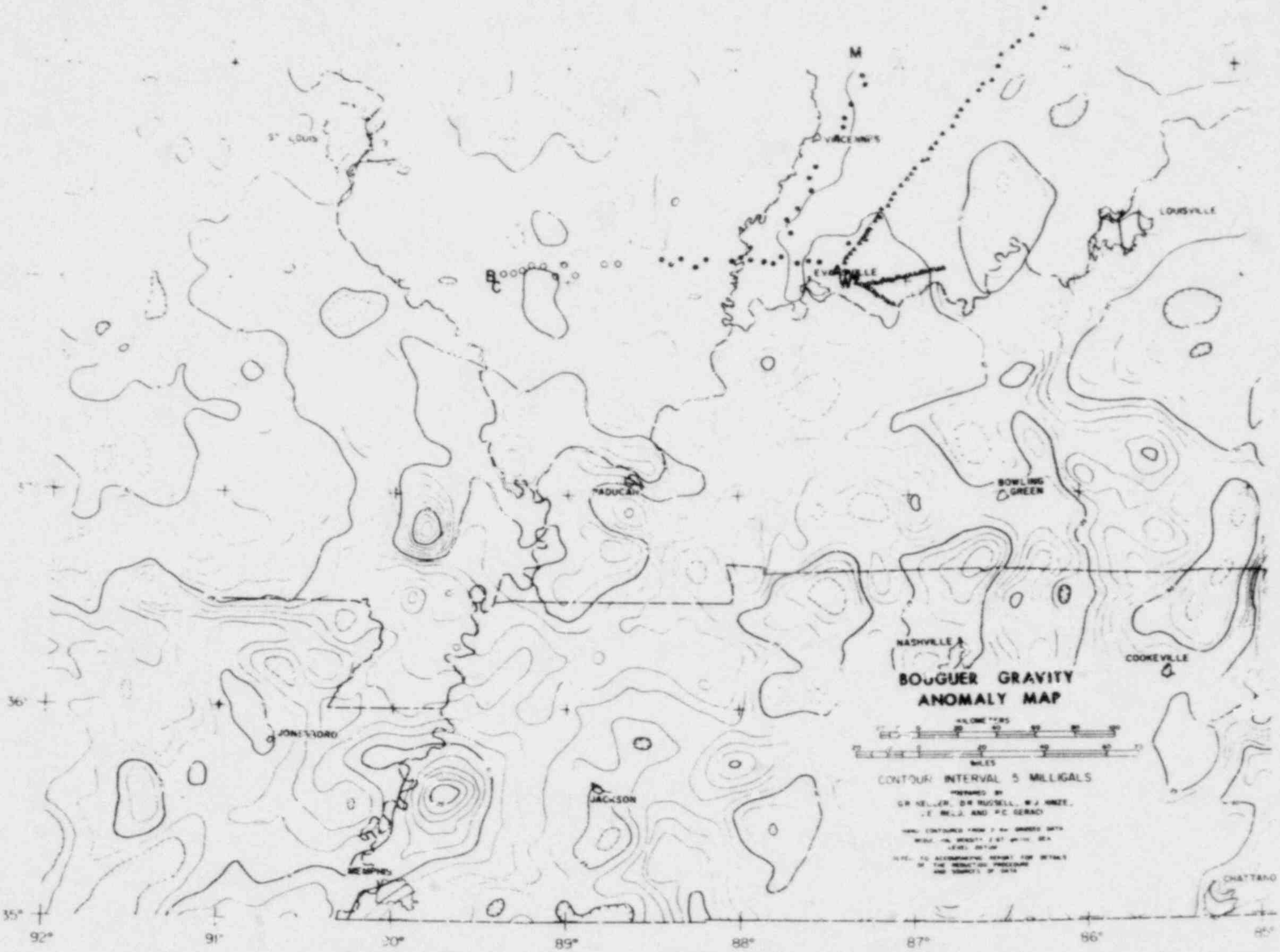


Figure B-16. Bouguer gravity anomaly map showing positions of recording stations for crustal seismic investigation in the Wabash River Valley (see Figure B-8).

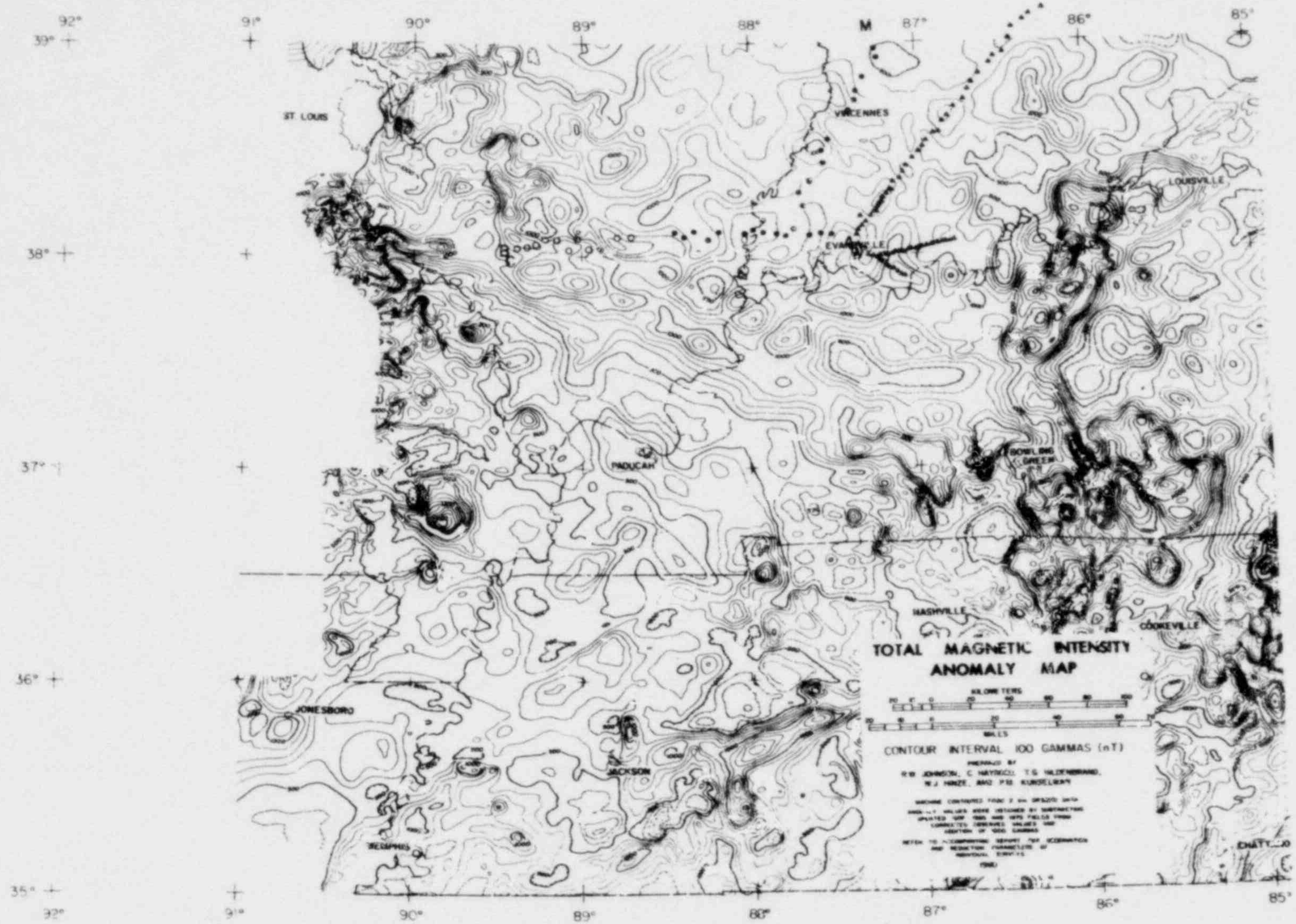


Figure B-17. Total magnetic intensity anomaly map showing seismograph locations used in the Wabash River Valley crustal seismic study.

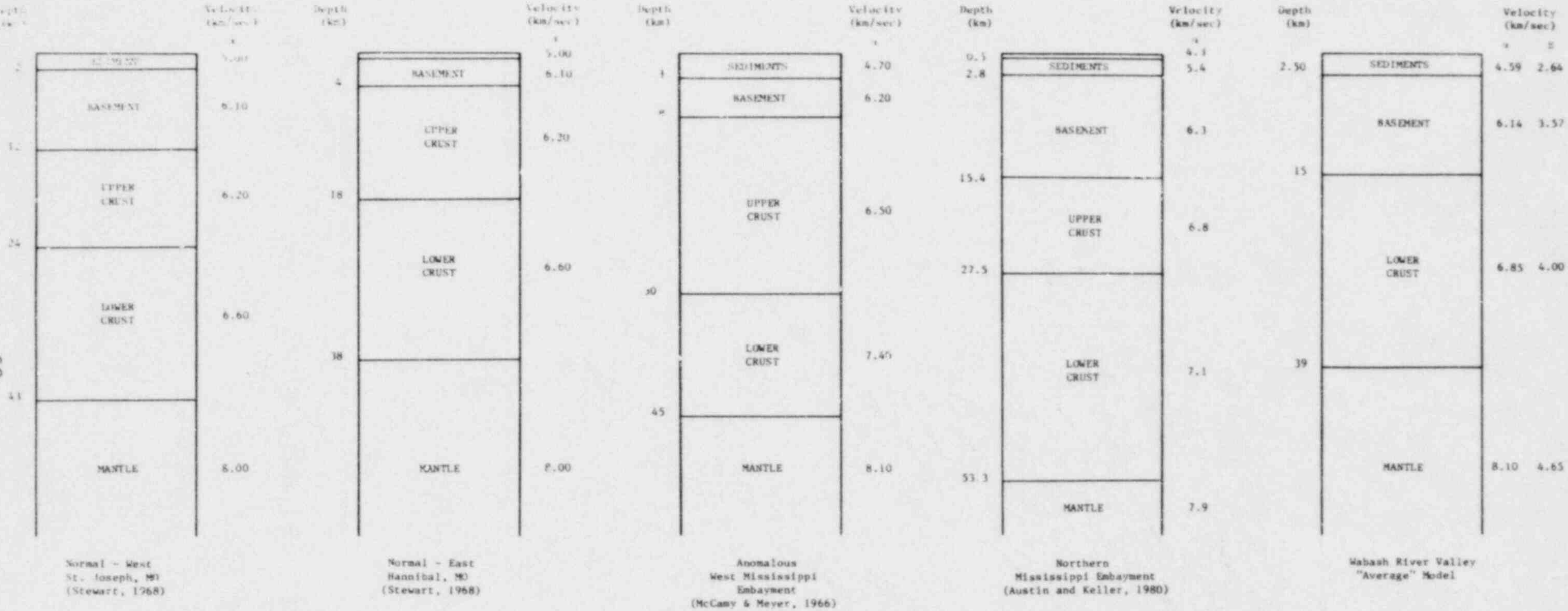


Figure B-18. Comparison of crustal models of the Mississippi Embayment region.

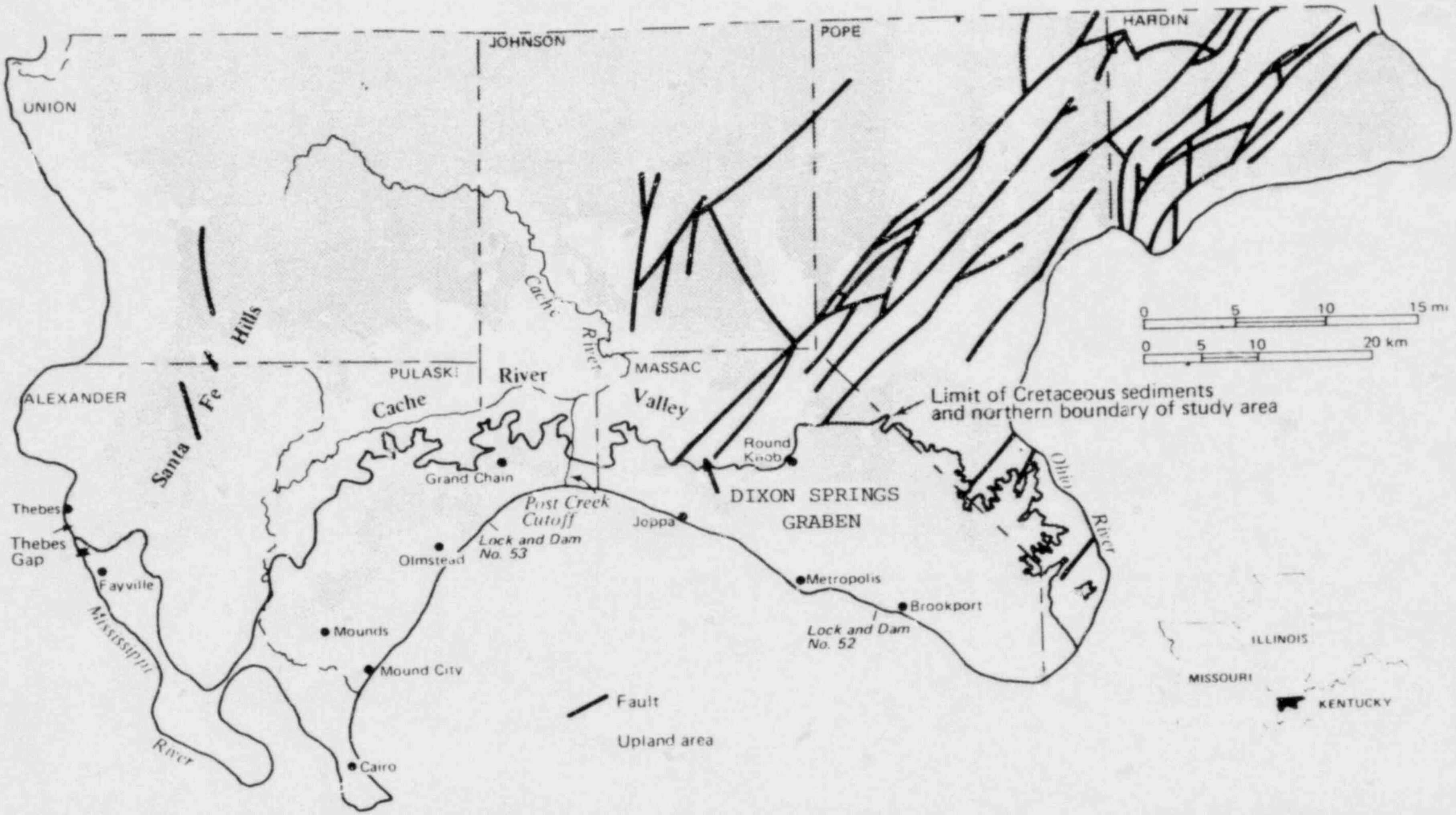


Figure B-19. Location map for Ohio River seismic reflection study.

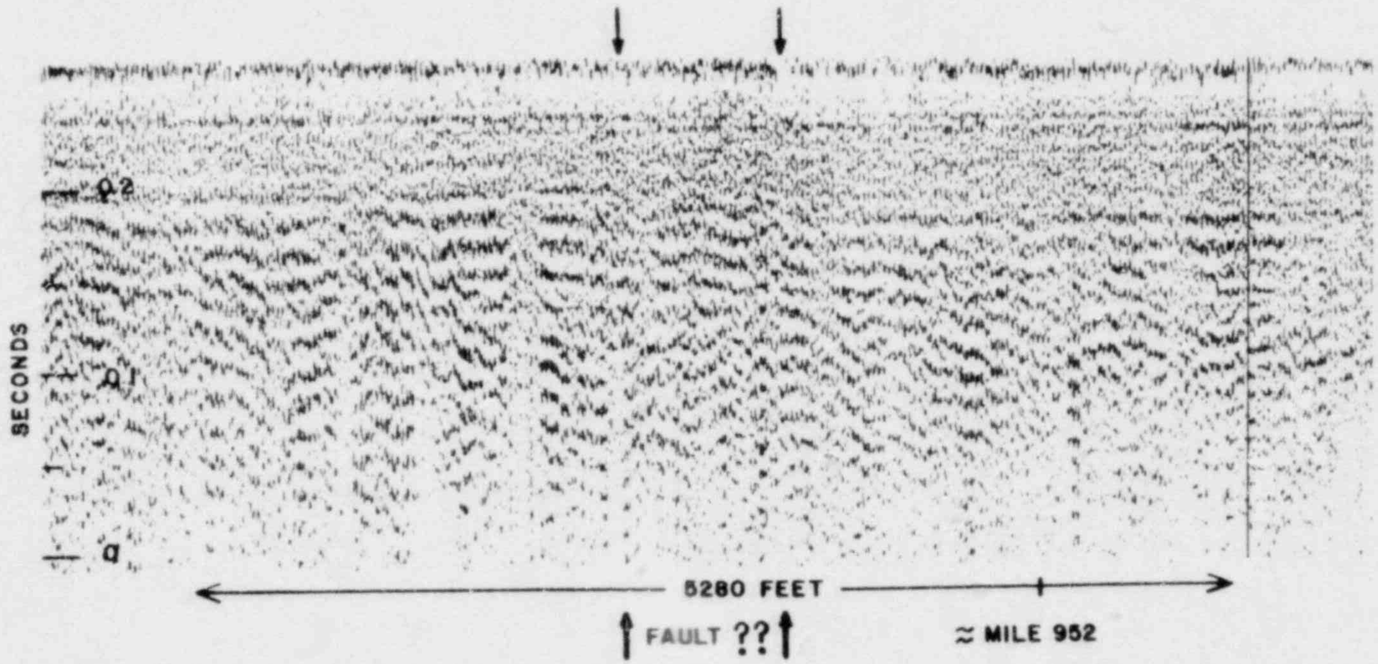


Figure B-20. Possible bedrock fault indicated in sparker seismic reflection record downstream of Joppa, Illinois.

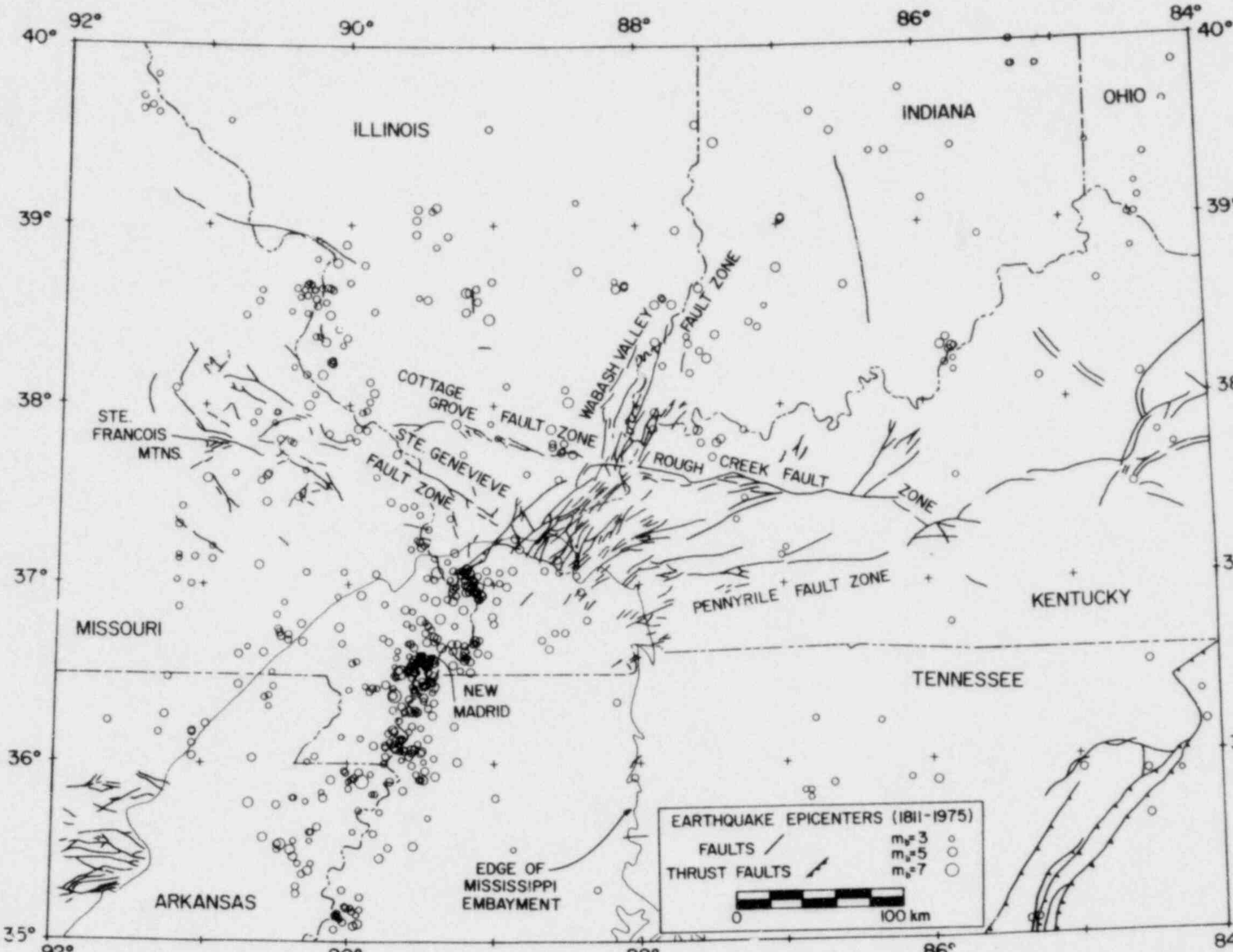


Figure B-21. Earthquake epicenters (1811-1975) and mapped faults in the vicinity of the 38th Parallel Lineament and its intersection with the extension of the New Madrid Fault Zone.

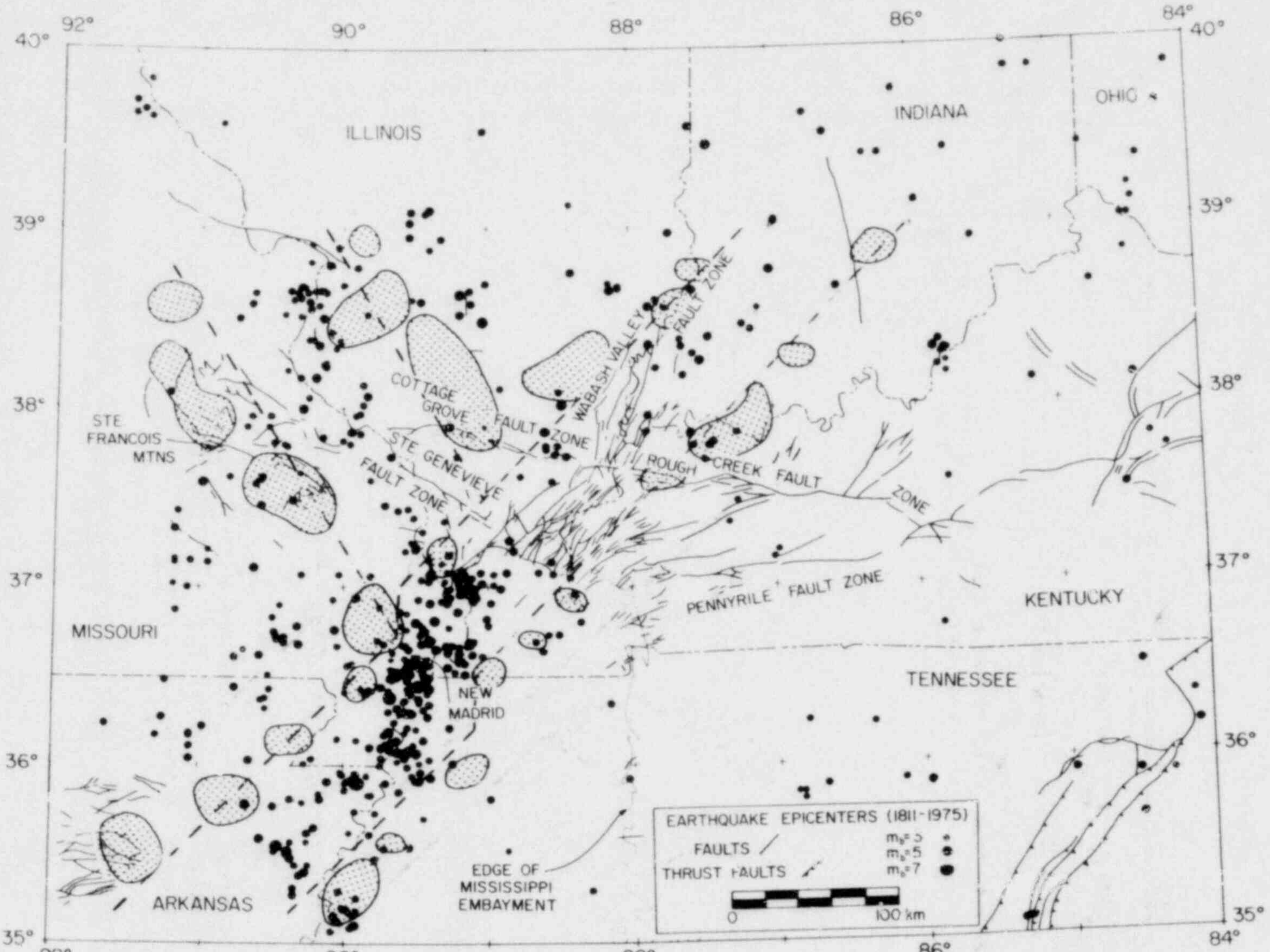


Figure B-22. Earthquake epicenters, mapped faults and inferred mafic intrusives (stippled pattern) and boundaries of linear basement features (heavy dashed lines).

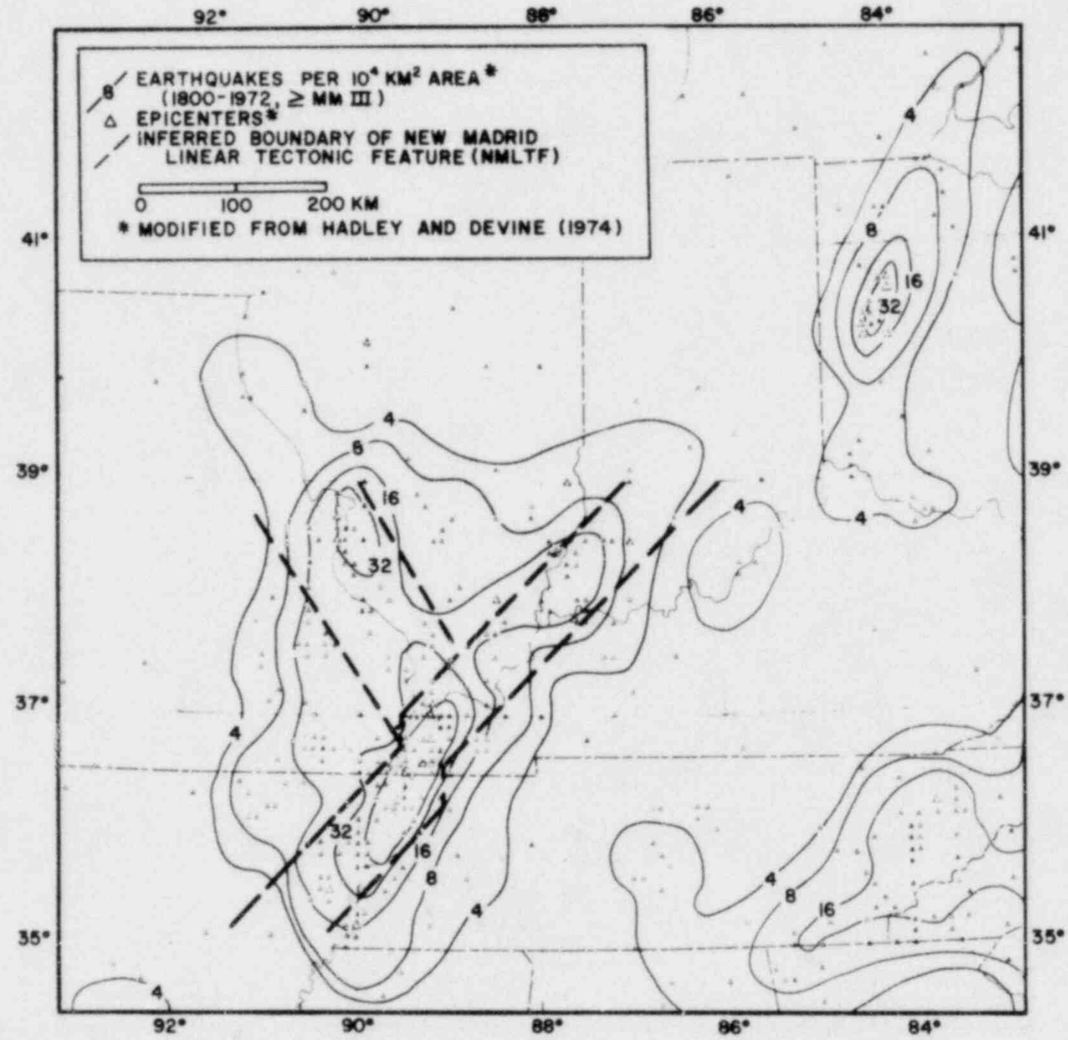
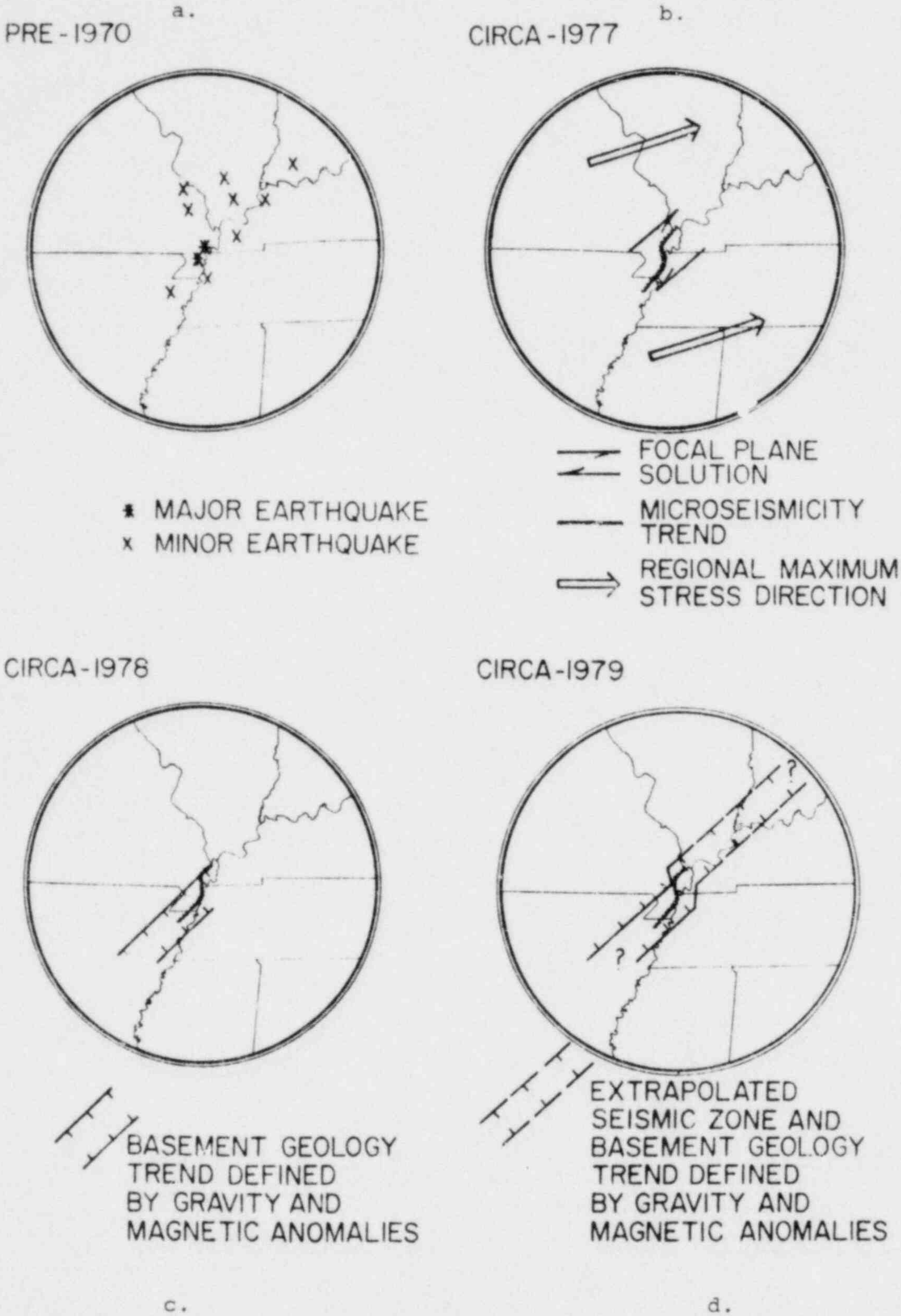


Figure B-23. Contour map of number of earthquakes per 10^4 km^2 area (from Hadley and Devine, 1974) and inferred boundaries of linear basement features (heavy dashed lines).



History of the development of the New Madrid tectonic model.

Figure BA1-1

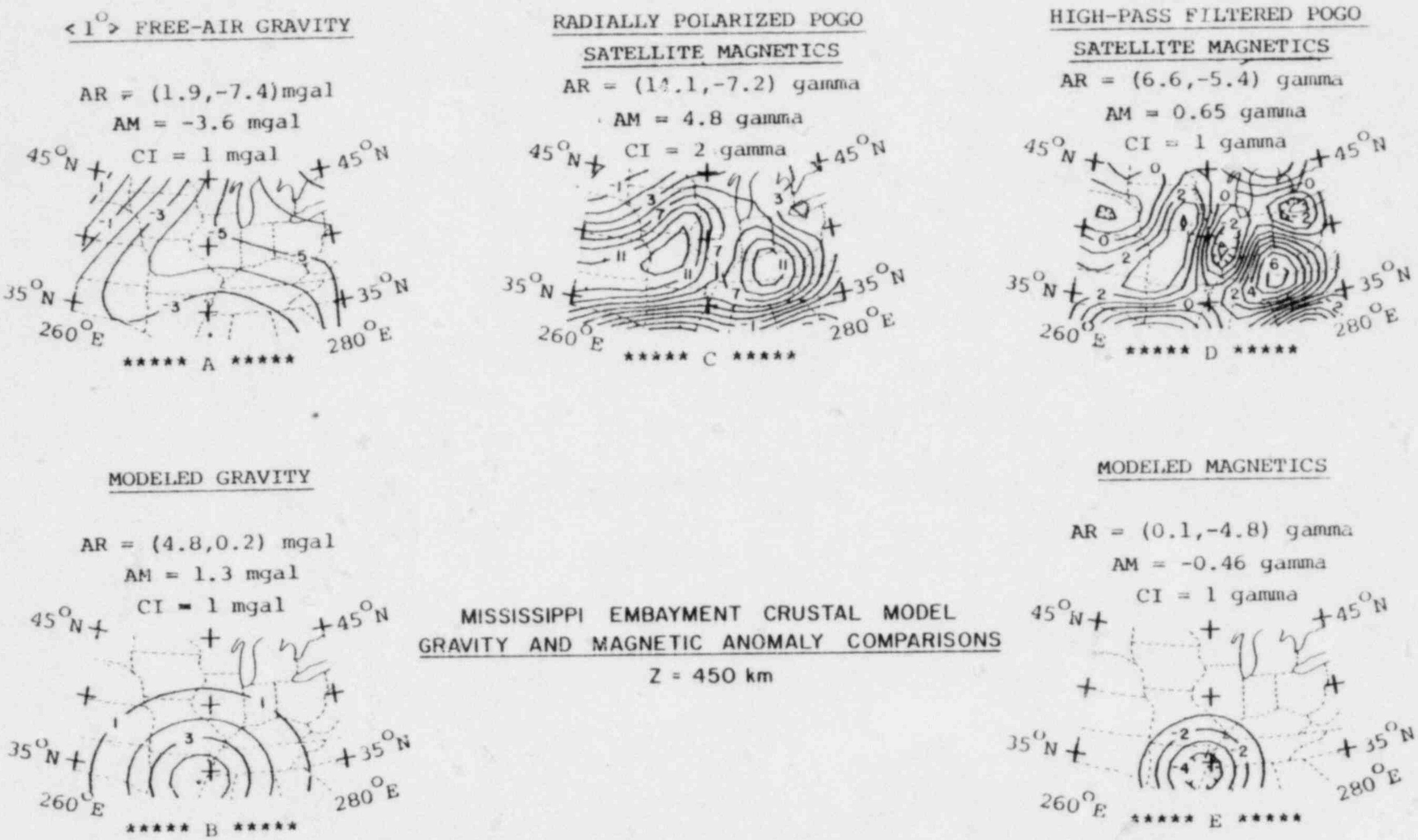


Figure BA2-1 Mississippi Embayment satellite level comparisons between Gauss-Legendre quadrature modeled gravity and magnetic anomalies and upward continued 1°-averaged free-air gravity and reduced to the pole POGO satellite magnetic anomaly data. Each anomaly field is plotted on a stereographic equal-area polar projection.

STRUCTURAL FRAMEWORK OF THE MISSISSIPPI EMBAYMENT
OF SOUTHERN ILLINOIS

Summary of

Annual Progress Report - Fiscal Year 1980

Contract No. NRC-04-77-159

Dennis R. Kolata, Janis D. Treworgy, and John M. Masters
Illinois State Geological Survey

ABSTRACT

Some of the northeast-trending faults that displace Paleozoic rocks in the Illinois-Kentucky Fluorspar District extend southwestward beneath the Gulfian (late Cretaceous) sediments of the Mississippi Embayment in southernmost Illinois. The relatively uniform thickness of the Cretaceous sediments and nature of the configuration of the base of the Cretaceous indicate that essentially all of the displacement on the faults in the underlying Paleozoic bedrock took place before the Cretaceous sediments overlapped the area. Outcrop and subsurface data indicate that the present relief on the sub-Cretaceous surface throughout the Mississippi Embayment of southern Illinois is due to the combined effects of pre-Gulfian erosion, post-Gulfian solution, and possibly minor deformation during and after Gulfian time. Although deformation of Gulfian or later age is suggested at several sites, the available evidence is too sparse and ambiguous to conclude that tectonic faulting is the cause of these local disturbances.

INTRODUCTION

This study is part of a coordinated program of geological, geophysical, and seismological investigations of the area that lies within a 200-mile radius of New Madrid, Missouri. New Madrid is situated near the epicenter of a series of the most intense earthquakes documented in this country (late 1811 and early 1812), and it is still an area of moderate seismicity. The goal of the program, the New Madrid Seismotectonic Study, is to develop a better understanding of the structural setting and tectonic history of the area in order to evaluate earthquake risk as it applies to the siting of nuclear facilities. The study is funded in part by the U.S. Nuclear Regulatory Commission and includes participants from various state geological surveys and universities. Research activities of the U.S. Geological Survey are also coordinated with this program.

The Mississippi Embayment of southern Illinois (as demarcated by the present boundary of the continuous Cretaceous deposits) lies between the

New Madrid Seismic Zone and the highly faulted area of the Illinois-Kentucky Fluorspar District (Figure C-1). The seismic zone and the faulting in the Fluorspar District in Illinois both have northeast-southwest trends, and structural continuity is commonly inferred between the two areas. Knowledge of the structural framework and tectonic history of the study area is important in the evaluation of seismic risk for the Central Mississippi Valley Region and parts of the Wabash and Ohio River Valleys. The main focus of this study is on the evaluation of evidence for faulting during and after Gulfian (late Cretaceous) time in the embayment area of southern Illinois.

This investigation of the structural framework of the southern Illinois portion of the Mississippi Embayment leads to a new interpretation based on a reevaluation of data used in previous studies and on new geological and geophysical (earth resistivity, seismic reflection, and seismic refraction) data. Our principal objectives are: (1) to describe the geologic features of the Paleozoic bedrock; (2) to describe the thickness and distribution of the embayment sediments; (3) to describe and interpret several surficial sites where the embayment sediments are faulted and folded; and (4) to summarize the structural history of the area.

METHOD OF STUDY

Detailed mapping in this investigation is based on outcrop and subsurface information obtained from cores, drilling chips, geophysical surveys, and drillers' logs. All available well cuttings and cores were reviewed. Data were plotted on computer-constructed base maps (ILLIMAP, see Swann et al., 1970) of 1:125,000 scale. The northern limit of continuous Cretaceous deposits in Alexander, Pulaski, Massac, and Pope Counties is the boundary of the study area (Figure C-2). A generalized stratigraphic column for this area is shown in Figure C-3. Four regional maps of the embayment area of southern Illinois were compiled to show: (1) the sub-Cretaceous geology (Figure C-4); (2) the configuration of the base of the Cretaceous (Figure C-5); (3) the distribution and thickness of the Cretaceous strata (Figure C-6); and (4) the structure of the base of the Paleocene Clayton Formation (Figure C-7).

Field work began in the fall of 1977 and continued into the summer of 1979. Detailed studies were conducted at selected sites where the embayment sediments show evidence of disturbance. Maps and cross sections of several sites were prepared, and geologic interpretations are given herein.

A conservative approach was taken in preparing the maps for the report, particularly in regard to faulting. The faults shown on the sub-Cretaceous geologic map (Figure C-4) are interpreted primarily from studies of well cuttings and cores. Although we suspect that faulting is widespread in the Paleozoic bedrock, no fault was extended beyond areas of control.

GEOLOGIC SETTING

The Mississippi Embayment is an inland extension of the Gulf Coastal Plain, a physiographic and structural province that reaches as far north as the southern tip of Illinois. The axis of the embayment generally coincides with the present course of the Mississippi River. The embayment is a down-warped structural trough that lies between the Ozark Dome on the west and the Nashville Dome on the east (Figure C-1). Mostly unconsolidated sediments of Mesozoic and Cenozoic age fill the trough. These sediments form a wedge that thickens southward from an erosional featheredge in southern Illinois to approximately 4,000 feet (Stearns and Marcher, 1962) in northeastern Mississippi and eastern Arkansas.

Except for a few small outliers of clays, sands, and gravels of suspected Gulfian age, the embayment strata in Illinois are confined to the southern part of the Santa Fe Hills in Alexander County and to the area south of the Cache Valley (Figure C-2). The Cache Valley is the former channel of the Ohio River. In Illinois the embayment sediments rest unconformably on Paleozoic bedrock that ranges in age from Ordovician to Mississippian (Figure C-4). Throughout a large part of the study area the embayment strata are overlain by the Pliocene-Pleistocene Mounds Gravel and Pleistocene loess, colluvium, and alluvium. The maximum depth to the Paleozoic bedrock in southern Illinois is approximately 600 feet; this is at the southern tip of Alexander County. The Gulfian and early Tertiary sediments that fill the embayment trough in Illinois have a southerly dip of about 50 feet per mile.

The structural framework of the embayment area of southern Illinois is complex. The embayment strata have a regional dip to the south toward the center of the embayment trough, whereas the underlying Paleozoic rocks have a regional dip to the northeast toward the Illinois Basin and away from the

Ozark Dome and Pascola Arch. In addition, the Paleozoic rocks are broken by numerous northeast-trending faults that extend from the Illinois-Kentucky Fluorspar District southwestward and apparently passing beneath the embayment sediments. Based on subsurface data, several northeast-trending faults are postulated within the study area and their locations are shown on the sub-Cretaceous geologic map (Figure C-4). Some of the faults can be observed in outcrop north of the study area in Pope and Hardin Counties. The faults are nearly vertical and have as much as 2,000 feet of displacement.

PREVIOUS STUDIES

The structural geology of southern Illinois has been discussed by numerous investigators including Stuart Weller (1920), Butts (1925), J. M. Weller (1940), Clark and Royds (1948), Stonehouse and Wilson (1955), J. M. Weller, Grogan, and Tippie (1952), J. M. Weller and Sutton (1940), and Heyl and Brock (1961). These studies dealt mainly with the geologic structure north of the Mississippi Embayment, with particular emphasis on the Illinois-Kentucky Fluorspar District.

The most detailed investigations of the geology of the Mississippi Embayment area of southern Illinois are those of Pryor and Ross (1962) and Ross (1963, 1964). Ross (1963) mad the first analysis of the structural framework of this area. From the field relations, subsurface data, and historical seismicity, Ross (1963, p. 23) concluded that "the structural framework of southernmost Illinois is closely related to the structure of the Illinois-Kentucky Flurospar District and to the structure of the Mississippi Embayment." Ross (1963, p. 23) reasoned that much of the relief on the sub-Cretaceous surface, shown in his Figure 7, is due to faulting which postdates deposition of the Gulfian sediments and which, in part, postdates deposition of the Eocene sediments. Ross (1963, p. 18) supposed that "if the relief on the sub-Cretaceous surface was as great when the Cretaceous strata were deposited as it is now, the Tuscaloosa Formation should locally be much thicker, and its distribution more irregular." The present investigation has shown that the Tuscaloosa is in fact irregular in thickness and distribution. Ross (1963, p. 3) further argued that the evidence "suggests that the fault system which cuts the Paleozoic strata at the head of the Embayment (in the Fluorspar District) extends for a considerable distance southwestward beneath the

Embayment sediments and has remained active to the present."

In recent years the term "New Madrid Fault Zone" (Heyl and Brock, 1961) has been applied to the broad belt of northeastward trending faults that extends from southwest to the broad belt of northeastward trending faults that extends from southwest of New Madrid, Missouri, northeastward through southernmost Illinois to near Vincennes, Indiana. Burke and Dewey (1973) interpreted the "New Madrid Fault Zone" to be the failed arm of a plume-generated triple junction that led to the formation of the Mississippi Embayment during Mesozoic time. Ervin and McGinnis (1975) accepted the triple rift juncture model, but reasoned on the basis of geological and geophysical data that the embayment is a reactivated rift (Reelfoot Basin of Schwalb, 1969) that originated late in Precambrian time. Accordingly, reactivation of the rift late in Mesozoic time led to isostatic subsidence within the embayment and formation of the elongate depositional trough observed today. Present-day seismicity and the region of principal historical earthquake activity lie along the axis of the rift zone (Hildenbrand et al., 1979), primarily in the Bootheel region of southeastern Missouri. Geophysical studies by Hildenbrand and Hendricks (1977), Kane and Hildenbrand (1977), Braile et al., (1979), and Hildenbrand, Kane, and Hendricks (1979) indicate a rather sharply bounded zone of low gravity and magnetic relief that corresponds with the "New Madrid Fault Zone" as defined by Heyl and Brock (1961).

STRATIGRAPHY

As much as 15,000 feet of Paleozoic strata (Figure C-3), ranging in age from Cambrian to Mississippian, overlie Precambrian crystalline rocks. The oldest stratigraphic unit encountered in the study area is the Canadian (lower Ordovician) Shakopee Dolomite observed in the Cache Oil Co. No. 1 George Moses test in southern Pulaski County. Pryor and Ross (1962, p. 5, 6) describe this well in detail. The deepest well (total depth 4,100 feet) in the area is the Rigney and Dodson Oil Co. No. 1 J. H. Lewis test in southern Pope County; the well was drilled through a thick succession of Mississippian, Devonian, Silurian, and Ordovician rocks (finished in the Champlainian Platteville Group). A summary description of this well was published by Ross (1964, p. 24-28). A significant deep well located immediately north of the study area is the Texas Pacific Oil Co. No. 1 B. Farley et al., test in southern

Johnson County (SE NE SE Sec. 34, T. 13 S., R. 3 E.). The well was drilled to a total depth of 14,284 feet and penetrated a stratigraphic succession that ranges in age from Chesterian to Cambrian.

Discussions of the Paleozoic stratigraphy in the area are given by Weller (1940), Weller and Ekblaw (1940), Grohskopf (1955), Pryor and Ross (1962), Lineback (1966), and Schwalb (1969).

Mississippi Embayment deposits of Gulfian (late Cretaceous) and early Tertiary age overlie the Paleozoic bedrock in the area. These sediments consist primarily of unconsolidated clay, silt, sand, and gravel of both marine and non-marine origin. In the lowland areas these sediments are buried by alluvium. In the uplands they are mostly masked by the Pliocene-Pleistocene Mounds Gravel and Pleistocene loesses.

The post-Paleozoic strata in the area have been described by Lamar and Sutton (1930), Weller (1940), Grohskopf (1955), Potter (1955), Stearns and Armstrong (1955), Stearns (1957, Pryor (1960), Pryor and Ross (1962), Ross (1964), and Willman et al. (1975).

Although post-Cambrian igneous intrusive rocks are known to occur in the surrounding areas, none have been reported in the study area.

SUB-CRETACEOUS GEOLOGY

Knowledge of the sub-Cretaceous geology in southern Illinois is important in determining the existence of Cretaceous or later faulting. The amount and quality of outcrop and subsurface data, however, is quite limited. The few bedrock outcrops that are exposed in the area are situated in the uplands adjacent to the Cache Valley and Ohio River bluffs in Pope and Massac Counties, in the Post Creek Cutoff in southeastern Pulaski County, and in the bluffs of the Mississippi River Valley south of Thebes, Alexander County. The relatively few drill holes that penetrate the Paleozoic bedrock commonly are not drilled deep enough to confidently identify the Paleozoic stratigraphic unit. Because of the cyclic nature of some parts of the stratigraphic succession and the lateral facies changes, especially in the Mississippian units, a thick section of rock must be studied to make a positive identification. Some formations are relatively thick and uniform in lithology, and it is very difficult to locate faults in them even where the well control is closely spaced. Many drill holes in the area have been completed in a cherty unit that may be cherty bedrock, residual chert lying over the bedrock, the Tuscaloosa Formation, or a cherty bed in the McNairy Formation. Because of these uncertainties, we suspect that the bedrock contact has not always been identified consistently by drillers and by those who have studied samples.

An interpretation of the distribution of Paleozoic strata is shown on the sub-Cretaceous geologic map (Figure C-4). The contacts between stratigraphic units on this map are based on subsurface control and the southward projection of outcrop data. Because the bedrock dips northeastward away from the Ozark Dome and Pascola Arch toward the Illinois Basin, successively younger Paleozoic strata occur at the bedrock surface from west to east: Champlainian (middle Ordovician) in western Alexander County, to Chesterian (upper Mississippian) in northern Massac and southern Pope Counties.

The faults that are shown in Figure C-4 are based on apparent stratigraphic anomalies at the bedrock surface. Trends of the faults are based on a few control points and are inferred from the regional trend of faulting, which is northeastward. Most of the faults that are shown in eastern Massac and southern Pulaski Counties cannot be connected confidently to the faults that project into the area from the Illinois-Kentucky Fluorspar District. We suspect that the fluorspar district faulting extends into the area, but the density, extent, and magnitude of faulting cannot be substantiated with the available subsurface data.

Our sub-Cretaceous geologic map (Figure C-4) differs from that published by Ross (1963, Figure 6, p. 15) in that the latter shows a mosaic of bedrock faults much more numerous and extensive than can be substantiated with the available information. There are several reasons for this difference. (1) A check of the landowners or contractors listed in the well records against the county plat books showed that several critical datum points on Ross' map were mislocated, probably because of geographic errors in the records used in his study. (2) A restudy of all drilling samples in the area indicates that some stratigraphic units at the bedrock surface were misidentified. Some of the stratigraphic information used by Ross was obtained from sample studies made by various people over a long period of time and lacked consistency. (3) New subsurface information has become available since Ross' work that does not fit his conclusions.

Ross (1963) described four major northeast-trending graben belts in the embayment of southern Illinois including the America, Dixon Springs, Rock Creek, and Paducah Grabens. According to Ross, the America Graben lies parallel to the Ohio River and extends from near Mound City (T. 16 S., R. 1 E.) to near Olmsted (T. 15 S., R. 1 E.) in southern Pulaski County, about 10 miles. Although we interpret the sub-Cretaceous geology in this area to be somewhat different from that of Ross (1963, Figure 6), we do interpret several northeast trending faults in the general area including a rather wide graben situated to the west of his America Graben in T. 15 S., R. 1 E. and R. 1 W., and T. 16 S., R. 1 E. and R. 1 W. (Figure C-4). The stratigraphic relations shown by several wells in the area suggest that at least three parallel faults displace the Paleozoic bedrock. A thrust fault described by Schwalb (1969, p. 16) in the Indiana Camp Development Co. No. 1 T. J. Wilson test in Carlisle County, Kentucky, (20-E-5, 900' FSL x 2425' FEL of sec.), may be the southward extension of this structure.

The Dixon Springs Graben is well documented in the outcrop area north of the Cache Valley. It extends from the northeast corner of Pope County southwestward to northwestern Massac County and passes beneath the embayment sediments (Figures C-2, C-4). Displacement of the faults that bound the graben is nearly 1,000 feet in places (J. M. Weller, 1939, p. 11). On the basis of subsurface data, Ross (1963) extended the graben beneath the embayment sediments through the area just west of Joppa and across the Ohio River into Kentucky. We agree that a graben, probably a segment of the Dixon Springs Graben, underlies the area, but we interpret the bedrock within the graben to be Ste. Genevieve Limestone rather than Chesterian rocks as shown by Ross (1963, Figure 6). The key datum to the new interpretation is the Layne Western No. 1 Missouri Portland Cement Co. boring, which encountered Ste. Genevieve Limestone at the bedrock surface. Data on this well apparently were not available to Ross (1963). The nearest subsurface control to the east and west of this boring shows Ullin Limestone at the bedrock surface at a slightly higher elevation. The boring is also significant because the St. Louis and Salem Limestones appear to be faulted out with the Ste. Genevieve resting directly on top of the Ullin Limestone.

The Rock Creek Graben (Figure C-2) extends from the northeast corner of Hardin County southwestward through western Livingston County, Kentucky, and back into Illinois west of Bay City in Pope County. In Hardin County the bounding faults have as much as 2,000 feet of displacement, but displacement diminishes considerably to the southwest (J. M. Weller et al., 1952, p. 79). A graben has been interpreted beneath the embayment sediments between Metropolis and Brookport (T. 15 S. and T. 16 S., R. 5 E.: See Figure C-4) on the basis of apparent offsets in the Paleozoic bedrock as observed in closely spaced wells. This graben may be a southern extension of the Rock Creek Graben.

The Paducah Graben, described by Ross (1963) as "a narrow complex fault zone in its Illinois length," could not be substantiated with the available subsurface control and is not shown on our maps.

CONFIGURATION OF THE SUB-CRETACEOUS SURFACE

Configuration of the Paleozoic bedrock surface beneath the Cretaceous sediments is shown in Figure C-5. The most reliable data used in constructing this map are concentrated in the densely drilled area near Joppa and 4 or 5 miles west of there near the Pulaski-Massac County line, where the bedrock can be seen in outcrop. The data provided by the Paducah Dam site borings in southeastern Massac County also provide relatively good subsurface control. The area of least information is in southern Pulaski and Alexander Counties, where the bedrock is most deeply buried. Throughout the study area the bedrock is generally covered by either the Little Bear Soil, the Tuscaloosa Formation, or the McNairy Formation.

Generally, a gently undulating surface is shown that dips southward into the embayment trough (Figure C-5). The most unusual feature is the northeast-oriented elliptical depression in southeastern Pulaski County that generally coincides with the America Graben of Ross (1963). The depression is about 6 miles wide and nearly 350 feet lower at its center than the elevation of the Paleozoic bedrock in the surrounding area. The northern limit of the feature appears to be in the area of Grand Chain (Figure C-2). The southern limit, however, is not clear. It may continue southward through Ballard and Carlisle Counties, Kentucky, in the manner shown by Schwalb (1969, Figure 4, p. 10). Available subsurface data are too sparse in the area to establish the presence or absence of faulting in the Cretaceous sediments. Therefore we show no faulting on the maps of the configuration of the base (Figure C-5) or the distribution and thickness (Figure C-6) of the Cretaceous.

In Massac and Pope Counties the faults and grabens that project into the study area from the fluorspar district have little or no expression on the configuration of the base of the Cretaceous. This indicates that all or most of the movement on these structures and truncation of the Paleozoic bedrock by erosion occurred before the overlap of the Cretaceous sediments.

Several drill holes in the study area show the bedrock surface to be at anomalously low elevations. These anomalies are considered to be localized because of their proximity to drill holes that encountered bedrock at consistently shallower elevations. Because ground water commonly follows joints and faults, we suspect that where limestone occurs at the bedrock surface preferential solution has followed many of these linear features and has formed a karstic surface that reflects the structural fabric of the area. The trend of these joints and faults is predominantly northeast. For example, evidence obtained from closely spaced exploratory borings and outcrops near the Post Creek Cutoff in eastern Pulaski County (discussed later in this paper) indicates that solution has lowered the bedrock surface by as much as 90 feet within a horizontal distance of less than 50 feet. In Post Creek Cutoff (table C-1, h), where the bedrock surface is exposed, the predominantly northeast-trending joints are the sites of channel-like sinkholes and cavities (Ekblaw, 1936). A similar karstic topography was encountered during excavation and exploratory drilling at the Smithland Locks and Dam site on the Ohio River in Pope County (Bedrock surface map by F. W. Swartz made available by the U.S. Army Corps of Engineers, Louisville District, Geologic Branch).

The effect of solution can present problems in determining the age of faults. For example, solution along quiescent pre-Gulfian faults could result in collapse of the overlying embayment or younger sediments and give the erroneous impression that the faults have been active in relatively recent times. Locally, the geologic relations can be so complicated that the date of latest tectonic faulting may be impossible to determine.

Ross (1963) believed that the present relief on the sub-Cretaceous surface in southernmost Illinois is due primarily to post-Tuscaloosa faulting and warping. He reasoned that if the relief on the sub-Cretaceous surface was as great when the Cretaceous sediments were deposited as it is now, that the Tuscaloosa should be locally much thicker and its distribution more irregular. Further, the close parallel between the major struc' ι features of his sub-Cretaceous geologic map, his structure contours on the base of the Cretaceous sediments, and his projected trends of stru ..es exposed to the northeast of the embayment, suggested to him that the faults bounding the grabens of Paleozoic strata were sites of renewed movement after the deposition of Cretaceous sediments.

Primarily this hypothesis assumes that the Tuscaloosa Formation is widespread and uniform in thickness and, therefore, was deposited on a relatively flat surface, which Ross considered a structural datum for post-Gulfian deformation. The available data, however, do not convincingly support this assumption. In well cuttings, which are the main source of subsurface control, the Tuscaloosa commonly is not lithologically distinct from cherty bedrock, residual chert lying over the bedrock, or chert gravel within the lower part of the McNairy Formation. The chert gravel that occurs between the micaceous sand of the McNairy Formation and bedrock is actually variable in thickness and distribution. This chert gravel is absent in many drill holes throughout the area, and in the Layne Western No. 5 Metropolis well it apparently is more than 168 feet thick.

In the closely spaced Paducah Dam site borings in southeastern Massac County, the chert gravel ranges from 0 to 50 feet thick. The thicker sections of gravel occur where the bedrock surface is at a low elevation, and the gravel is absent in those borings where the bedrock is high. Distribution of the chert gravel appears to be controlled by pre-Gulfian topography.

Available evidence indicates that the present relief on the sub-Cretaceous surface throughout the Mississippi Embayment of southern Illinois is due to the combined effects of pre-Gulfian erosion, post-Gulfian solution, and possibly only minor deformation during and after Gulfian time.

DISTRIBUTION AND THICKNESS OF CRETACEOUS AND TERTIARY SEDIMENTS

The distribution and thickness of Cretaceous sediments, including the Little Bear Soil and the Tuscaloosa, McNairy, and Owl Creek Formations, are shown in Figure C-6. The Cretaceous sediments undoubtedly covered a much greater area in southern Illinois, but they have been eroded back to an area that is confined primarily to the south side of the Cache Valley. In general the Cretaceous sediments thicken from north to south.

The thickest Cretaceous deposits in Illinois are situated in southeastern Pulaski County in an area that generally corresponds to the America Graben of Ross (1963). The Cretaceous sediments here are about 300 feet thicker than in the surrounding area. It is not entirely clear whether these sediments filled a graben, a series of grabens, or a downwarped basin, all of which would have subsided during Gulfian time, or whether they filled a depression that existed on the sub-Cretaceous surface before the overlap of Cretaceous sediments. A combination of these factors may have influenced the thickness of the Cretaceous sediments. The structure contour map (Figure C-7) of the base of the Paleocene Clayton Formation (top of Cretaceous) indicates that the area underwent broad regional sinking in conjunction with the whole Mississippi Embayment area, but there is little or no evidence of localized post-Gulfian subsidence in southeastern Pulaski County.

In Massac and Pope Counties where the prominent grabens in the Paleozoic bedrock project into the embayment area from the northeast, the thickness of the Cretaceous does not appear to change abruptly. This again suggests that the movement on those structures took place before the Cretaceous sediments overlapped the area.

The Paleocene Porters Creek and Clayton Formations are confined to southern Pulaski and Alexander Counties (Figure C-7) and dip to the south at about 50 feet per mile. These formations thicken southward in the embayment trough.

AREAS OF DISTURBED CRETACEOUS AND POST-CRETACEOUS SEDIMENTS

All reported sites of suspected faulting (tectonic and gravity) in Cretaceous and post-Cretaceous sediments in the area were field checked, and a reconnaissance was made of areas where geologic mapping suggested possible faulting. The study was hindered by several problems. (1) Because of the unconsolidated nature of the sediments, surface expression of disturbances such as faulting would not be expected to last long after the initial movement. The effects of weathering and erosion would have masked most such features more than a few hundred years old. (2) Subsurface data are sparse and, even where available, not detailed enough to detect small offsets. (3) In some areas gravity-induced disturbances, such as landslides and solution collapse structures, can not be easily distinguished from tectonic faults. Solution collapse is probably common along bedrock faults (tectonic in origin) and joint systems that involve carbonate rocks. The sequence and time of events then becomes even more difficult to interpret.

Sites near Mounds, Round Knob, Post Creek Cutoff, Metropolis, and Thebes Gap (Figure C-2) were selected for detailed study. Field studies, exploratory drilling, earth resistivity, and refraction seismography were conducted at these sites.

STRUCTURAL HISTORY

The northeast-trending faults that displace Paleozoic rocks in the Illinois-Kentucky Fluorspar District extend southwestward beneath the Gulfian (upper Cretaceous) sediments of the Mississippi Embayment in southernmost Illinois. The relatively uniform thickness of the Cretaceous sediments and configuration of the base of the Cretaceous indicate that essentially all of the displacement on the faults in the underlying Paleozoic bedrock took place before the Cretaceous sediments overlapped the area. The faulting occurred sometime after mid-Pennsylvanian time because strata of this age are involved in the major displacements in the Fluorspar District. Although the hiatus between Pennsylvanian and Gulfian time is more than 100 million years, it is highly probable that the faulting occurred late in Paleozoic time concurrent with the intense tectonic activity of the Appalachian Orogeny, about 250 million years ago.

At no place can it be deomonstrated unequivocally at this time that faults of tectonic origin displace post-Paleozoic sediments. There is some suggestion of relatively minor deformation during and/or after Gulfian time in the areas of Thebes Gap, southeastern Pulaski County, Round Knob, and Metropolis, but the available evidence is too sparse and ambiguous to conclude that tectonic activity is the cause of these local disturbances.

During Gulfian and early Tertiary time southernmost Illinois underwent broad, regional subsidence as a result of downwarping within the Mississippi Embayment. The extent and magnitude of subsidence is shown in part on the structure map of the base of the Paleocene Clayton Formation (Figure C-7). The 35- to 40-million-year hiatus between Eocene and Pliocene-Pleistocene time does not appear to have been a time of intense or widespread deformation in southern Illinois. No offsets or disturbed zones have been observed in the

Pleistocene or Holocene sediments that can be attributed to tectonic faulting.

Earthquake epicenters within the Mississippi Embayment of southern Illinois in historic time appear to show no relationship to known faults. Where the numerous faults of the Illinois-Kentucky Fluorspar District project into the Mississippi Embayment of southern Illinois (Massac and Pope Counties) and adjacent parts of Kentucky (McCracken County), the pattern of seismicity is diffuse. Relative to the areas north (Wabash Valley) and south (New Madrid) of here, southernmost Illinois and western Kentucky have experienced less seismicity in historic time. Furthermore, there is no available geologic evidence to indicate that the fault complex that extends through Massac and Pope Counties is presently active. In southern Alexander and Pulaski Counties the intensities and numbers of historic earthquakes are somewhat greater than in Massac and Pope Counties, but again, there is no available evidence of recent movement on the interpreted faults that underlie Alexander and Pulaski Counties.

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Table C-1. Outcrops to supply data in compiling maps of sub-cretaceous geology, configuration of base of Cretaceous, and structure of base of Paleocene Clayton Formation (Figs. C-4, C-5, C-7).

	Location 1/4	1/4	1/4	1/4	Soc.	Twp.	Rng.	Paleozoic bedrock formation	Elev. of base of Cretaceous (ft, datum m.s.l.)	Elev. of base of Paleocene (ft, datum m.s.l.)
Alexander County										
a.	SW	SE	NE	NW	34	15S	3W	Thebes Sandstone Member of Scales Shale	~+400	
b.	NE	NW	SE	SE	28	15S	3W	Girardeau Limestone	~+400	
c.	SW	NW	SW	NE	28	15S	3W	Girardeau Limestone	~+400	
d.	NW	SW	SE	SW	21	15S	3W	St. Clair Limestone	~+400	
Pulaski County										
e.	SW	NE	NW	NE	13	15S	1E			+380
f.	NW	SW	SW	NE	13	15S	1E			+375
g.	SE	NW	SW	SW	13	15S	1E			+380
h.		SE	SE	NW	2	15S	2E	Salem Limestone	+310	

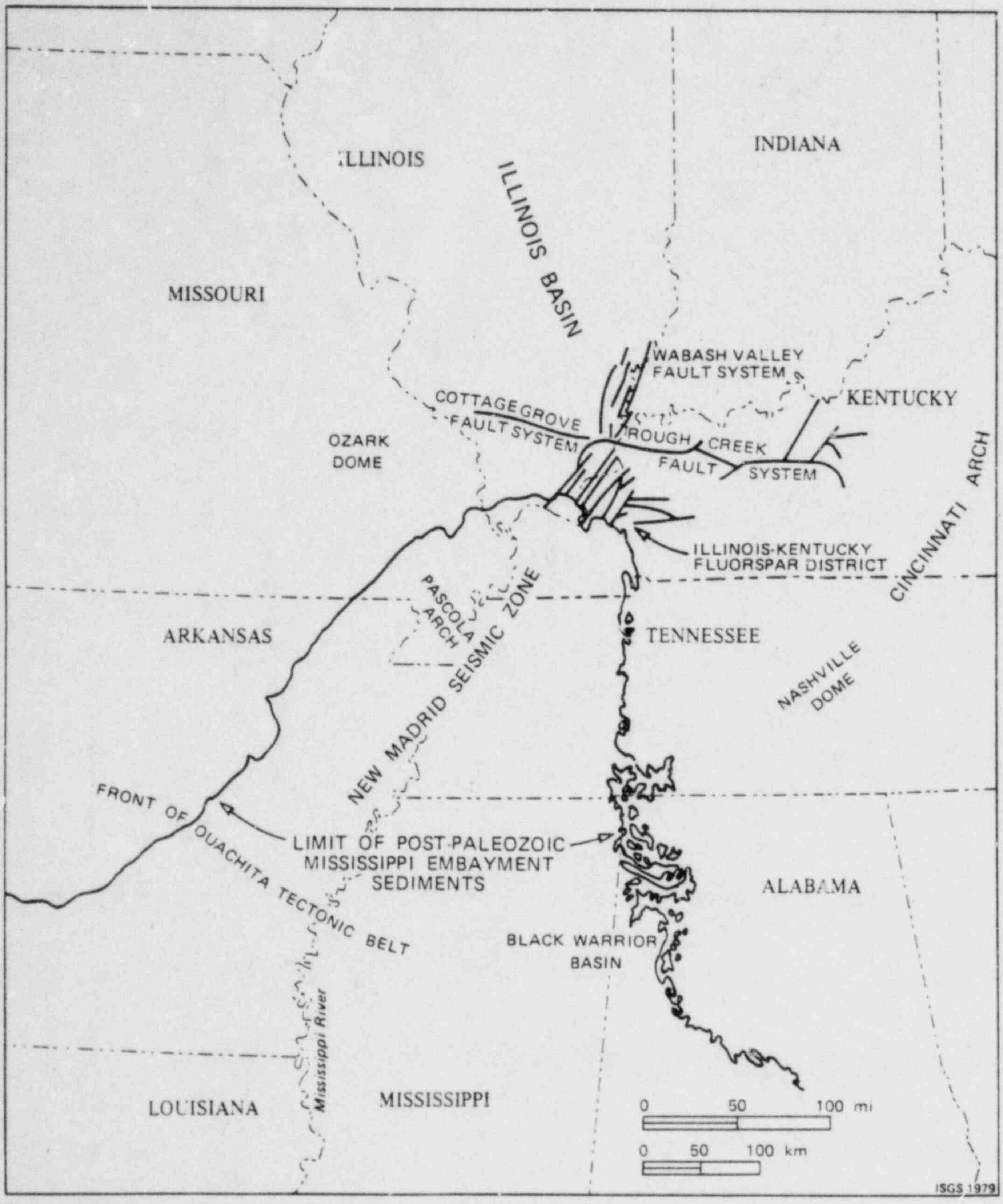

Figure C-1. Tectonic setting of the Mississippi Embayment area.

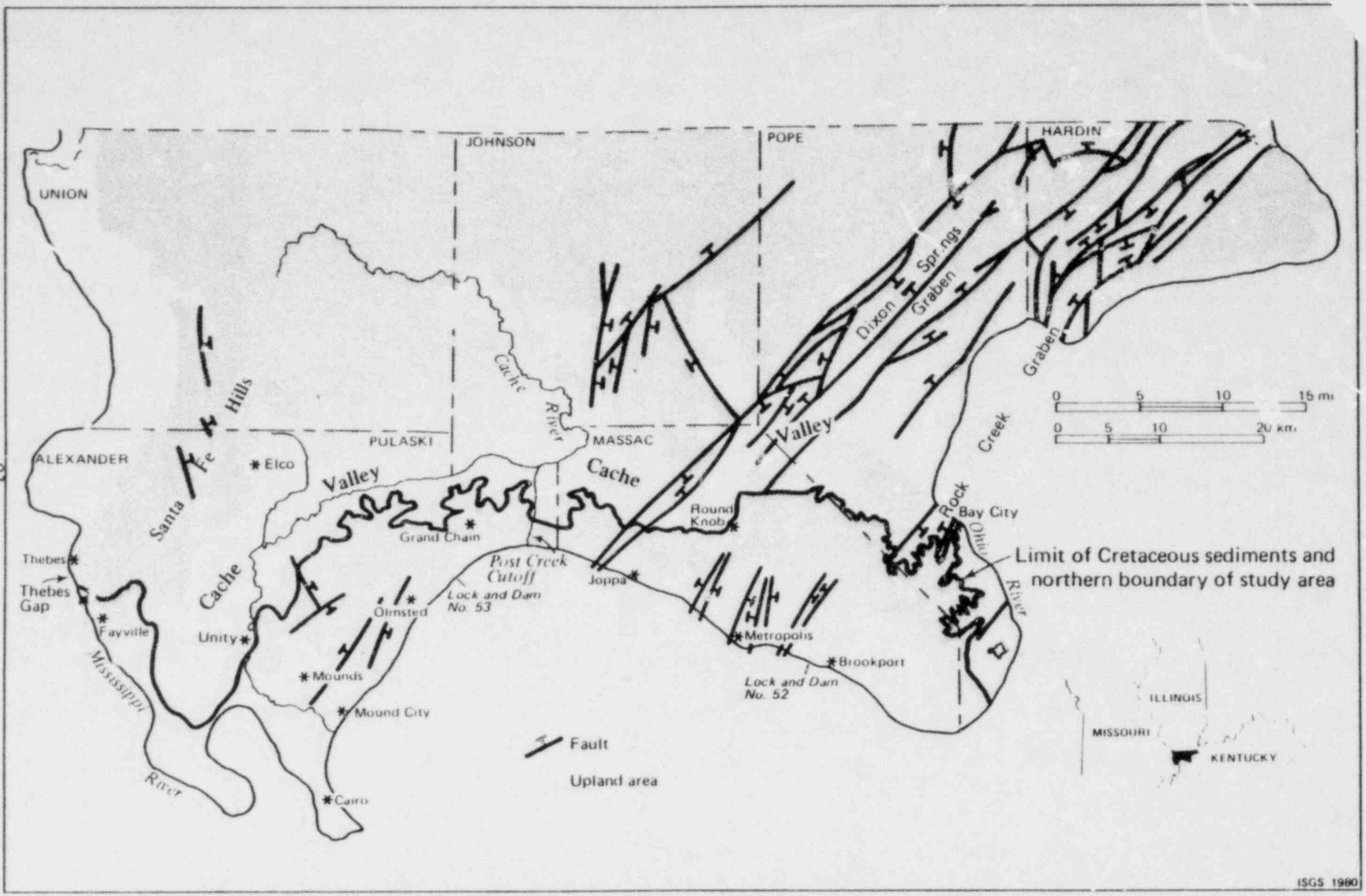

Figure C-2. Physiographic map of southernmost Illinois showing the major faults in the Paleozoic bedrock (faults north of the study area taken from Willman et al., 1967). Northern boundary of the study area is marked by the limit of Cretaceous sediments.

ERA	SYSTEM	SERIES	GROUP	FORMATION	GRAPHIC COLUMN	THICKNESS
CENOZOIC	QUATERNARY	PLEISTOCENE		Loess, alluvium, and colluvium		0-250
	TERTIARY-QUATERNARY	PLIOCENE-PLEISTOCENE		Mounds Gravel		0-50
	TERTIARY	EOCENE		Wilcox		0-250
		PALEOCENE		Porters Creek		0-150
				Clayton		0-20
MESOZOIC	CRETACEOUS	GULFIAN		Owl Creek		0-10
				McNairy (Levings Member)		25-455
				Tuscaloosa		0-170
PALEOZOIC	MISSISSIPPIAN	CHESTERIAN		Little Bear Soil*		0-10
				(formations not differentiated in this report)		1000
		VALMEYERAN		Ste. Genevieve		200-240
				St. Louis		350
				Salem		250-425
				Ullin		150-580
				Fort Payne		0-670
				Springville		5-50
		KINDERHOOKIAN		Chouteau		0-4
	DEVONIAN	UPPER	New Albany Shale			100-300
		MIDDLE		Alto-Lingle		0-50
				Grand Tower		0-80
		LOWER		Clear Creek		1200
				Backbone		
				Grassy Knob		
				Bailey		
	SILURIAN	? CAYUGAN ?		Moccasin Springs		200
		NIAGARAN		St. Clair		
		ALEXANDRIAN		Sexton Creek		5-90
				Edgewood		
	ORDOVICIAN	CINCINNATIAN		Girardeau		0-30
			Maquoketa Shale	Scales, Thebes Ss. Mbr.		100-300
				Cape		0-8
		CHAMPLAINIAN	Galena			100-150
			Platteville			550-650
			Ancell	Joachim		385
				Dutchtown		200
				St. Peter		100-150
				Everton		90-500
		CANADIAN	Prairie du Chien	Shakopee		3100-3300

* Soil developed on Paleozoic rocks that range in age from Ordovician to Mississippian.

ISGS 1980

Figure C-3. Generalized stratigraphic column of southernmost Illinois (Cambrian section not shown).

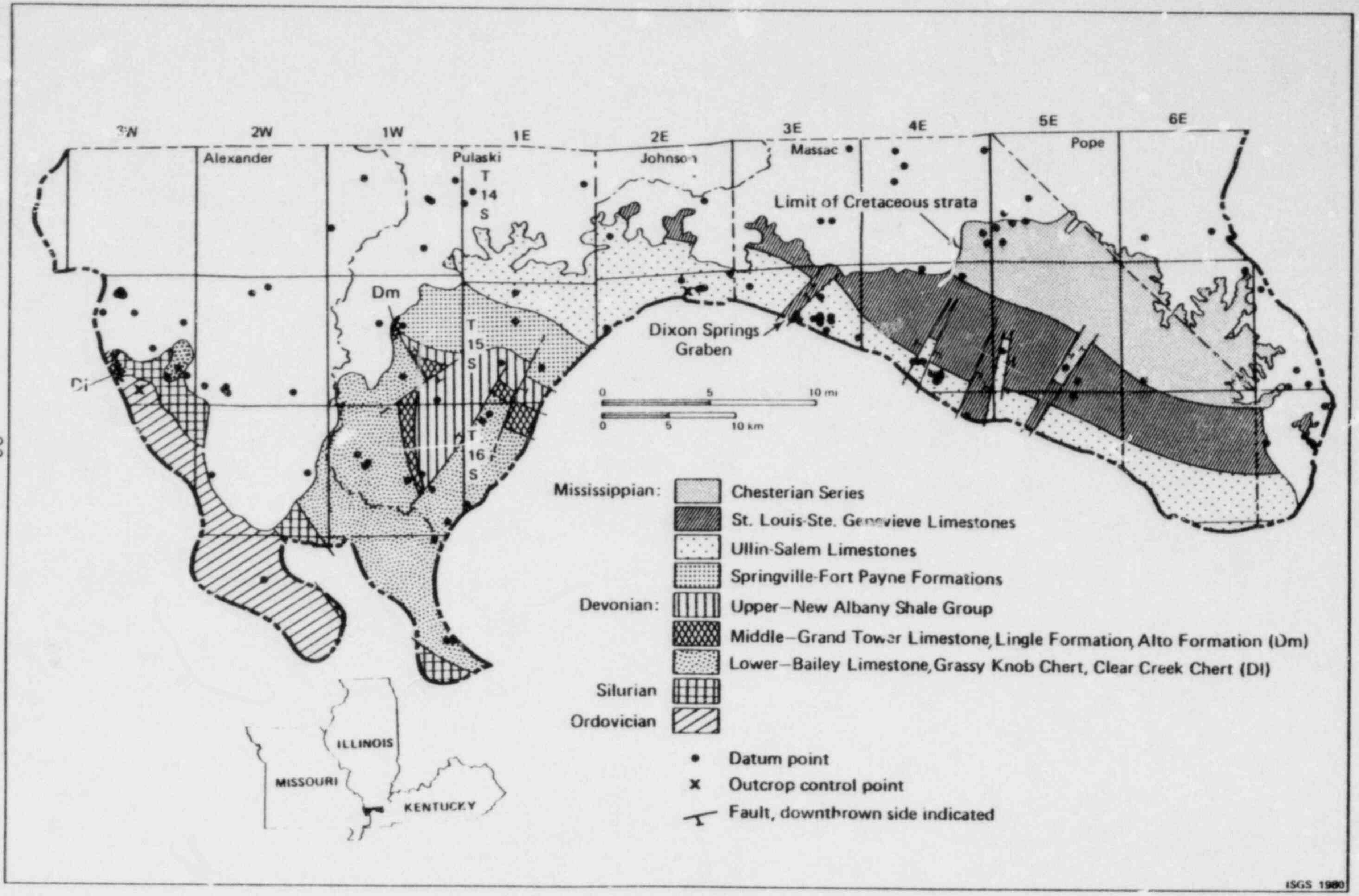

Figure C-4. Geologic map showing the sub-Cretaceous strata.

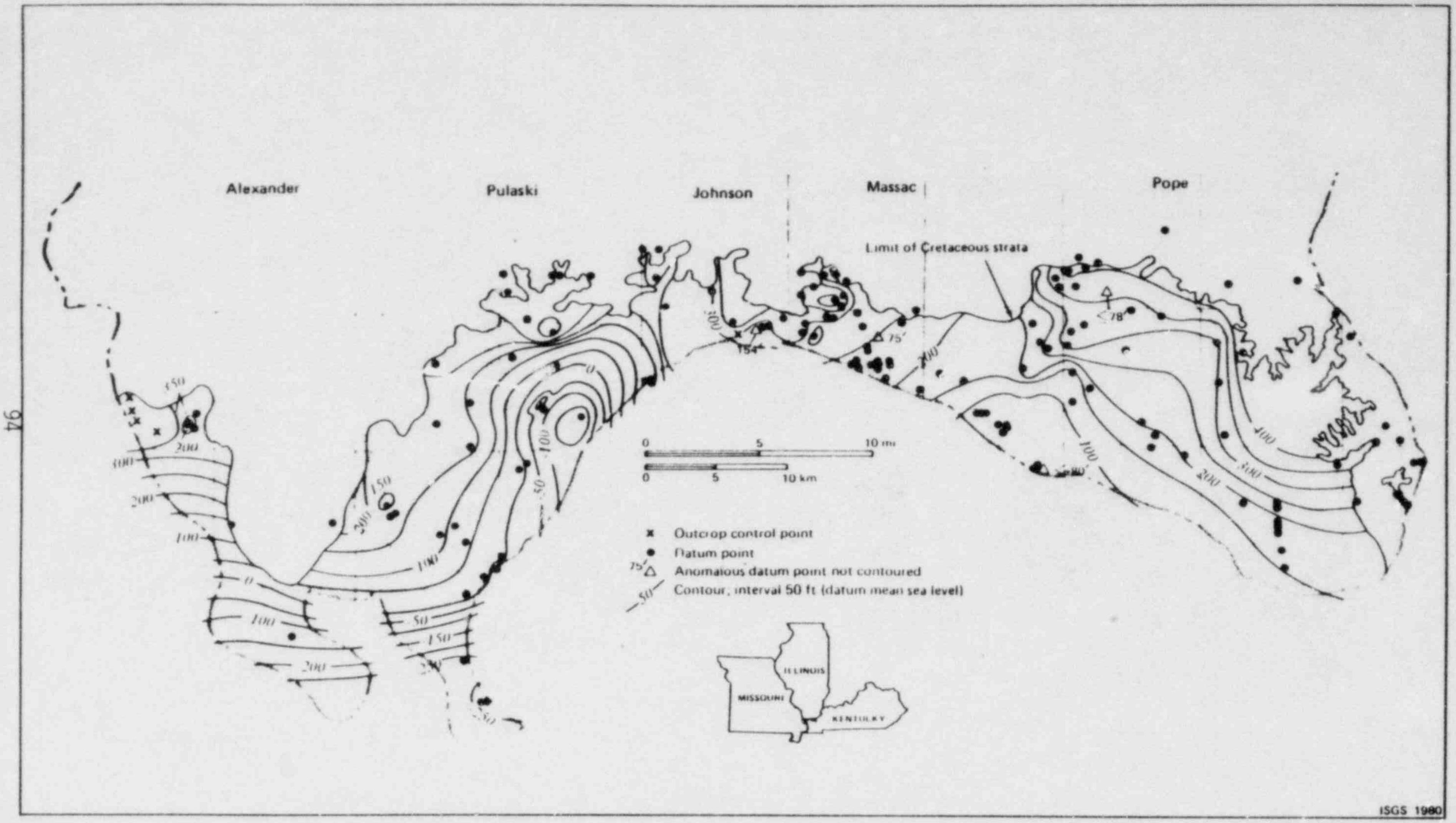

Figure C-5. Configuration of the base of the Cretaceous System.

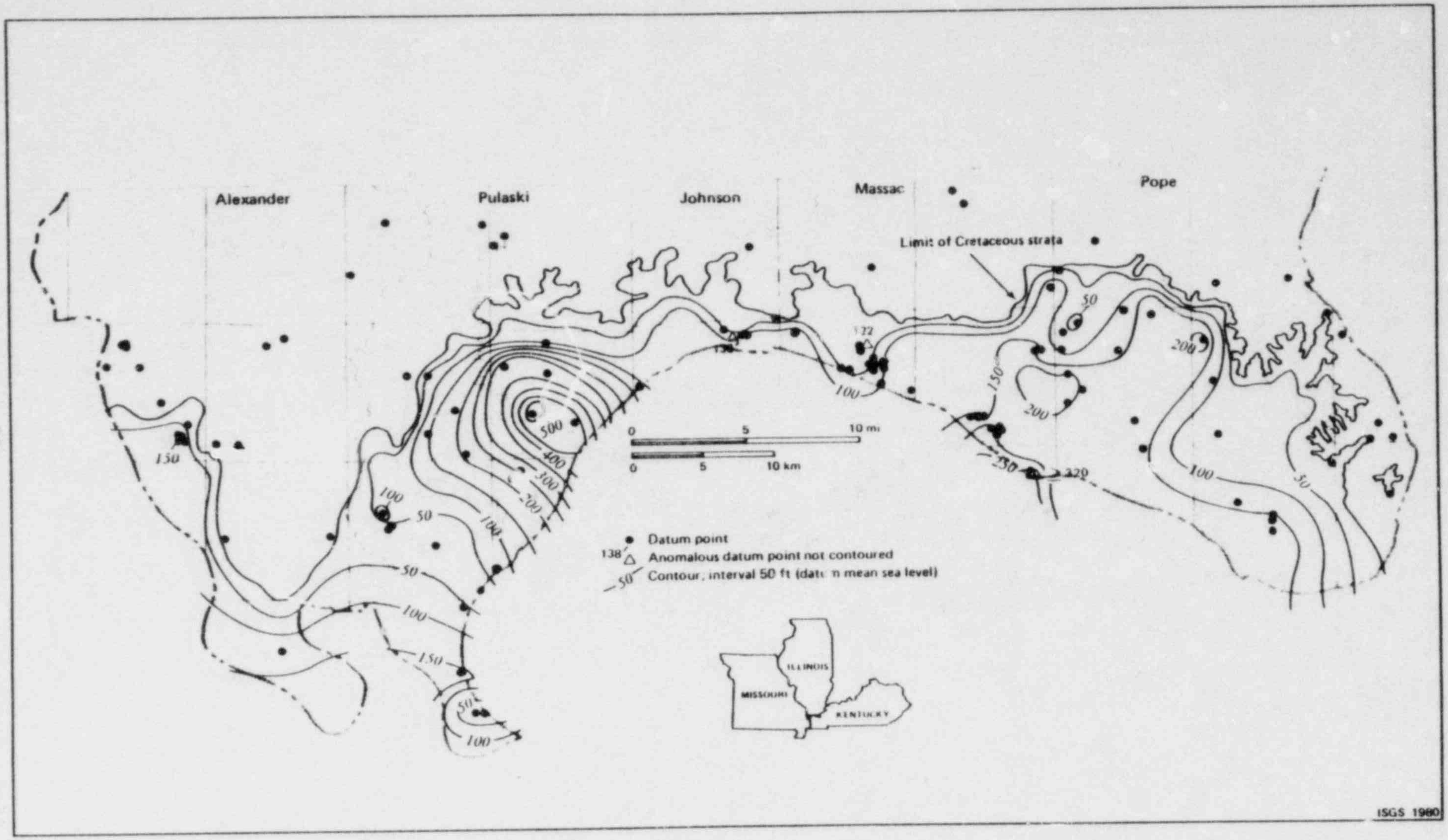

Figure C-6. Distribution and thickness of Cretaceous strata.

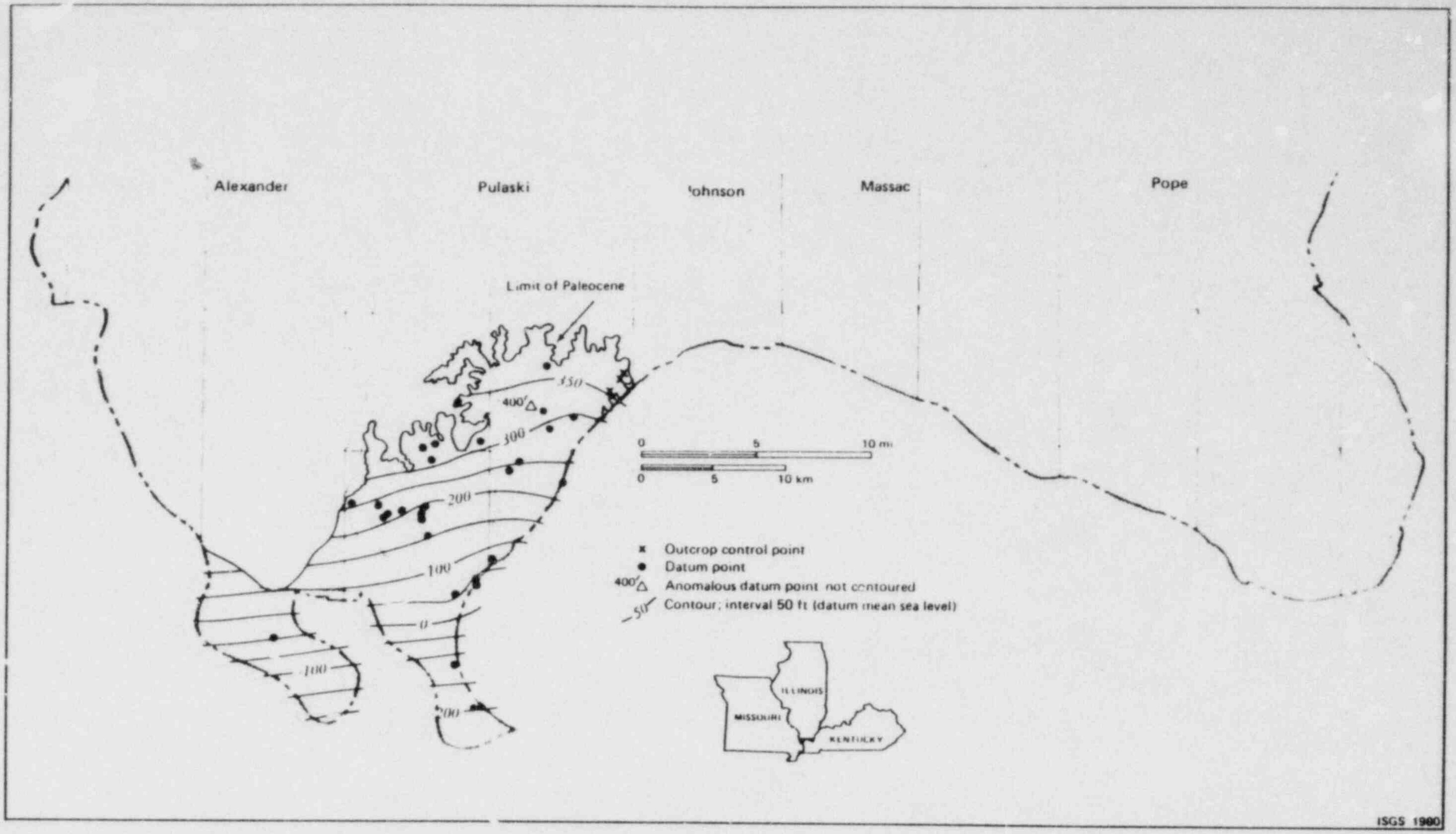

Figure C-7. Structure of the base of the Paleocene Clayton Formation.

NEAR SURFACE GEOLOGY OF THE REELFOOT LAKE DISTRICT OF NEW MADRID EARTHQUAKE REGION

Annual Progress Report - Fiscal Year 1980

Contract No. NRC-04-76-299

Richard G. Stearns
Vanderbilt University

ABSTRACT

The main effort this year was gravity surveying, and analysis of gravity and magnetic data. Five reports were prepared, one of which (NUREG/CR-1501) was published. Others are attached to copies of the first quarter and this annual report. Two gravity maps were prepared for publication, and are in press now. Gravity anomalies relate not only to the large density contrasts between Paleozoic rock and Embayment fill about 2000 feet below the land surface, but also to shallow features including both faults and old Mississippi River channels. Closely spaced (500 feet apart) ground magnetic stations provide evidence of shallow plutons, perhaps within 700 feet or less of the land surface. It is likely that a previously unknown post-Eocene fault zone at the edge of the Reelfoot Rift has been precisely located by means of detailed gravity surveys supplemented by earth resistivity.

TECHNICAL SUMMARY

The main effort this year was gravity surveying, and analysis of gravity and magnetic data. Five reports were prepared, one of which (NUREG/CR-1501) was published. One was attached to the first quarter report, and three are attached to this annual report. Two gravity maps were prepared for publication, and are in press now. Gravity anomalies relate not only to the large density contrasts between Paleozoic rock and Embayment fill about 2000 feet below the land surface, but also to shallow features including both faults and old Mississippi River channels. Closely spaced (500 feet apart) ground magnetic stations provide evidence of shallow plutons, perhaps within 700 feet or less of the land surface. It is likely that a previously unknown post-Eocene fault zone at the edge of the Reelfoot Rift has been approximately located by means of detailed gravity surveys, and we hope to precisely locate it by earth resistivity. Cuttings from oil test holes in the study area have all been logged this year, and descriptions have been furnished to other researchers and placed on open file at the Tennessee Division of Geology.

Vanderbilt personnel were the investigator, one graduate student and three undergraduate students. H.B. Burwell, a consultant, logged oil test well cuttings, and Terry Templeton, of Tennessee Division of Geology, is co-author of the west Tennessee regional gravity map.

Plans for continued investigation include earth resistivity surveys and drilling or trenching of likely fault sites, particularly the site at the edge of the rift. Also, reports in progress will require editing and revision for possible publication.

GENERAL

Main effort this year was geophysical surveying, analysis of data and preparation of maps and reports. Five reports were prepared in draft form, one was published (NUREG/CR-1501). Two are attached to this report as appendices. Two gravity maps were prepared for publication and were processed to final corrections of the publication negatives (Appendix D-1).

The most detailed gravity maps relate to near surface faults and Mississippi River channels. Ground magnetic data indicate plutons very close to the land surface (700 feet or less deep). Figure D-1 shows gravity anomalies having a shallow origin.

GRAVITY

Most effort was concentrated on gravity. Throughout the project since its beginning in 1976, this has been an important tool in exploring for faults. Most of any local anomaly comes from the density contrast between Paleozoic rock and Embayment fill, but shallower fault-related and channel-related density contrasts are detectable (Figure D-1).

Publication of Regional Gravity

The regional map of Tennessee west of 88° (scale 1:250,000) has been in process of publication throughout the year. It was compiled the first quarter and final editorial corrections were made in May. This map should be made ready for distribution by the Tennessee Division of Geology soon.

Publication of Detailed Gravity

A detailed gravity map of northwesternmost Tennessee and a small area of Missouri near the river (scale 1:62,500, contour interval ½ milligal, station spacing about 1 mile) was delivered for publication and editorial revisions were made in June. This map should also be ready for distribution by the Tennessee Division of Geology soon.

Report on Microgravity

A report on high precision gravity survey of the Reelfoot scarp has been prepared as a draft. A copy is attached. This survey demonstrates that gravity is a useful tool for shallow features (within 300 feet of the land surface). Figure D-1 shows relatively small anomalies owing to structure, a river channel, and possibly a sand dike.

Extension of Detailed Gravity to East Edge of Rift

Detailed gravity surveys were extended south of 36° 00' to the east edge of the Reelfoot Rift, and to the north side of the Covington anomaly. Sharon Wilson, an undergraduate assistant, used this data for an independent study course project. Her report is attached (see Appendix D-2) to show what can be done with detailed gravity data. Earth resistivity surveys will be made in the next quarter to test the hypothesis that narrow second derivative anomalies indicate faults that extend to the surface (see Figure D-2).

MAGNETICS

A ground magnetic survey across the Reelfoot Scarp provides evidence (Figure D-3) of shallow plutons in this faulted area. Lee Hagee, graduate assistant, did the survey and analysis. A pluton may well extend to within 700 feet or less of the land surface. Multiple intrusions are likely. A draft of Hagee's report is attached to this annual report as Appendix D-3.

DRILLING AND LOGGING SAMPLES

A paper on drilling the Reelfoot Scarp was presented at Midwest AGU in September, 1979 and a report published as NUREG Document (NUREG/CR-1501). H. B. Burwell, our consultant, finished logging samples of oil test wells in the study area. These have been sent to other workers, and they are on file at Tennessee Division of Geology.

PERSONNEL

Susan Towe finished her thesis (a draft copy was attached to the first quarter report) while employed elsewhere as a geophysicist. Virginia Lee Hagee continued as graduate assistant. Susan Nava, Mike Shea, and Sharon Wilson were undergraduate assistants. Terry Templeton of Tennessee Division of Geology is a co-author of the regional gravity map of West Tennessee.

PLANS FOR CONTINUED WORK

Earth resistivity will be used as a tool to test the hypothesis that faulting extends to the surface at the edge of the rift. Drilling will be used to attempt to verify any apparent near-surface faults. Reports will be revised and edited for possible publication. Stearns plans to contribute structural data to help develop regional maps of Cretaceous and younger structure.

APPENDIX D-1

PUBLICATIONS AND REPORTS THAT WERE PREPARED OR EDITED THIS YEAR

Publications

"Monoclinal structure and shallow faulting of the Reelfoot Scarp as estimated from drill holes with variable spacings" NUREG/CR-1501, 37 p. by R.G. Stearns.

"Structure and old river channels from shallow drill holes in the Reelfoot Lake Area, Tennessee" Abstract S-11, Midwest AGU Meeting, September 1979, Columbus, Ohio, by R.G. Stearns.

"Gravity survey of a part of the east boundary of the Reelfoot Rift, Dyer and Lauderdale Counties, Tennessee" Abstract, Tennessee Academy of Science Meeting November 1979, Nashville, Tennessee, by R.G. Stearns, V.L. Hagee, S.J. Nava, and S.L. Wilson.

Draft Maps (in Process of Publication)

"Gravity anomaly map of West Tennessee," scale 1:250,000 by R.G. Stearns, J.R. Keller, and T. Templeton, (in press, Tennessee Division of Geology).

"Gravity anomaly map of the Reelfoot Lake area, Tennessee" scale 1:62,500 by R.G. Stearns, (in press, Tennessee Division of Geology).

Draft Reports

"Gravity modeling and geologic interpretation of the Tiptonville dome, northwest Tennessee" draft of M.S. thesis Vanderbilt University, 117 p. September 1979, by Susan K. Towe. This was attached to the first quarter report.

"Microgravity, old Mississippi River channels, and shallow faults at Reelfoot Scarp, Lake County, Tennessee," Draft report, 73 p., (June 1980 by R.G. Stearns).

"Residual and second derivative mapping techniques as applied to a possible fault zone in the Ripley South quadrangle, Lauderdale County, Tennessee." Report for independent study course Vanderbilt University, 16 p., July 1980, by Sharon Wilson (Appendix D-2 of this annual report).

"Ground magnetic survey of the Reelfoot Lake region of northwestern Tennessee," Draft report, 20 p., June 1980, by V. Lee Hagee (Appendix D-3 of this annual report).

APPENDIX D-2

RESIDUAL AND SECOND DERIVATIVE MAPPING TECHNIQUES AS APPLIED TO A POSSIBLE FAULT ZONE IN THE RIPLEY SOUTH QUADRANGLE, LAUDERDALE CO., TN.

Sharon Wilson
Department of Geology
Vanderbilt University

INTRODUCTION

For the past several years Dr. Richard G. Stearns of Vanderbilt University has been conducting a gravity survey in West Tennessee to study earthquake features related to the New Madrid Fault System. Several regional gravity maps have been produced showing the general gravity of the area. The most recent maps were generated during the summer of 1979 and cover the area shown in Figure DA2-1. Several interesting anomalies were discovered in this area. Of particular interest was a strong linear trend in the Ripley South gravity map running approximately parallel to, and in the area of, the New Madrid Rift Zone as proposed by Hildenbrand and others in 1977 (Figure DA2-2). This anomaly is thought by Dr. Stearns to be a possible fault zone due to its linearity and location. AS the regional gravity of this area is strongly dominated by the effects of the Covington pluton, it was decided to use filtering techniques to resolve the actual field generated by this feature so that it could be modeled.

PROCEDURES

Two methods were chosen to filter the gravity data: the residual gravity and the second derivative of gravity. Residual gravity removes a gradient, or regional trend, in the original gravity field. Figure DA2-3 shows a two dimensional example of this. The curve, F(x), represents an original gravity profile. The line, Y_1, is the regional trend of this profile. Removing it leaves Y_2 as the residual gravity of the anomalies in the original field. The second derivative of gravity gives a measure of the curvature of the gravity field. Figure DA2-4 shows a two dimensional example of this. The curve, F (x), is the original gravity profile. Curve F" (x) is the second derivative of this profile, found here by simple differentiation of the equation for the profile.

In contour mapping, the residual can be found by either graphical or analytical methods. The graphical method involves smoothing the contours by hand to represent what the observer feels is the regional trend. From the smoothed contours, new values are interpolated for the original stations. These new values are substracted from the old to give the residual value. This value is contoured to produce the residual gravity map (Dobrin, 1976, p. 437-439). This method relies heavily on the judgement and experience of the observer in determining how much of the observed field is due to regional effects and how much of it is to be removed. Thus, it is subject to bias. On the other hand, the analytical method is not as subject to bias and is more precise. It is the method I chose to use for this report.

In the analytical method, the original gravity data must be interpolated to fit an evenly spaced grid of points. This interpolation is a source of some bias. From such a grid, the residual gravity of a grid point is the difference between the value at that point and the average of all values on a circle around that point. The grid spacing must be chosen such that an anomaly is adequately covered by this circle of average values, without including too much of the effects of other features. For the Ripley South Quadrangle, I used a grid cell spacing of 1 mile, expressed in kilofeet for later modeling.

Like the residual, the second derivative requires that the data be interpolated to fit an evenly spaced grid. The approximate equations for the residual and the second derivative are quite similar. In fact, for a circle of radius s, the residual divided by s^2 is directly proportional to the second derivative. These equations differ only by a factor of $4/r^2$. Thus, the shape of the contours of a residual map and a second derivative map will be approximately the same. The high/low values will differ in magnitude, but they will be in about the same places (Nettleton, 1976, p. 175-177: Dobrin, 1976, p. 447-448).

CONCLUSIONS

When both of these methods are applied to the gravity of Ripley South, some interesting features are resolved. Most are shallow, rounded highs and lows that do not appear to relate much to the original field and are not considered important. The linear trend in the original map, however, is resolved as a distinct narrow high in both maps (Figures DA2-5 and DA2-6).

The steepness and straightness of this high strengthens the assumption that this feature is a fault zone at depth. Hopefully, later this year, a series of test holes will be drilled to test this assumption. If it is a fault zone, it could well be related to Hildenbrand's rift zone, if not a part of the edge of the rift itself.

The second derivative and residual gravity methods are perhaps not as precise as more complex filtering techniques, but they are a useful indicator of what the real effects of anomalies are. As such, they allow a more precise determination of the origins of anomalies through modeling and give a better idea of where to locate future surveys to study these features than the original maps might.

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APPENDIX D-3

GROUND MAGNETIC SURVEY OF THE REELFOOT LAKE REGION OF NORTHWESTERN TENNESSEE

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Department of Geology
Vanderbilt University

INTRODUCTION

Extensive and detailed ground gravity surveying by Dr. R. G. Stearns and his students prior to 1978 in the Reelfoot Lake region of northwestern Tennessee provided a detailed gravity map of the region which was used to try to model the subsurface structural features of the area over the Reelfoot scarp (Towe, 1979). At the time the only magnetic data available for the region was the U.S.G.S. gridded aeromagnetic data. Gridding of data removes much detail and, in most cases, gridded points do not correspond to actual observation locations. For comparing gravity and magnetics, closely spaced, accurately located data is necessary. Therefore, in conjunction with the gravity sruvey program, a smaller gound magnetics survey was undertaken in the immediate vicinity of Reelfoot Lake (Figure DA3-1).

PURPOSES

It was the aim of this survey to ascertain whether magnetic data could be related to gravity data. Since gravity data can be correlated with faults, it was hoped that magnetic data could also be successfully utilized for fault studies. It was hoped that we could make some interpretations of the subsurface geology using the combined gravity and magnetic data. Another major objective was to determine whether there were any features (such as dikes or plutons) that were not obvious on the gravity maps.

FIELD WORK

The survey was cond[illegible] in February and March of 1978 using a Sharpe MF-1-100, a portable fluxgate magnetometer. The main survey consisted of five traverses, three across the bluffs to the east of Reelfoot Lake and two to the west of the lake. These latter two traverses cross the Reelfoot scarp and represent the data of particular interest in this paper. The survey was run along existing gravity lines and measured the vertical component of of the local magnetic field only. These survey lines consisted of seventy three magnetic stations at approximately tenth of a mile intervals. These lines are shown in Figure DA3-2. Base stations were reoccupied approximately every twenty minutes to ensure accuracy. In addition, when feasible, a tripod was used with the instrument during observations to increase accuracy; however, in most instances, the nature of the terrain made this impractical. For most readings, therefore, the magnetometer was hand-held. This did not seem to seriously impair the accuracy of the survey.

DATA REDUCTION AND ANALYSIS

Reduction of Data

The data were corrected for instrument drift and diurnal variations simultaneously. Base station 01-01 was the primary base station with all other secondary bases tied to it. Station 01-01 was established as an arbitrary datum and reduced to zero. All secondary bases and their associated stations were then reduced to the arbitrary datum. The resulting data constituted the observed magnetic values then used for further analysis.

Analysis

The observed magnetics were analyzed in several ways. Initial analysis was statistical in nature. The analysis was designed to determine the approximate amount of error in the survey by a determination of standard deviations. The standard deviations varied from 1.41 to 10.73. It can be assumed that the observed magnetics probably lie within an average range of 7.39 gammas of the actual magnetics or within a maximum range of 10.73 gammas.

Residual Anomalies

In order to eliminate the regional magnetic gradient from the data a linear regression of the data along each line was calculated. These regressions are shown as dashed lines in Figures DA3-3 and DA3-4. By removing these values from the observed magnetics, it is possible to study only the anomalies in the local magnetic field. Graphic representations of the data sets are shown in Figures DA3-5 and DA3-6. As can be seen in the figures there are apparent anomalies with amplitudes of up to approximately 70 to 80 gammas. Even using the maximum standard deviation value, these large anomalies persist. This indicates that they are indeed due to anomalous subsurface structures. In addition, the narrow width of these anomalies (generally two to three kilofeet) implies that these features are at relatively shallow depths.

MODELING

General

Several attempts to model the magnetic anomalies encountered in this study have been made. There have been two approaches to this modeling. Initially, an attempt was made to simply model individual anomalies independently. This procedure was used primarily to approximate the large anomaly found on the southern traverse. This can be seen at about 8 to 10 kilofeet distance in Figure DA3-5. Later evaluation of the data included attempts to approximate the entire line using multiple body models.

Initial Depth Estimates

During the initial modeling two depth estimation methods were utilized. Peter's quick depth estimate method yielded a depth of approximately 0.960 kilofeet, while the half-slope method gave a depth of only 0.625 kilofeet.

Standard Geometric Models

Calculations showed that an anomaly of this width and this magnitude could not be caused by variations in the unconsolidated sediments and rock known in the region. It was assumed that the anomaly could be the result of an igneous mass intruded into the subsurface sediments. Igneous intrusions, such as dikes, are well known in areas of western Kentucky and southeastern Missouri, near the study area. For purposes of modeling, it was assumed that the anomalous feature was an igneous intrusion of basaltic or diabasic composition. A magnetic susceptibility of 0.000600 at H = 0.6 Oe was used.

Three models closely approximated the observed anomaly. These models were hand-calculated using standard formulae (Dobrin, 1976). The first was a vertical plate 0.700 kilofeet thick with a depth to top of 0.700 kilofeet and a depth to bottom of 2.000 kilofeet. The second was a horizontal cylinder at a depth to center of 1.000 kilofeet and a radius of 0.450 kilofeet. The third model that closely approximated the anomaly was a sphere with a depth to center of 0.)0 kilofeet and a radius of 0.500 kilofeet.

Computer Models

More recent attempts to model the magnetic data have been oriented toward modeling entire lines of magnetic data rather than individual features. This demands the use of a computer modeling program. For this procedure I used GRAVMAG, a two-dimensional gravity and magnetics modeling program originally based on a program by J. W. Cady. This program was first modified by J. F. Baxter, Jr., of Stanford University and, more recently, I included further modifications. GRAVMAG will generate two-dimensional gravity and magnetic data for multiple body models.

The residual magnetics (Figures DA3-5 and DA3-6) show a series of small anomalies, generally with a width of two to three kilofeet. These anomalies, with a few exceptions, have roughly similar widths and amplitudes. This would seem to suggest that there exists a group of similar features (such as a dike swarm) at approximately the same depth in the subsurface. In addition, there appears to be four large anomalies. Two of these are high, narrow anomalies, and two are high, wide anomalies. These anomalies appear to represent single, independent features not related to the previous group.

To facilitate the comparisons of the observed data and the models, a graph showing the full range of values (observed magnetic values plus or minus one standard deviation) was utilized (Figures DA3-7 and DA3-8). Multiple body models were generated by GRAVMAG, graphed, then compared with the residual magnetics.

At this point, no models have been found which completely satisfy the data. However, one thing has become apparent. Due to the summation of magnetic values in areas where the influence of individual anomalies overlaps, the observed values tend to be somewhat higher than would be expected if either anomaly was isolated. Although this does not seem to affect the peak values to any extent, it does greatly modify values at the edges of individual anomaly curves. Thus, it seems likely that, if the individual anomalies were isolated, the features would be somewhat narrower. This would seem to suggest that the subsurface structure responsible is actually at a shallower depth than originally anticipated.

ADDITIONAL RESEARCH

The large anomaly on the southern traverse would have to be caused by a fairly shallow body of igneous material. It seemed reasonable to assume that this body, if real, would be apparent in a closely spaced gravity survey. Therefore, in June 1980 I returned to the study area to collect gravity data for the immediate area over the anomaly. The survey consisted of a line of readings at one tenth of a mile intervals about fifty feet south of the magnetic line. The survey utilized a Worden "Prospector" gravitimeter. When the data had been reduced, the Bouguer anomaly did indeed show a small peak in the data that appears to correspond in location with the magnetic anomaly.

CONCLUSIONS

The work done on magnetics in the Reelfoot Lake region has had several results. Based on the findings of this survey, it appears that magnetics cannot be successfully utilized for fault studies. At least in this region, magnetic surveying has shown no correlation to known or assumed faults. It can also be said on the basis of this study that correlation between gravity and magnetic data is strictly dependent on the nature of the subsurface materials causing anomalies in the first place. Only a situation in which there is both a density contrast and a difference in magnetic susceptibilities between the materials involved would be expected to present related gravity and magnetic anomalies. In the case of the faults in the region, there is simply not enough variation of magnetic susceptibilities on either side of the fault to produce an apparent magnetic anomaly.

The most important information gleaned from this survey is really twofold. The data show that magnetics can be used to locate features that were not obvious on the gravity maps. In addition, the data showed that there were, indeed, features not previously recognized in the northwestern corner of Tennessee.

The magnetic data suggest the existence of igneous intrusions about the Paleozoic boundary in this region. Since shallow igneous intrusions are known from adjacent regions of Missouri and Kentucky, this interpretation does not seem entirely unreasonable. Depth estimates and modeling on the largest anomaly in the data place the feature in the Eocene or possibly post-Eocene rock. Most of the anomalies, however, are probably the result of somewhat deeper features.

ACKNOWLEDGMENTS

I would like to acknowledge G. Boyd Sexton for his part in the original field work and anlysis for this project and Dr. C. Roanld Seeger of Western Kentucky University for the loan of equipment and for helpful discussions. I would also like to thank Dr. R. G. Stearns for his suggestions and R. W. Ridd, Jr., for his help in the field in the latter stages of this study. Financial support was provided by the U.S. Nuclear Regulatory Commission under Contract NRC-04-76-299.

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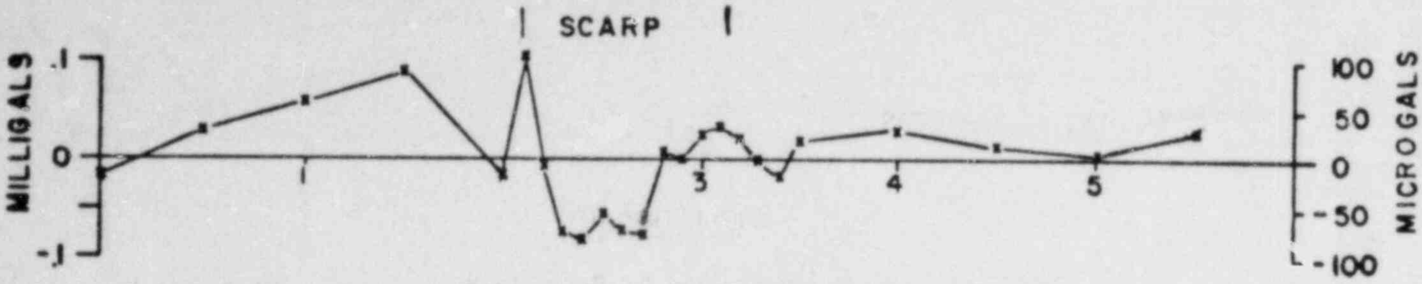


Fig. D-1. A microgravity profile across Reelfoot scarp. The horizontal axis is in kilofeet. A negative anomaly characterizes the left (upper) side of the scarp from 1.5 to 2.7 kilofeet, and a positive anomaly marks a sand filled grabben from about 2.7 to 3.5. The negative anomaly is accentuated and the positive one is reduced by a Mississippi River clay-filled channel centering at about 3 kilofeet.

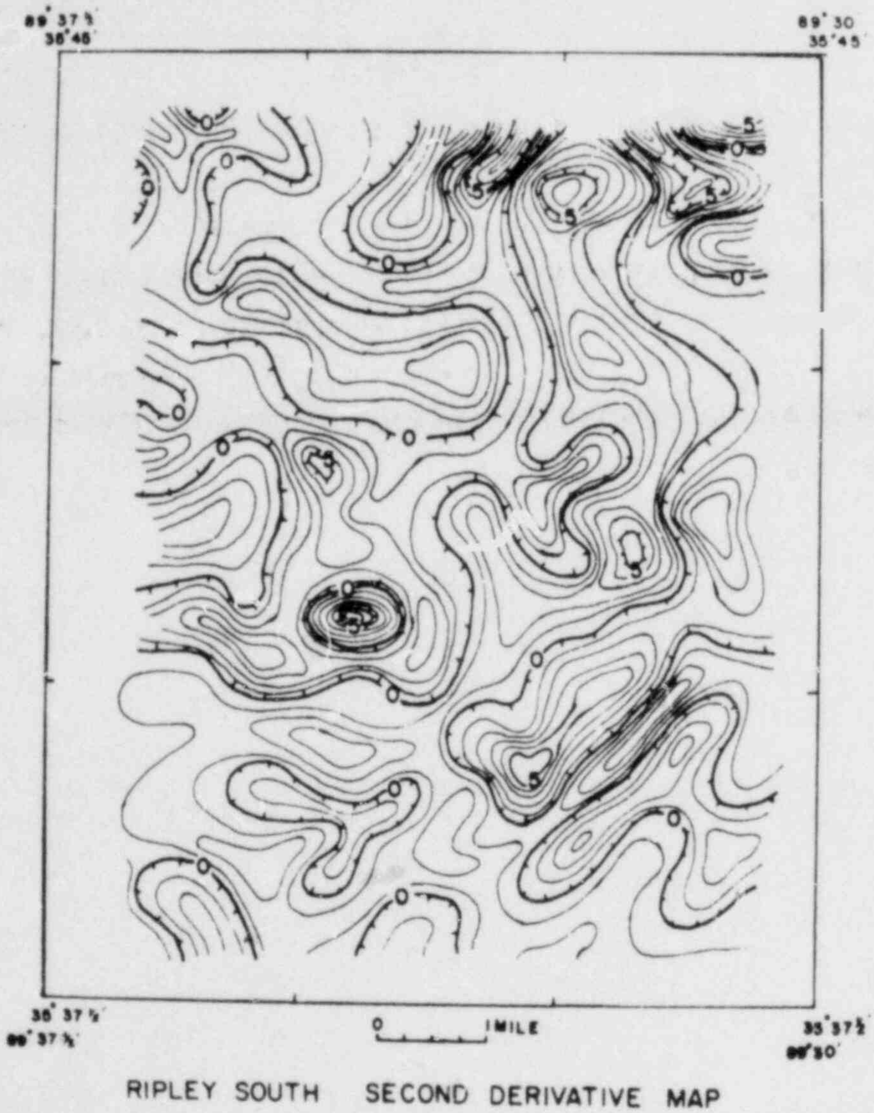


Fig. D-2. Second derivative of the Bouguer gravity anomaly. The northeast-southwest trend in the southeast corner of the map is thought likely to mainly reflect density contrasts along faults cutting the Paleozoic-Cretaceous boundary about 2500 feet below the land surface.

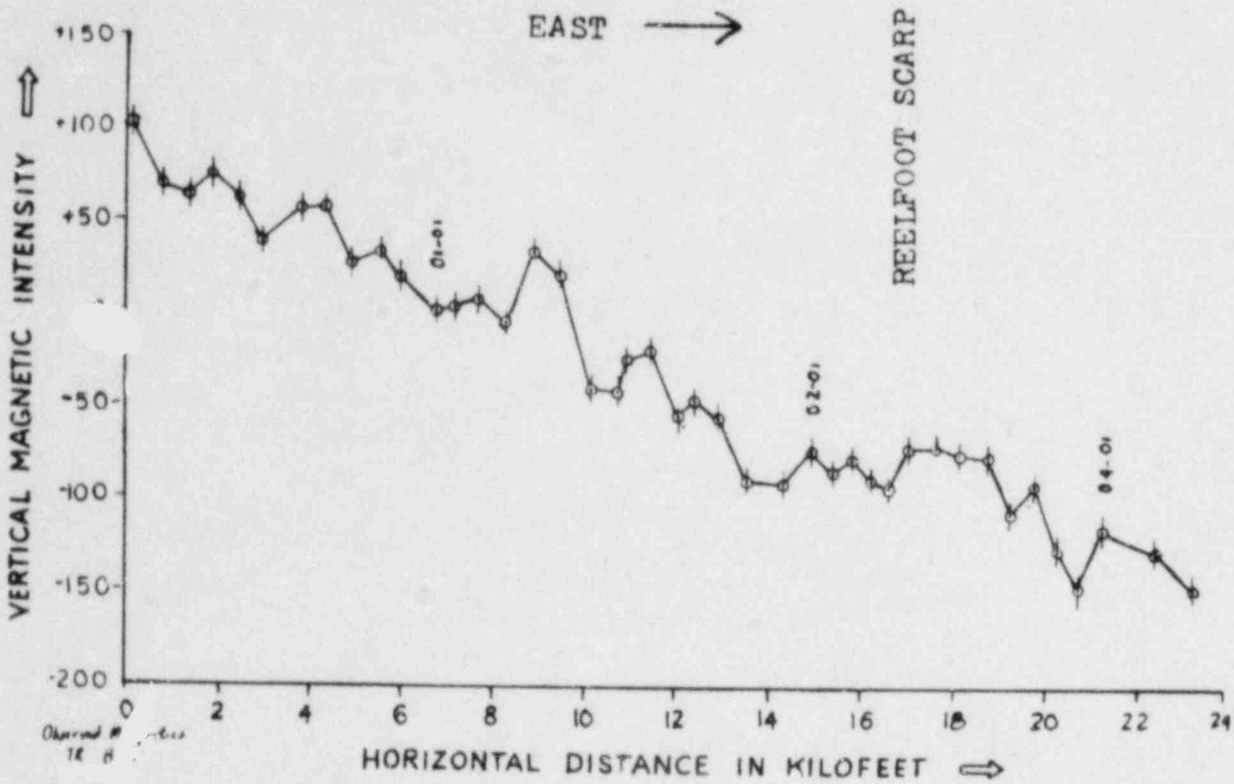


Fig. D-3. Vertical magnetic intensity on an east-west profile across Reelfoot Scarp. The short vertical bars are one standard deviation above and below the survey value. The 50 gamma positive anomaly at about 9 kilofeet is believed likely to have originated from a shallow pluton (see Appendix D-3).

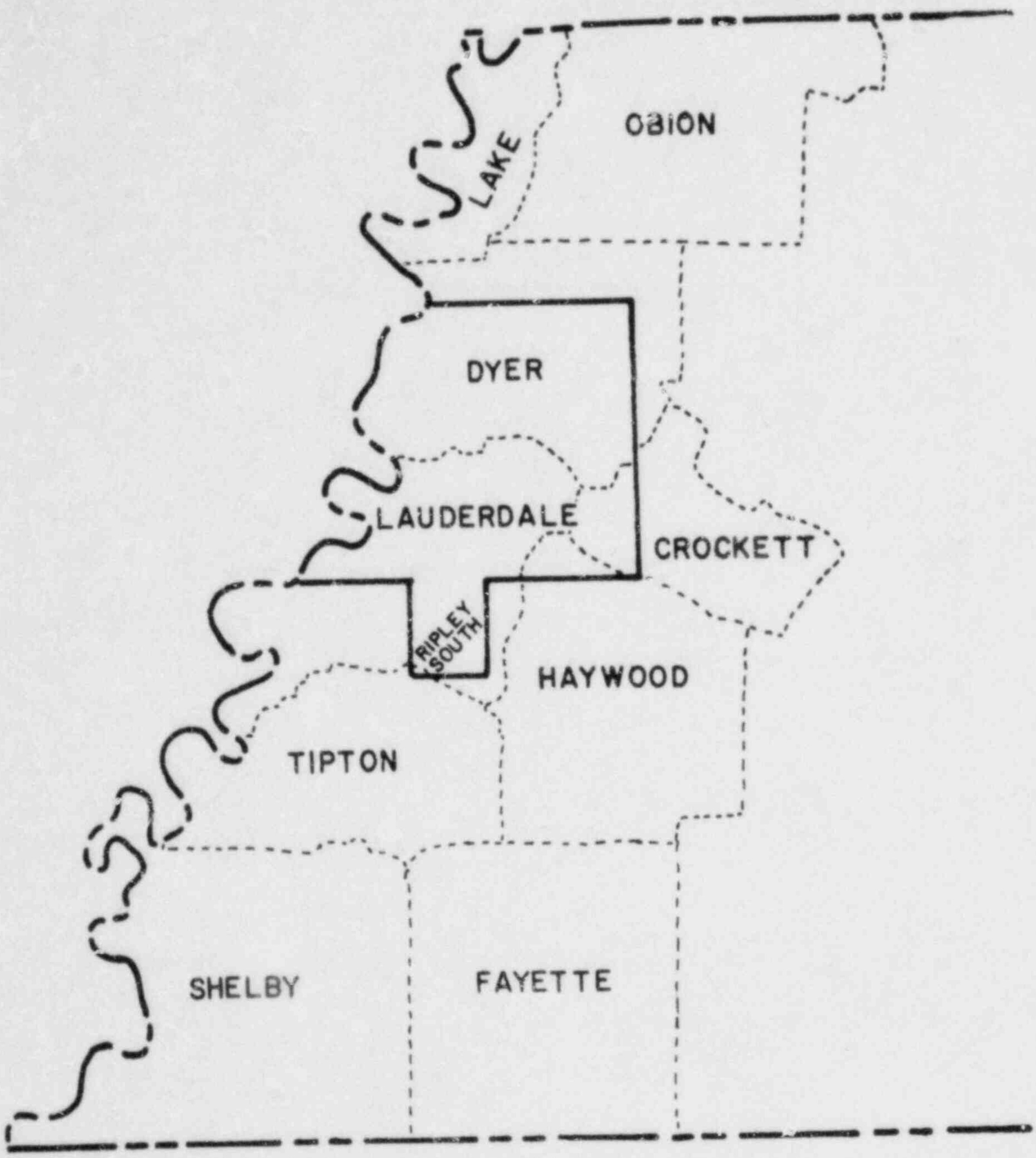
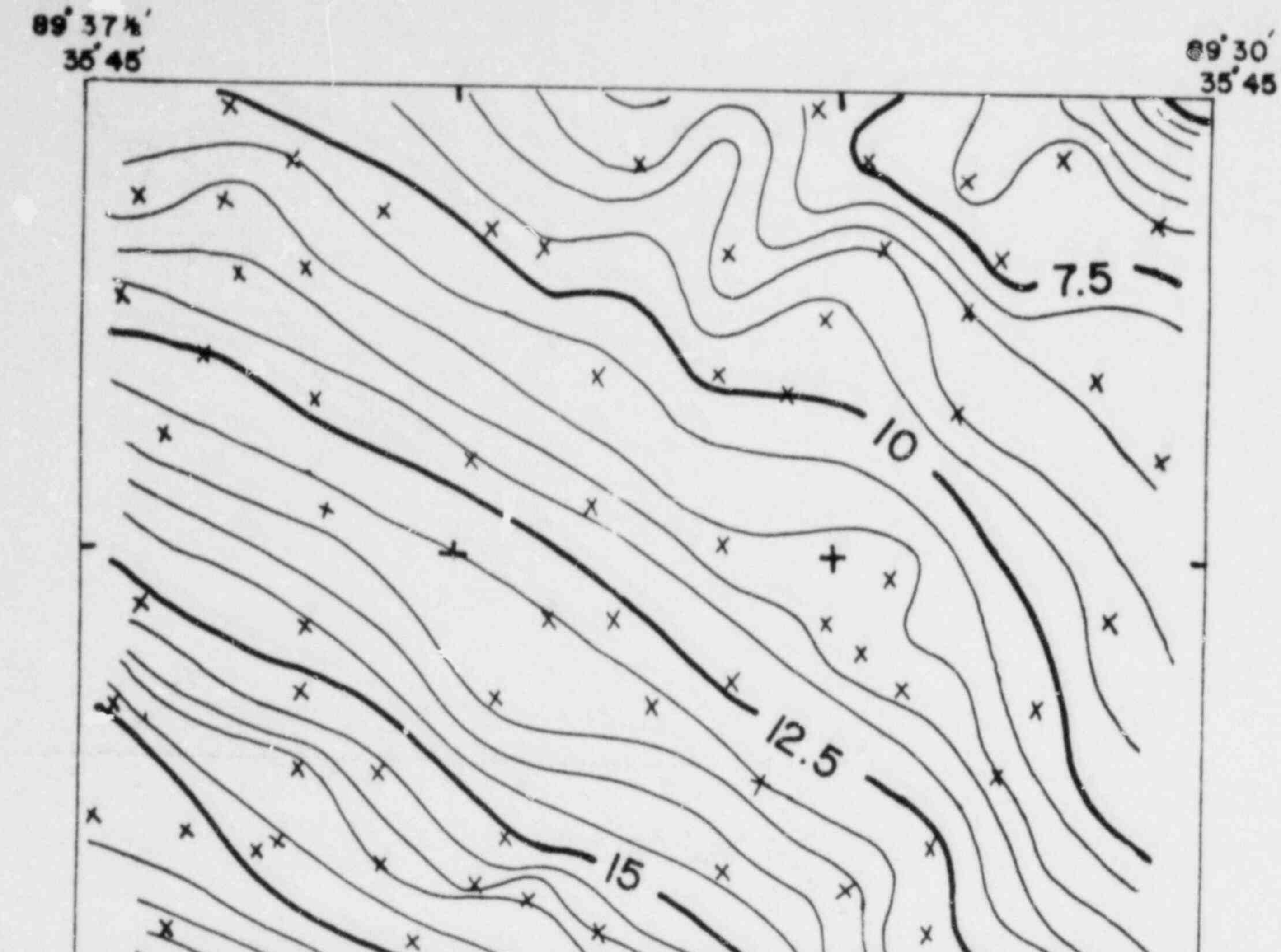
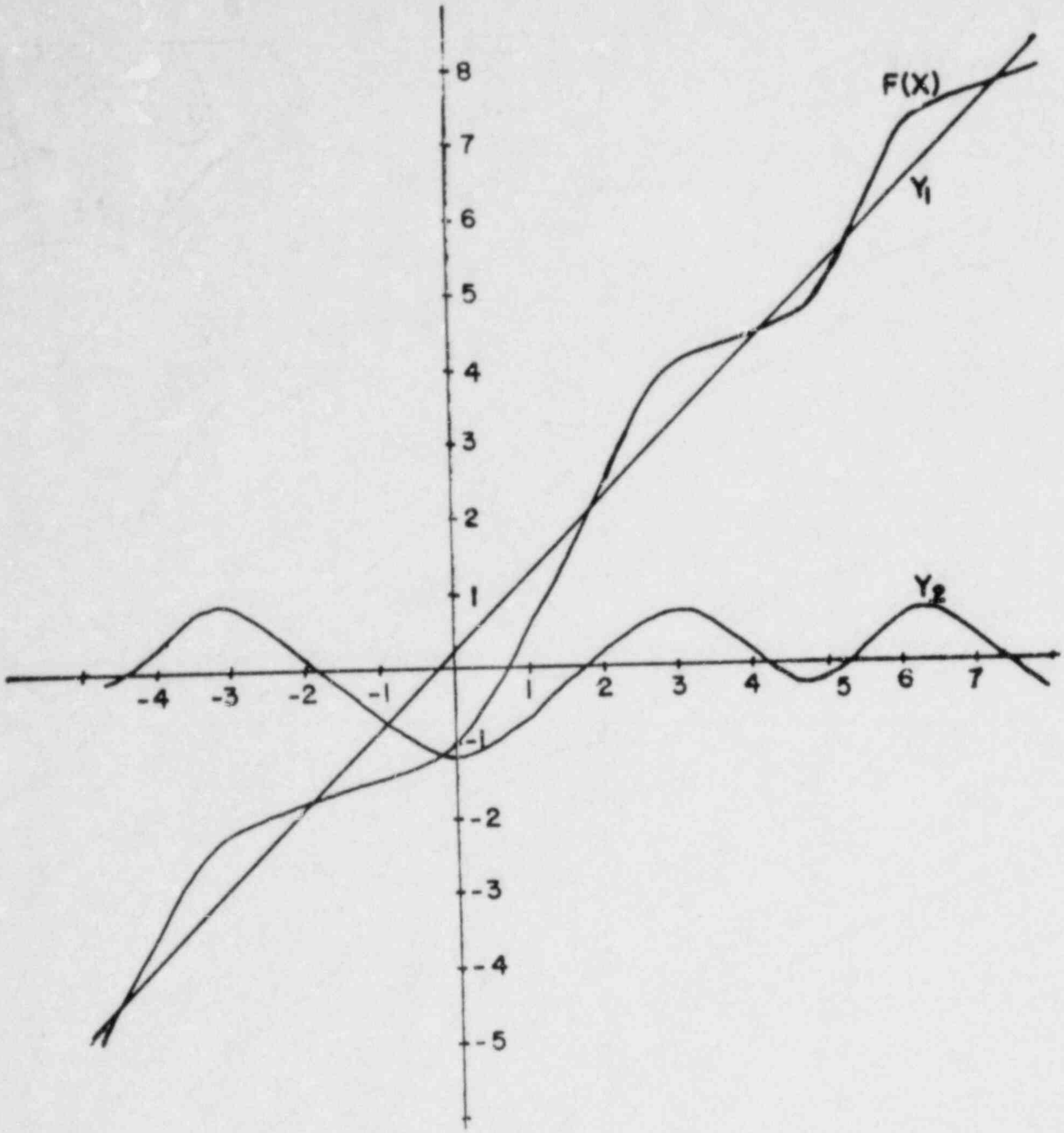


Figure DA2-1. Location of study area and the Ripley South Quadrangle.



RIPLEY SOUTH GRAVITY MAP

Figure DA2-2

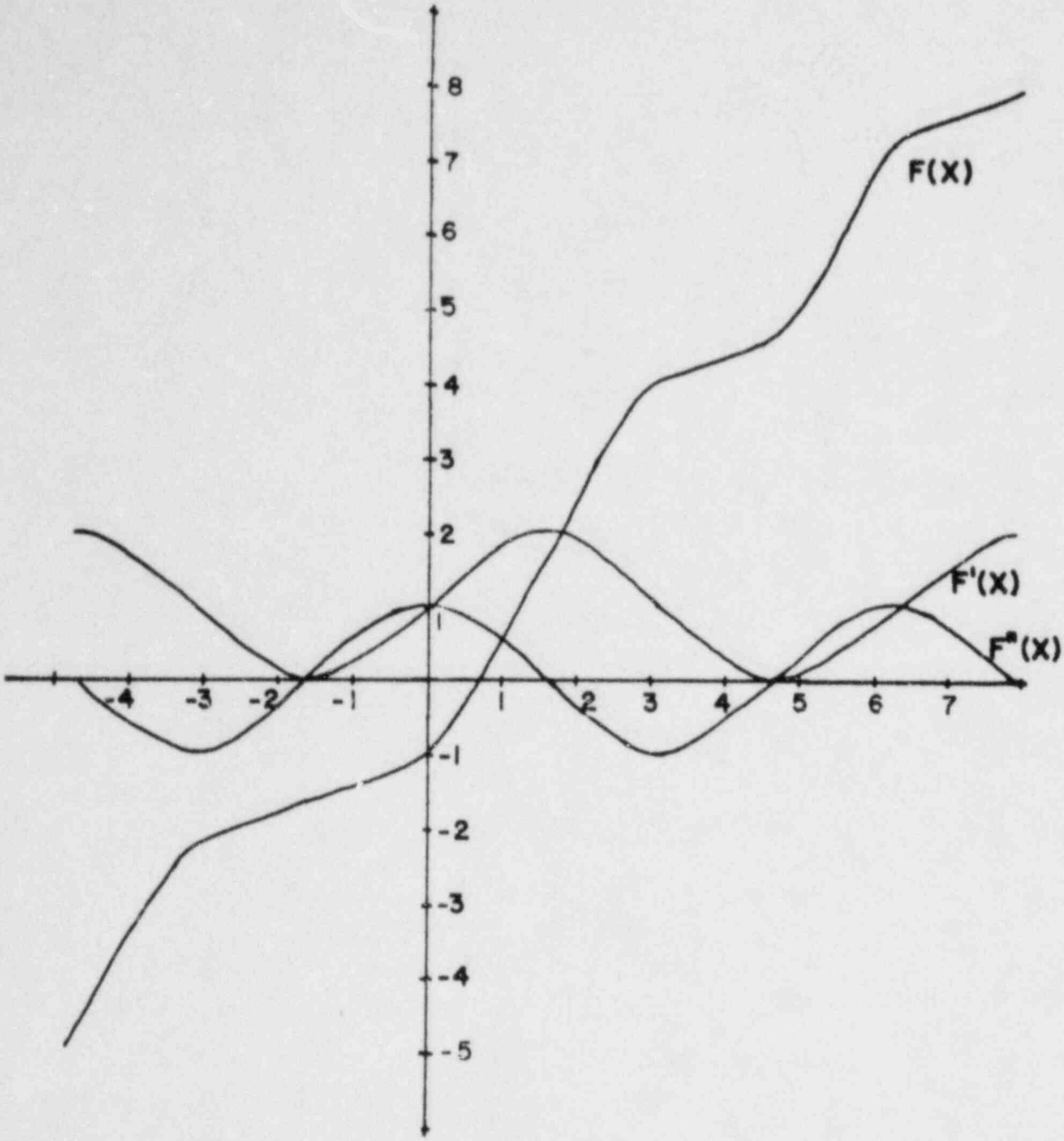


$F(X) = -\cos(X) + AX + B \quad ; A=1, B=0$

$Y_1 = 1.02X + 0.20$

$Y_2 = F(X) - Y_1$

Figure DA2-3. Example of Residual Gravity.

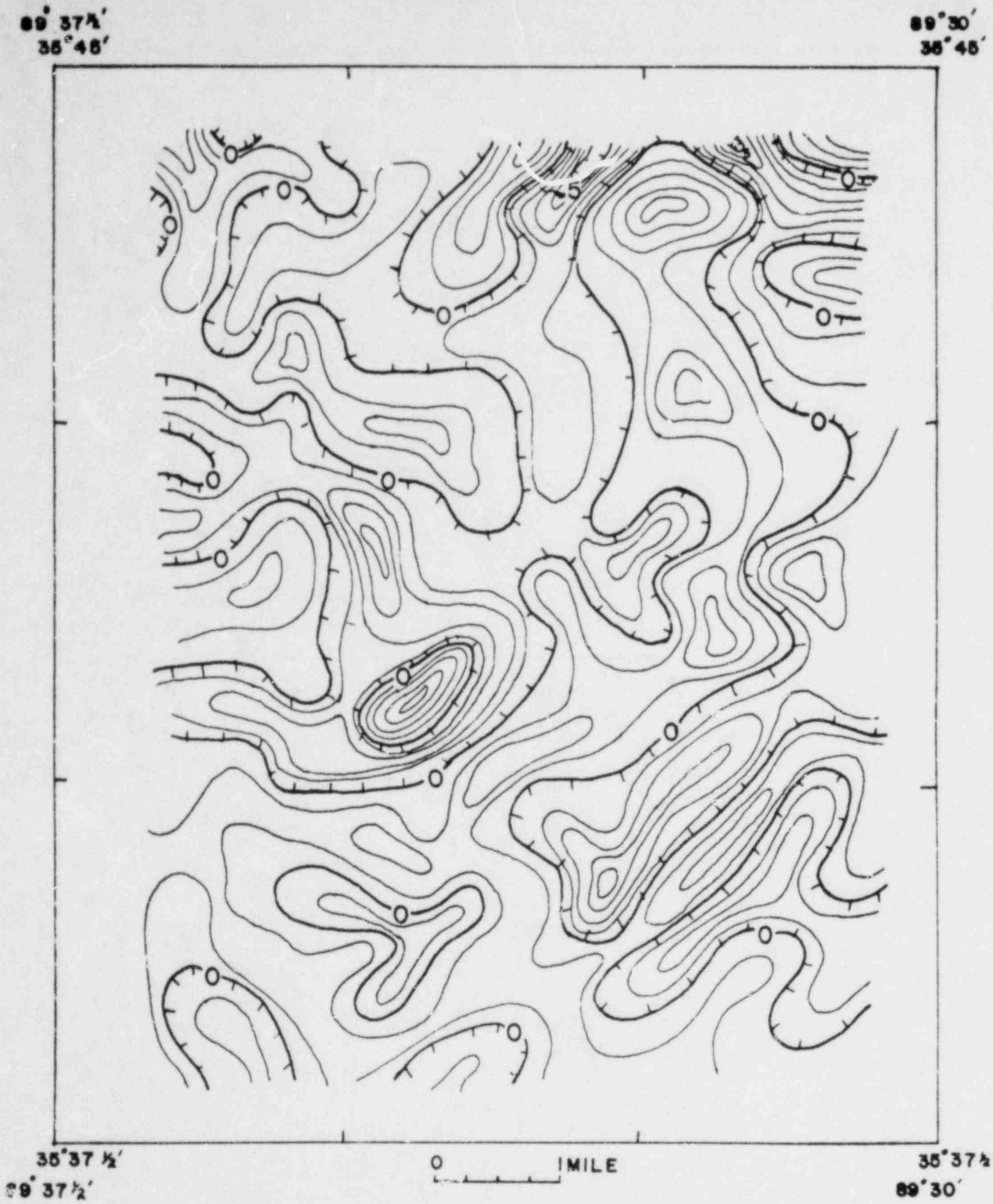


$F(X) = -\cos(X) + AX + B \quad ; \; A = 1, B = 0$

$F'(X) = \sin(X) + A$

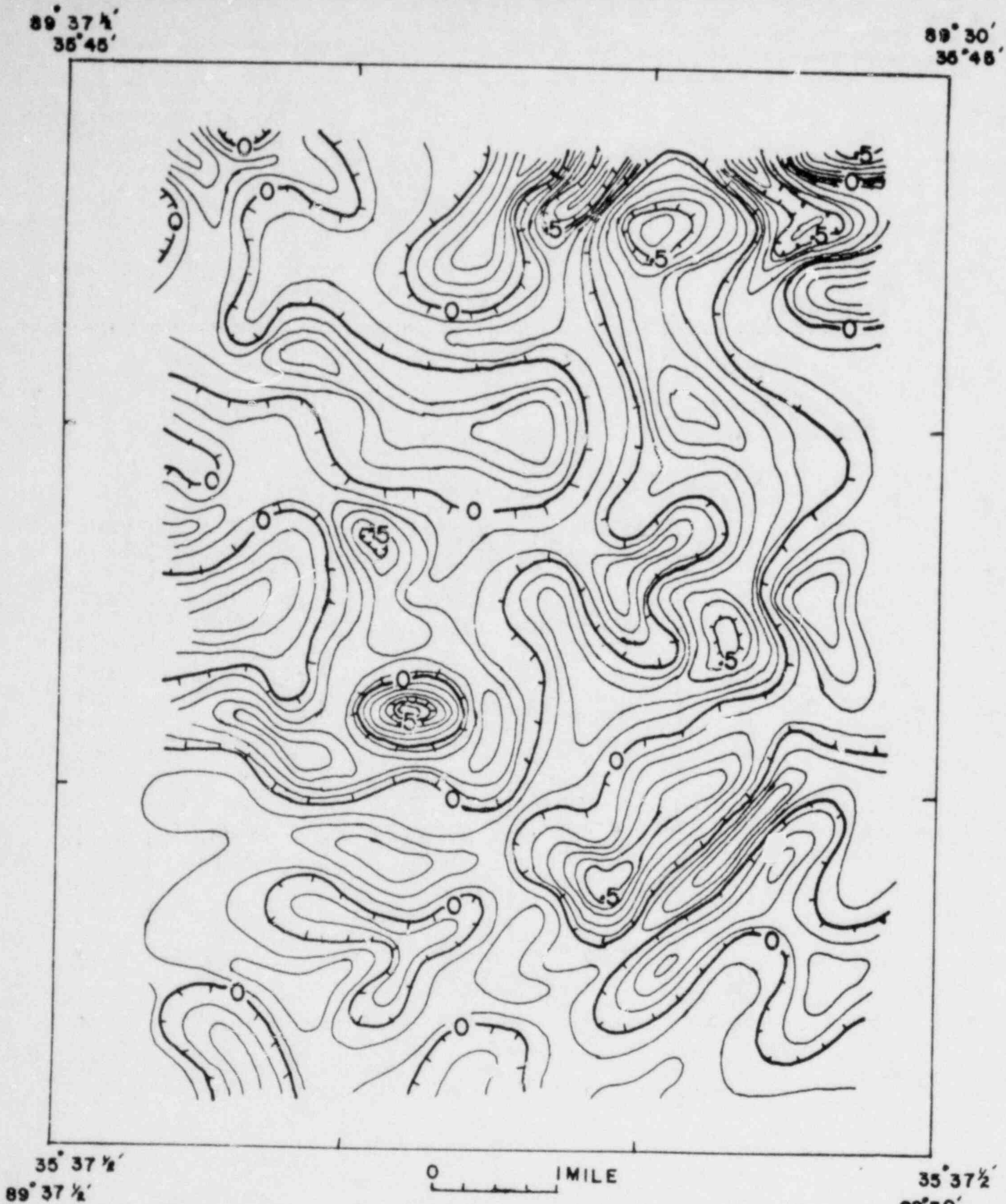
$F''(X) = \cos(X)$

Figure DA2-4. Example of the Second Derivative of Gravity.



RIPLEY SOUTH RESIDUAL MAP

Figure DA2-5



RIPLEY SOUTH SECOND DERIVATIVE MAP

Figure DA2-6

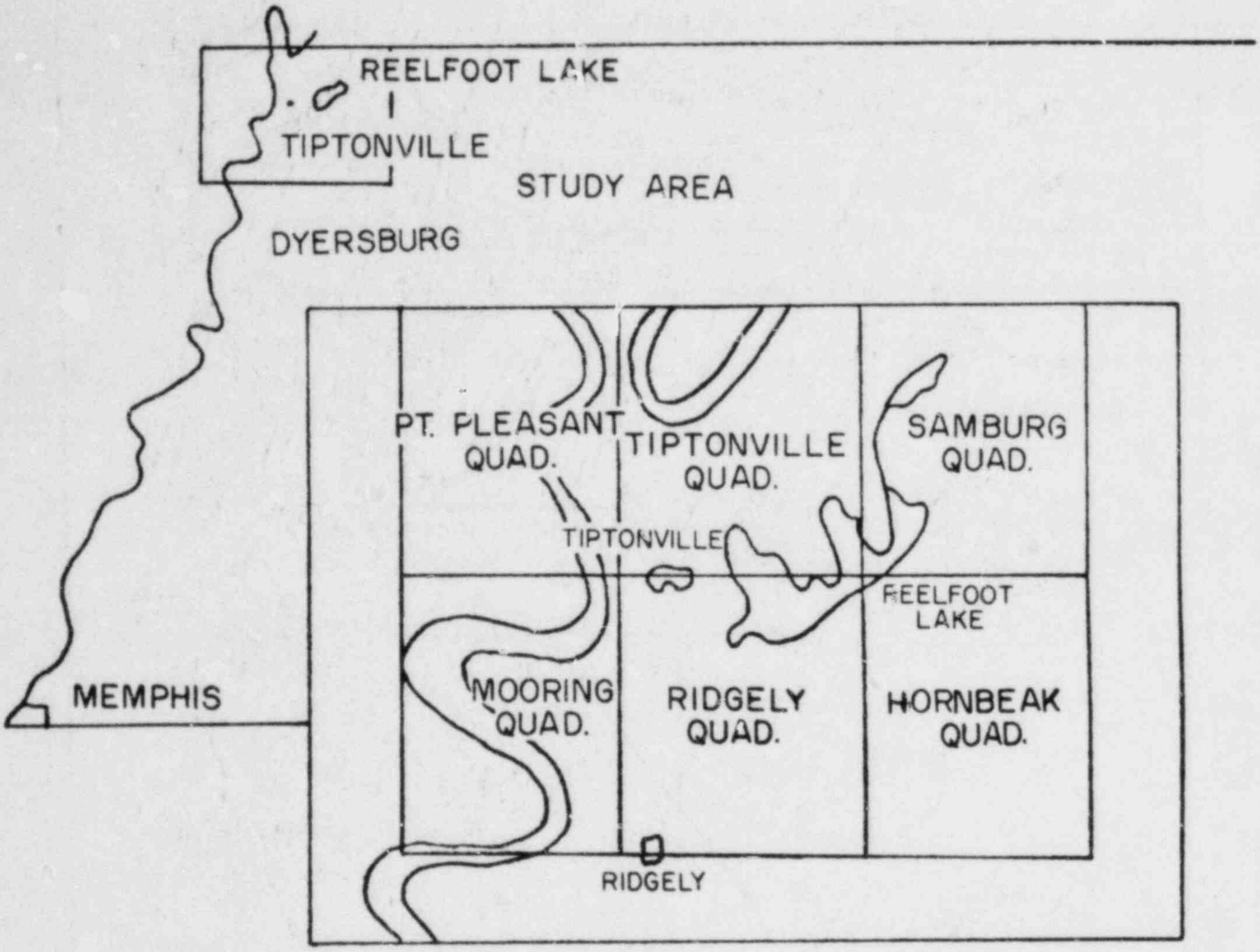


Figure DA3-1--Location of the study area (after Haselton, 1977).

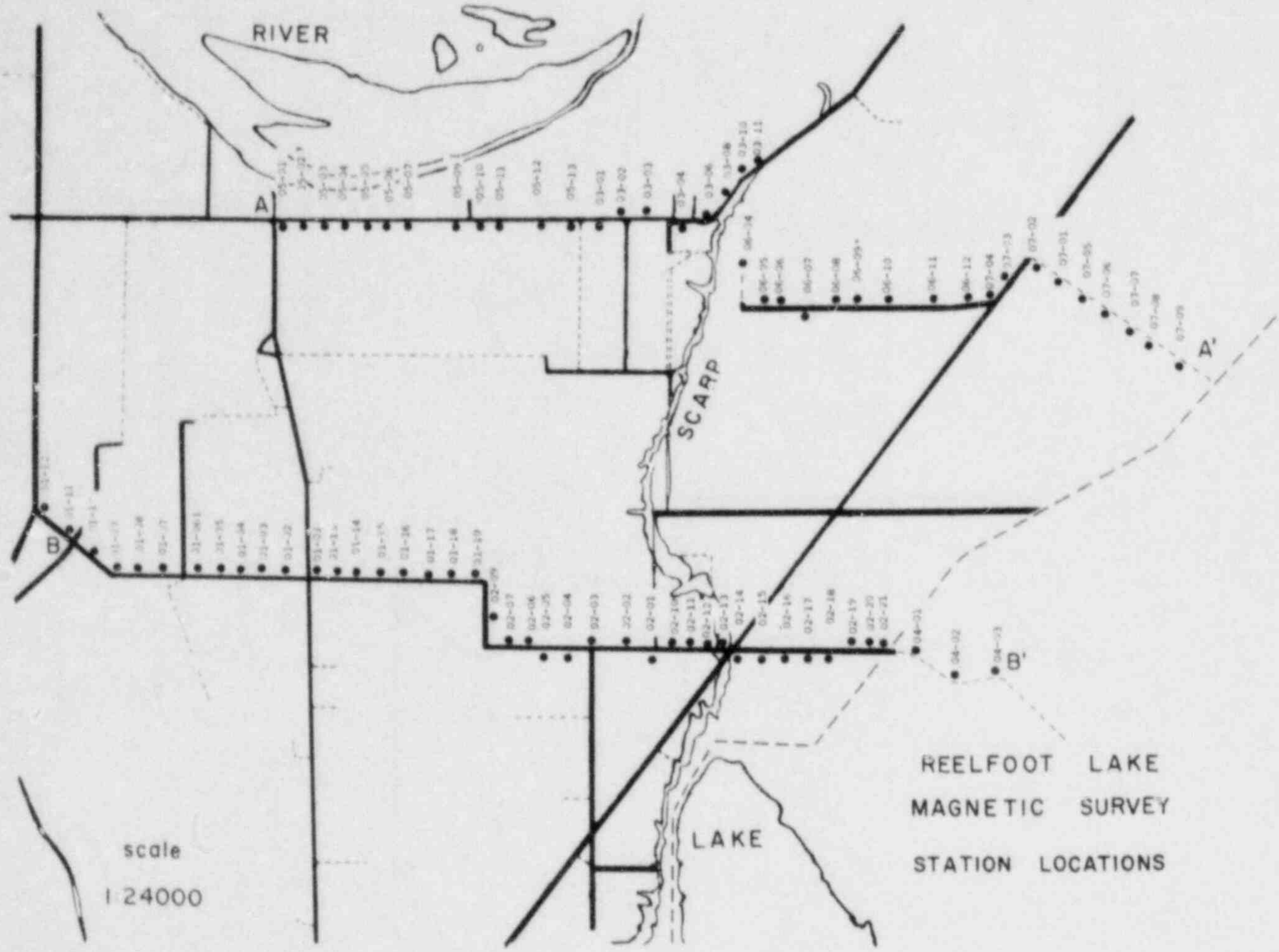


FIG. DA3-2--Magnetic survey station location map.

FIG. DA3-3--OBSERVED MAGNETIC VALUES: SOUTHERN TRAVERSE (B-B')

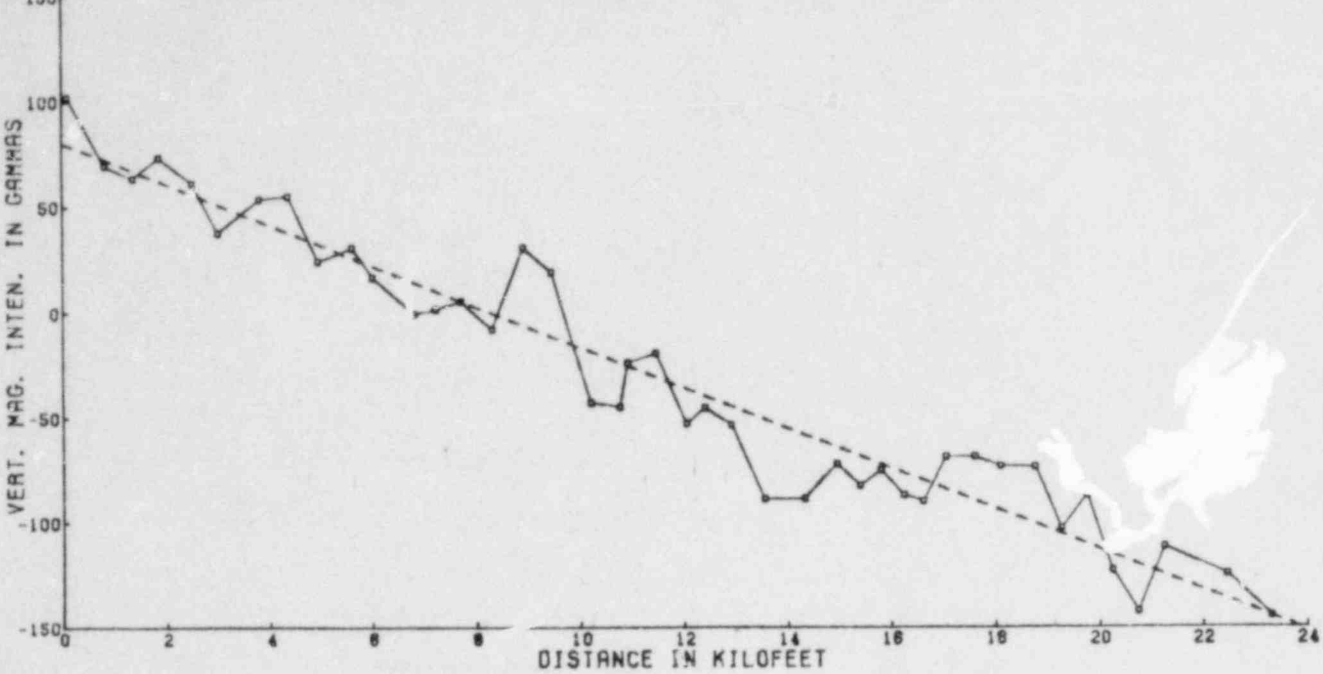


FIG. DA3-4--OBSERVED MAGNETIC VALUES: NORTHERN TRAVERSE (A-A')

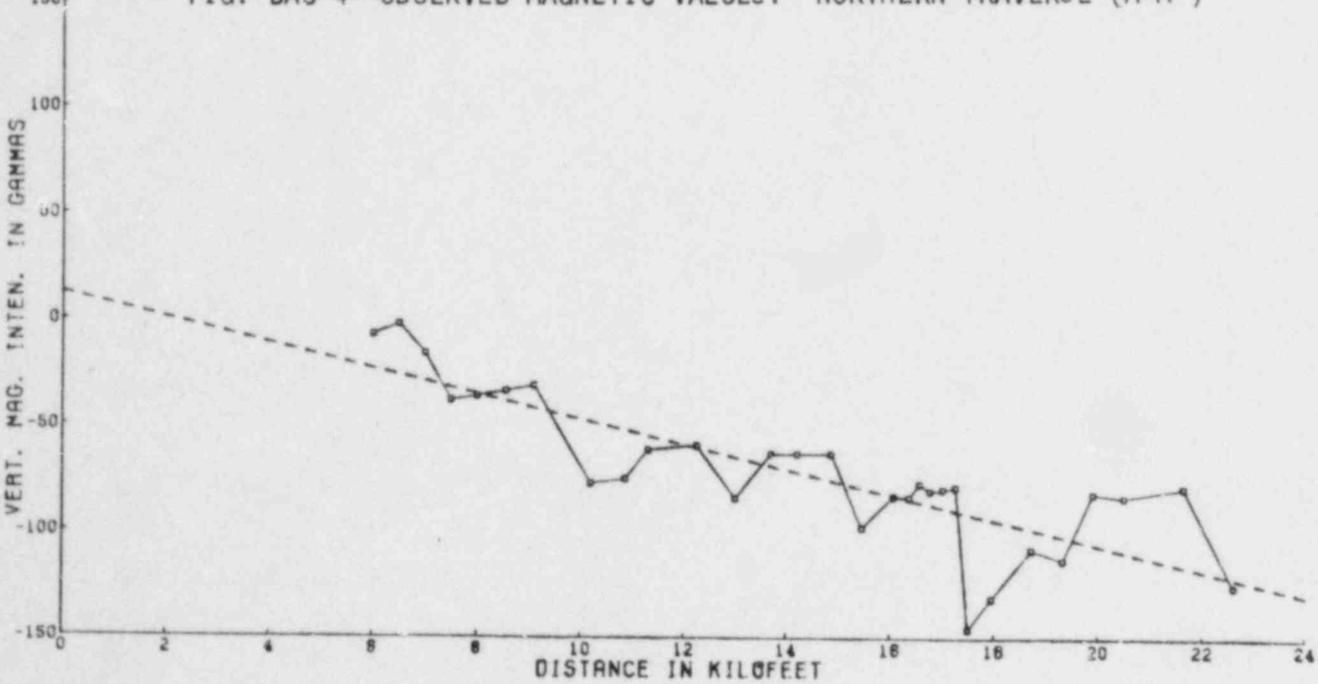


FIG. DA3-5--RESIDUAL MAGNETIC VALUES: SOUTHERN TRAVERSE (B-B')

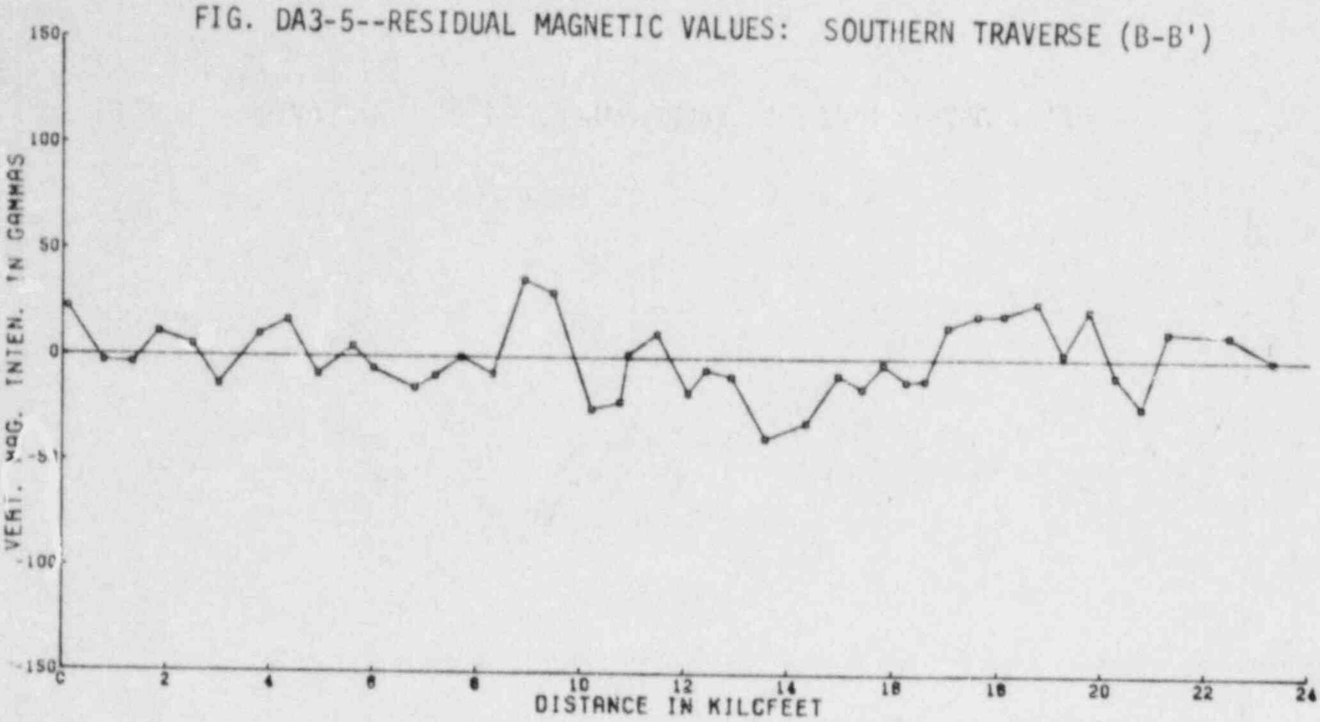


FIG. DA3-6--RESIDUAL MAGNETIC VALUES: NORTHERN TRAVERSE (A-A')

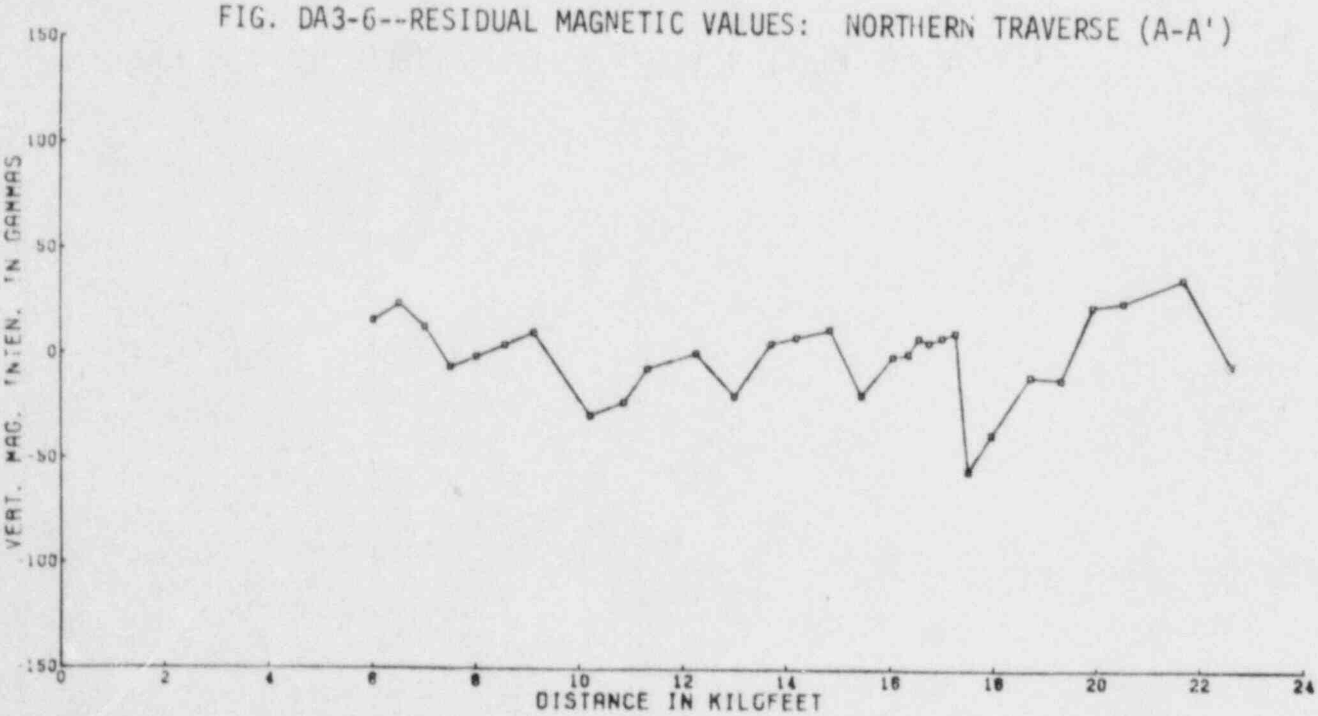


FIG. DA3-7--MAGNETIC VALUE RANGE: SOUTHERN TRAVERSE (B-B')

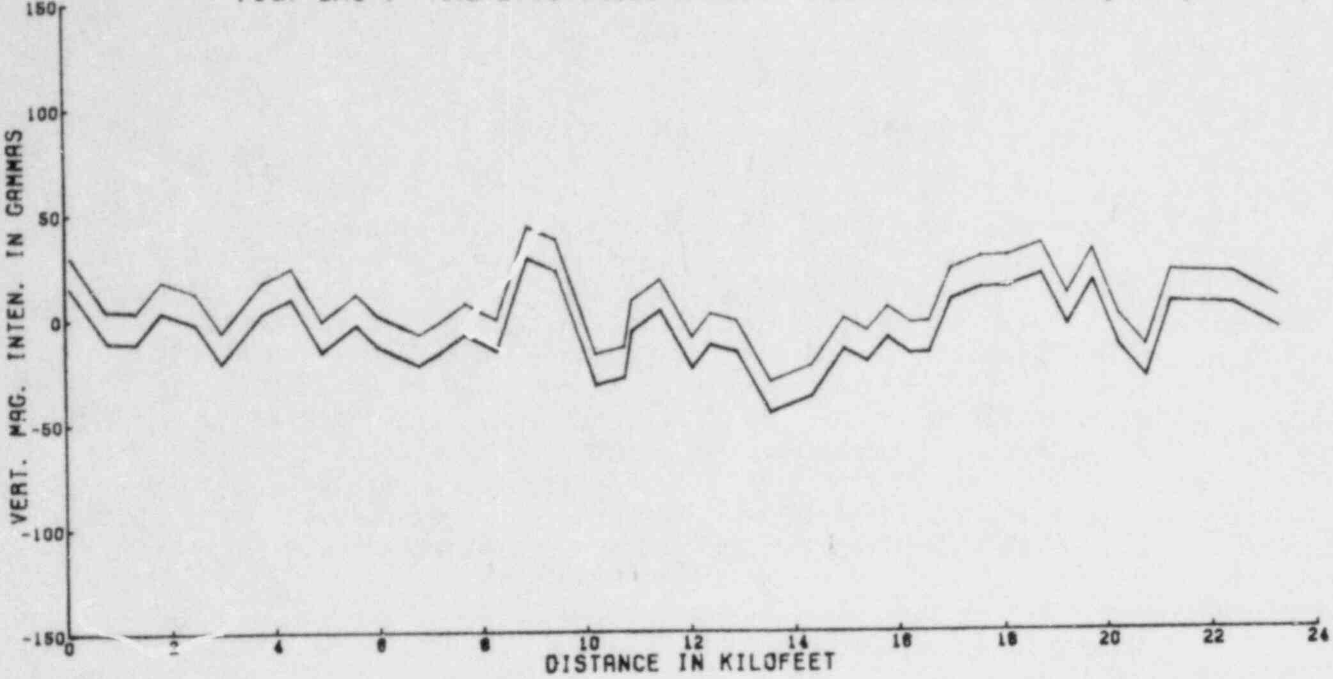
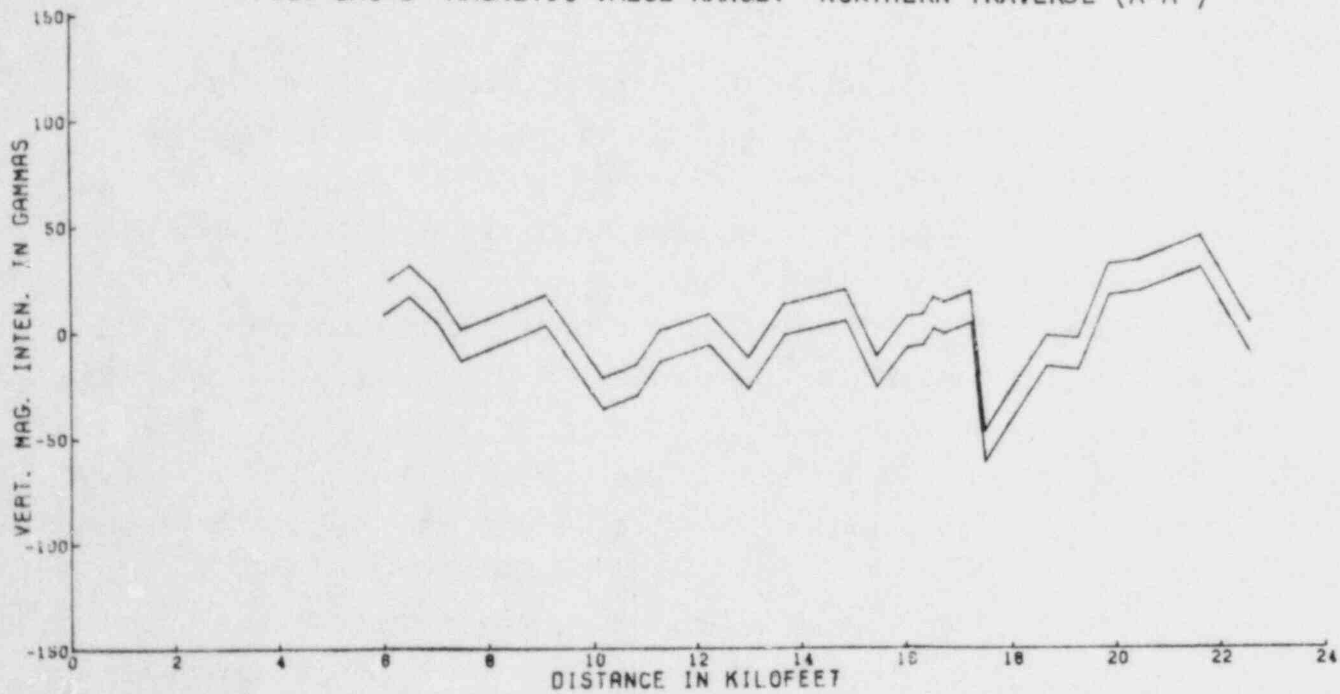


FIG. DA3-8--MAGNETIC VALUE RANGE: NORTHERN TRAVERSE (A-A')



GENERAL GEOLOGY, GEOPHYSICS, AND SEISMICITY
OF NORTHWEST ALABAMA

Annual Progress Report - Fiscal Year 1980

Contract No. NRC-04-78-262

Jack T. Kidd
Geological Survey of Alabama

ABSTRACT

The Geological Survey of Alabama and the U.S. Nuclear Regulatory Commission are making a study of the structural geology of northwest Alabama, with emphasis on areas of Cretaceous faulting and subsurface geology. Numerous faults have been reported in rocks of Cretaceous age but most are unconfirmed. Only one "tectonic" fault was observed by the investigator in rocks of Cretaceous age. Numerous faults were observed by the investigator in rocks of Cretaceous age associated with collapse features. These collapse features are assumed to be the result of solution of the Bangor Limestone of Mississippian age and subsequent collapse of overlying Cretaceous rocks.

Numerous structural features have been reported from the study area. However, selected test well data indicate only four major structural features in the subsurface at the mapping horizons. These features include the Detroit fault zone and associated fault splay in Lamar County, an anticline in Lauderdale County, and a structural high in parts of Madison and Limestone Counties that may reflect the southern extension of the Nashville dome.

INTRODUCTION

The study area includes that part of northwest Alabama lying within a 200-mile radius of the epicenter of the 1811-1812 New Madrid earthquakes. This area of Alabama includes all or part of the following 10 northwest Alabama counties: Lauderdale, Limestone, Madison, Colbert, Lawrence, Morgan, Franklin, Winston, Marion, and Lamar (Figure E-1).

The objectives of this study are to investigate areas of reported Cretaceous faulting and provide an overview of the subsurface geology of the study area with emphasis on structural geology and subsurface stratigraphy. Data presented include isopach and surface configuration maps, a revised map of structural features, location map of test wells, and an appendix of test well data.

The age of surface geologic units in the study area range from Recent to Ordovician (Figure E-2). The oldest unit penetrated in the subsurface is the Cambrian-Ordovician Knox Group. Figure E-3 shows selected wells in the study area and the appendix includes data on the geologic systems and series penetrated.

A map and data table of structural features were previously compiled and include data on 44 faults and 53 folds (Kidd, 1980). These data are modified from field investigations during fiscal year 1980. Faults and folds have been mapped in rocks as young as Late Cretaceous and possibly as old as Precambrian.

CRETACEOUS FAULTING

Revised maps of structural features have been compiled showing faults, folds, and collapse features in the study area (Figures E-4 and E-5).

Seven faults deforming Cretaceous and older rocks in the study area were previously reported and include Nos. 2, 10, 11, 12, 39, 40, and 41 (Kidd, 1980). Two additional faults, Nos. 43 and 44 in Winston County, reported from an unidentified horizon (Kidd, 1980) were mapped in Clements and Sandy (1970-A) in rocks of Cretaceous and Pennsylvanian ages. These two faults appear to be the result of erroneous data and have been omitted from Figure E-4.

Fault No. 10 was postulated by Martin (1965) on an apparent offset of stratigraphic units. Outliers of Cretaceous rocks occur east of the fault but not adjacent to it. Fault No. 12 was reported by Martin (1965) and Clements and Sandy (1970) as cutting Cretaceous rocks. Martin (1965) reports two exposures of the fault plane in the NE¼, section 11, Township 9 South, Range 11 West, Marion County. Martin (1965) did not observe the fault in rocks of Cretaceous age but Cretaceous rocks lie on the downthrown side adjacent to the fault.

Faults Nos. 40 and 41 were reported from rocks of Pennsylvanian and Cretaceous ages by Clements and Sandy (1970). However, detailed mapping in the area by Martin (1965) does not indicate any evidence of these faults and they are therefore considered questionable.

Fault No. 11 was previously reported by Clements and Sandy (1970) in rocks of Pennsylvanian and Cretaceous ages. Detailed mapping by Martin (1965) indicates the fault occurs only in rocks of Pennsylvanian age.

Faults Nos. 2 and 39 were previously reported as two faults (Kidd, 1980) but appear to be equivalent. This fault has been reported from rocks of Mississippian, Pennsylvanian, and Cretaceous ages (Clements and Sandy, 1970; and Holmes, 1978) and borders the southwest side of the abandoned Hamilton gas field in Marion County. Fault No. 2 (Figure E-4) shows the correct location and fault No. 39 has been omitted.

A previously unreported fault (No. 49) was observed in a highwall of an open-pit coal mine near the Franklin-Marion County boundary in section 35, Township 8 South, Range 11 West. This fault strikes northwest, dips steeply to the southwest, and has disturbed rocks of Pennsylvanian and Cretaceous ages (Figure E-5). The amount of displacement is unknown.

A possible graben or fault zone previously unknown to the writer has been reported in sections 9 and 10, Township 2 South, Range 13 West, Lauderdale County, (Frederic F. Mellen, personal communication). These faults are shown as Nos. 50 and 51 on Figure E-4 and are mapped where younger Mississippian shales, sandstones, and limestones are reportedly jextaposed with older Mississippian limestones and cherts.

Several collapse features were previously mapped in northwest Alabama (Kidd, 1980). Three additional collapse features were noted approximately 5 to 10 miles southwest of Russellville in Franklin County in the highwalls of abandoned open-pit brown iron ore mines. These collapse features occur in the unconsolidated deposits of sand, gravel, and clay of the Gordo Formation of Cretaceous age and are assumed to be the result of solution of the underlying Bangor Limestone of Mississippian age and subsequent collapse of the Gordo Formation. The western three-fourths of Franklin County includes large areas underlain by the Bangor Limestone and overlain by the Gordo Formation and similar collapse features in these areas are highly probable.

SUBSURFACE GEOLOGY

Regional Structural Contour Map Showing Configuration of the Top of Lower Ordovician Rocks

Figure E-6 illustrates the surface configuration of the Lower Ordovician horizon in northwest Alabama. The mapping horizon is the top of the Knox Group of Early Ordovician and Late Cambrian ages. The surface of the Knox Group dips approximately 30 to 60 feet per mile to the southwest in most of the study area. Structural features interpreted from test well data include an anticline in Lauderdale County and a "high" area in Limestone and

Madison Counties that may reflect the southern extension of the Nashville dome.

All structure and isopach maps include only those major structural features interpreted from test well data at the mapping horizons.

Units below the Knox Group have not been penetrated in the study area and the thickness of the Knox Group is uncertain. Southeast of the study area the Shenandoah Oil Corporation and Occidental Petroleum's F.W. Smith 26-6 No. 1 penetrated, in descending order, the Knox Group, Ketona Dolomite (?), Conasauga Formation, and Rome Formation before penetrating the basement complex. The Knox was 3240 feet thick; Ketona, 760 feet; Conasauga, 1410 feet; and Rome, 290 feet.

Regional Isopach Map of Upper and Middle Ordovician Rocks

Upper and Middle Ordovician rocks include, in ascending order, the Stones River, Nashville, Eden, Maysville, and Richmond Groups (Figure E-2). The Nashville, Eden, Maysville, and Richmond Groups are undifferentiated in parts of the study group and are treated as one unit.

Upper and Middle Ordovician rocks range in thickness from less than 500 feet in Lamar County to greater than 1100 feet in parts of Limestone, Madison, Lawrence and Morgan Counties (Figure E-7). In northeast Alabama east of the study area Upper and Middle Ordovician rocks are as much as 1800 feet thick (Kidd, 1975).

Regional Structural Contour Map Showing Configuration of the Top of Upper and Middle Ordovician Rocks

The top of Upper and Middle Ordovician rocks dips to the southeast at approximately 80 feet per mile in Lamar County and approximately 40 feet per mile in southwestern Lawrence County (Figure E-8). The anticline in Lauderdale County and the "high" area of Limestone and Madison Counties mapped on top of the Lower Ordovician horizon are also mapped on top of the Upper and Middle Ordovician horizon.

Throughout most of the study area Ordovician rocks are overlain by Silurian rocks. However, in parts of Limestone and Madison Counties where Silurian rocks are absent, Ordovician rocks are overlain by Devonian rocks. Upper and Middle Ordovician rocks are covered by younger sediments throughout most of the study area and are exposed along the major rivers and streams in the northeastern part of the study area.

Regional Isopach Map of Silurian Rocks

Silurian rocks are absent in parts of Limestone, Madison, and Lauderdale Counties and reach a maximum thickness of greater than 400 feet in the study area in western Franklin County (Figure E-9). A sedimentary basin of thick Silurian rocks trends northwest to southeast in Franklin and Marion Counties where Silurian rocks range in thickness from 300 to greater than 400 feet. South of the study area Silurian rocks are more than 600 feet thick (Kidd, 1975).

Regional Structural Contour Map Showing Configuration of the Top of Silurian Rocks

Silurian rocks dip to the southwest from 30 to 100 feet per mile in the study area (Figure E-10). The major structural feature indicated at the mapping horizon is a northwest-southeast trending anticline in Lauderdale County. Silurian rocks are overlain by the Devonian Chattanooga Shale throughout the eastern part of the study area and by undifferentiated Devonian rocks in the western part of the study area. Silurian rocks are exposed in Lauderdale County along Bluewater, Shoal, and Butler Creeks.

Regional Iospach Map of Devonian Rocks

Devonian rocks in the study area range in thickness from 0 to greater than 500 feet (Figure E-11). Devonian rocks reach their maximum thickness in Lamar County and include a thick section of Devonian undifferentiated rocks and the Chattanooga Shale. Throughout the eastern two-thirds of the study area Devonian rocks are represented by the Chattanooga Shale which is generally less than 50 feet thick. Devonian rocks are generally overlain by Mississippian rocks in the study area.

Regional Structural Contour Map Showing Configuration of the Top of Devonian Rocks

Devonian rocks in the study area generally dip to the southwest from 25 to 60 feet per mile (Figure E-12). Structural features indicated at the mapping horizon by drill hole data include an anticline in Lauderdale County, a "high" area in Limestone and Madison Counties that may represent the southern extension of the Nashville dome, and the Detroit fault zone and associated fault splay in Lamar County (faults Nos. 3 and 4). The Detroit fault zone has been penetrated by several wells in Lamar County in Pennsylvanian and Mississippian sediments, and test well data indicate the fault zone probably extends into Devonian and possibly older sediments. The Detroit fault zone is shown as one fault on Figure E-12 but consists of several en echelon faults. The faults are normal, downthrown to the southwest, with a cumulative throw of approximately 350 feet (Moore, 1971). Fault No. 3 trends northwest-southeast and is normal, dips to the northeast, and exhibits a throw of probably less than 100 feet (Tolson, 1979).

Regional Isopach Map of Mississippian Rocks

Mississippian rocks in the study area thicken to the northwest ranging from less than 1100 feet in northwest Lamar County to greater than 1500 feet in northwest Marion and southwest Franklin Counties (Figure E-13). Mississippian rocks are covered by Pennsylvanian and Cretaceous rocks in the southern part of the study area. In the western part of the study area Mississippian rocks are exposed in the stream valleys and covered by Cretaceous rocks on the hills and ridges. In the northeastern part of the study area Mississippian rocks are exposed except where eroded along the major streams and rivers in parts of Lauderdale, Limestone, and Madison Counties.

Regional Structural Contour Map Showing Configuration of the Top of Mississippian Rocks

Mississippian rocks in the southern part of the study area dip to the south at approximately 50 feet per mile (Figure E-14). The contact with the overlying Pennsylvanian rocks appears to be conformable. In the northwestern part of the study area Mississippian rocks dip to the west at approximately 30 feet per mile and are overlain unconformably by Cretaceous rocks. This change in dip of the surface of the Mississippian rocks is apparently due to erosion of the Mississippian rocks during deposition of the overlying Cretaceous rocks.

Major structural features interpreted from test well data at the mapping horizon include the Detroit fault zone and associated fault splay.

Regional Isopach Map of Pennsylvanian Rocks

Pennsylvanian rocks range in thickness from 0 in parts of Franklin, Lawrence, and Marion Counties to greater than 1500 feet in Lamar County (Figure E-15). Pennsylvanian rocks are overlain unconformably by Cretaceous rocks in southwestern part of the study area. This contact is locally irregular in the outcrop and it is assumed that the thickness of the Pottsville varies locally in the study area in the subsurface due to this irregular contact. Pennsylvanian rocks thicken abruptly on the downthrown side of the Detroit fault zone due to erosion of the upper part of the Pottsville following deformation and preservation of a greater volume of Pennsylvanian sediments on the downthrown block.

Regional Structural Contour Map Showing Configuration of the Top of Pennsylvanian Rocks

The surface of Pennsylvanian rocks dips to the southwest from 15 to 40 feet per mile (Figure E-16). Pennsylvanian rocks in the study area are represented by the Pottsville Formation which is overlain unconformably in the southwestern part of the study area by the Tuscaloosa Group of Cretaceous age. This unconformable contact is locally irregular and varies vertically as much as 80 feet in northeast Marion County approximately 1½ miles west of Haleyville. Pennsylvanian rocks are absent in the northern part of the study area due to erosion and (or) nondeposition.

Regional Isopach Map of Cretaceous Rocks

Cretaceous rocks thicken from northeast to southwest, reach a maximum thickness of more than 500 feet in Lamar County, and are absent in the northeastern part of the study area (Figure E-17). Values shown on Figure E-17 represent the approximate maximum thickness expected at higher elevations on the hills and ridges in the study area. Throughout much of the outcrop area, Cretaceous rocks are absent at lower elevations along major rivers and streams where older rocks are exposed.

SUMMARY

Eight faults have been reported in rocks of Cretaceous age in the study area and include Nos. 2, 10, 11, 12, 40, 41, 43, and 44 (Kidd, 1980).

Faults Nos. 43 and 44 appear to be the result of erroneous data and have been omitted. Detailed mapping in the vicinity of faults Nos. 11, 40, and 41 by Martin (1965) indicates that fault No. 11 occurs in rocks in Pennsylvanian age and not in rocks of Cretaceous age as previously reported. Martin (1965) reports no evidence of faults Nos. 40 and 41.

Fault No. 10 was postulated by Martin (1965) from an apparent offset of stratigraphic units and the fault plane was not observed. The fault plane of fault No. 12 was observed by Martin (1965) only in rocks of Pennsylvanian age but Cretaceous rocks occur adjacent to the fault on the downthrown side and are assumed to have been present during deformation. Faults Nos. 2 and 39 were previously reported as two faults (Kidd, 1980) but appear to be equivalent, and therefore fault No. 39 has been omitted.

A previously unreported fault was observed by the investigator in rocks of Cretaceous and Pennsylvanian ages near the Franklin-Marion County boundary. This fault (No. 49) strikes northwest and dips steeply to the southwest.

Numerous faults with displacements of a few inches to several feet were observed by the investigator in rocks of Cretaceous age associated with collapse features in Franklin County. These collapse features are assumed to be the result of solution of the Bangor Limestone and subsequent collapse of the overlying Cretaceous rocks. The western three-fourths of Franklin County includes large areas with a similar geologic setting and collapse features in these areas are probable.

The thickness of subsurface units varies in distribution and amount. Cretaceous and Devonian rocks thicken to the southwest; Pennsylvanian rocks thicken to the south and southeast; Mississippian rocks thicken to the northwest; Silurian rocks are thickest in a northwest-southeast trending basin and thin to the northeast and southwest; and Upper and Middle Ordovician rocks thicken to the northeast.

Figures E-4 and E-5 are maps of structural features reported in the study area. Figures E-6 to E-17 are predominantly subsurface maps and include only those structural features indicated by test well data at the mapping horizons. These features include the Detroit fault zone and associated fault splay in Lamar County, and an anticline in Lauderdale County. A structural high is indicated in parts of Madison and Limestone Counties that may reflect the southern extension of the Nashville dome. A northwest-southeast trending basin is indicated in Franklin and Marion Counties where Silurian rocks reach a maximum thickness greater than 400 feet.

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Tolson, Janyth S., 1979, Structure on the top of the Tuscumbia Limestone (Mississippian) in the Black Warrior basin of Alabama: Alabama State Oil and Gas Board open-file map.

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

APPENDIX E-1

SUBSURFACE DATA

MAP NUMBER	STATE OIL AND GAS BOARD PERMIT NUMBER	WELL NAME OR NUMBER	OPERATOR OR OWNER	LOCATION (section, township, range)	ELEVATION[1]	TOTAL DEPTH (feet)	SYSTEM/SERIES PENETRATED[2] (depth in feet to top of System/Series) QUATERNARY	CRETACEOUS	PENNSYLVANIAN	MISSISSIPPIAN	DEVONIAN	SILURIAN	UPPER AND MIDDLE ORDOVICIAN	LOWER ORDOVICIAN AND CAMBRIAN
COLBERT COUNTY														
1		Water Well No. 1	City of Cherokee	25 - 3S - 14W	528 G. L.	414				S	409			
2		BS - 137 + 00	Tennessee Valley Authority	15 - 3W - 9W	659 G. L.	486				S	234	244	303	
3	2	Mrs. W. B. Alsobrook No. 1	Vellen and Gear	10 - 4S - 15W	515 D. F.	1679				S	441	544	795	1639
4	576	Mrs. Frances Thomas No. 1	Edward T. Merry	31 - 5S - 13W	665 D. F.	.978				S	777	837	1065	1949
5	792	Henry Berry No. 2	Discovery Corp., Inc.	18 - 5S - 10W	515 D. F.	864				S	414	454	550	
FRANKLIN COUNTY														
1	2038	Verdner Thorne et. al. No. 1	William A. Brewer and Bryant A. Fehiman	13 - 6S - 14W	594 D. F.	2146				S	813	830	1140	2015
2	318	E. L. Thorn No. 1	D. E. Loveridge and Owen Heath	18 - 6S - 13W	615 D. F.	2232				S	745	778	1043	1900
3	281	Reggie Johnson No. 1	D. E. Loveridge and Owen Heath	17 - 6S - 13W	540 T. C.	2007				S	787	75?	1060	1912
4	B-233	Frankfort No. 1	United Oil Co.	7 - 6S - 12W	745 D. F.	2005				S	770	784	998	1765
5	4	Hester No. 1	E. O. Heath	4 - 6S - 12W	770 D. F.	995				S	955			
6	B-184	Woodward No. 1	Woodward Oil and Gas Co.	16 - 7S - 11W	705 D. F.	2561				S	1215	1240	1400	2290
7	2051	G. Pierce Webber 35-4 No. 1	Shenandoah Oil Corp.	35 - 8S - 15W	693 K. B.	3994		S	A	320	1520	1602	2003	2617
8	519	W. W. Bedford No. 2	Warrior Basin Oil Corp.	26 - 8S - 14W	727 D. F.	3702			S?	40?	1550	1625	2005	2765
9	180-A	Audie Harris No. 1-A	Herbert M. Ogg and H. D. Easton	26 - 8S - 12W	950 D. F.	2999		S	40	300?	1740	1780	2060	2930
10	993	Hester - White No. 3	James L. Duffey et. al.	11 - 8S - 11W	921 G. L.	1275			S	225				
11	156	George B. Conover No. 1	George B. Conover	34 - 8S - 11W	965 G. L.	1600		S	20	390				
LAMAR COUNTY														
1	1593	James Rye No. 1	Willard McKinney	17 - 12S - 15W	394 D. F.	1450		S	250	1015				
2	1581	W. A. Delaney No. 16-14	Cleary Petroleum Corp.	16 - 12S - 15W	493 D. F.	1900		S	340	1483				
3	1594	W. A. Delaney No. 9-16	Cleary Petroleum Corp.	9 - 12S - 15W	497 D. F.	2756		S	?	1120	2370	2630		
4	1783	Ogden No. 2-11	Cleary Petroleum Corp. - Cardinal Petroleum Corp.	2 - 12S - 15W	548 K. B.	1625		S	360	1123				
5	1785	Delaney No. 14-6	Cleary Petroleum Corp. - Cardinal Petroleum Corp.	14 - 12S - 15W	495 D. F.	1552		S	310	1195				
6	1627	Louis Crump 24-4 No. 1	Murvin Oil Corp.	24 - 12S - 15W	374 D. F.	2304		S	130	1202				
7	1623	W. L. Ogden 18-7 No. 1	Cleary Petroleum Corp.	18 - 12S - 14W	372 D. F.	2350	S	?	?	1070	2250			
8	1588	H. W. Mathews No. 1	Cleary Petroleum Corp.	23 - 12S - 14W	649 D. F.	2982		S	200	1460	2628	2958		
9	1611	S. Spruiell No. 1	Skelton Operating Co., Inc.	35 - 12S - 15W	368 D. F.	2974		S	80	1175	1508	2705		
10	2033	Beddow No. 3-6	APCO Oil Corp.	3 - 13S - 16W	3.J D. F.	3077		S	300	1645	2738			
11	2032	Blaylock No. 10-10	APCO Oil Corp.	10 - 13S - 16W	369 D. F.	323?		S	360	1682	2738	3178		

[1] G. L., Ground level; D. F., Derrick Floor; T. C., Top of Casing; K. B., Kelly Bushing.

[2] S, Surface; A, Absent.

MAP NUMBER	STATE OIL AND GAS BOARD PERMIT NUMBER	WELL NAME OR NUMBER	OPERATOR OR OWNER	LOCATION (section, township, range)	ELEVATION[1]	TOTAL DEPTH (feet)	QUATERNARY	CRETACEOUS	PENNSYLVANIAN	MISSISSIPPIAN	DEVONIAN	SILURIAN	UPPER AND MIDDLE ORDOVICIAN	LOWER ORDOVICIAN AND CAMBRIAN
							SYSTEM/SERIES PENETRATED[2] (depth in feet to top of System/Series)							
LAUDERDALE COUNTY														
1		Shaw Hollow No. 1	Tennessee Valley Authority	12 - 1S - 16W	426 G. L.	256					S	135		
2		Shaw Hollow No. 2	Tennessee Valley Authority	15 - 3S - 9W	429 G. L.	86				S	36			
3		H-14	U. S. Geol. Survey	21 - 1S - 14W	462 G. L.	290				S	?	200		
4	1714	E. R. and H. B. Abramson No. 1	Bison Oil Co., Inc.	14 - 1S - 12W	640 D. F.	3459				S	?	320	530	1490
5		Test Well No. 4	Tennessee Valley Oil Co.	12 - 1S - 11W	765 G. L.	270				S	255			
6		Test Well No. 8	Tennessee Valley Oil Co.	13 - 1S - 11W	672 G. L.	186				S	172	182		
7		Test Well No. 9	Tennessee Valley Oil Co.	21 - 1S - 11W	629 G. L.	194				S	171			
8		Test Well No. 10	Tennessee Valley Oil Co.	33 - 1S - 11W	672 G. L.	290				S	245	252		
9		Test Well No. 1	Tennessee Valley Oil Co.	5 - 1S - 10W	554 G. L.	135					S	11	117	
10		Test Well No. 2	Tennessee Valley Oil Co.	7 - 1S - 10W	567 G. L.	65				S	2[illegible]	39		
11	736	Killen No. 1	Tennessee Valley Oil Co.	4 - 1S - 10W	554 D. F.	2058						S	55	1043
12	843	D. R. Hollis No. 1	Candif Oil Co.	9 - 1S - 10W	579 D. F.	1537						S	?	1110
13		Test Well No. 3	Tennessee Valley Oil Co.	18 - 1S - 10W	743 G. L.	249				S	214	230		
14		C-24	Redder	17 - 1S - 9W	758 G. L.	194				S	182			
15	B-338	Mecke No. 1	B. L. Fillingame	20 - 1S - 10W	540 G. L.	366				S	18	66	151	
16	B-339	Mecke No. 2	B. L. Fillingame	21 - 1S - 10W	525 G. L.	1055						S	35	1030
17		Test Well No. 7	Tennessee Valley Oil Co.	30 - 1S - 10W	675 G. L.	188				S	165	184		
18		Test Well No. 5	Tennessee Valley Oil Co.	27 - 1S - 10W	5[illegible] G. L.	188				S	149	172		
19	53	Janet C. Simpson No. 1	J. L. Jaynes, et. al.	33 - 1S - 10W	530 D. F.	500					S	8	105	
20		C-37	H. B. Barnett	23 - 1S - 9W	750 G. L.	162				S	140			
21		B-62	U. S. Geol. Survey	15 - 1S - 8W	758 G. L.	168				S	143	151		
22		A-3	H[illegible]ert Goode	1 - 1S - 7W	838 G. L.	210				S	160	182		
23		A-60	U. S. Geol. Survey	33 - 1S - 7W	678 G. L.	225				S	55	60	137	
24	B-292	O'Neal Estate No. 1	A. D. Morton	8 - 2S - 13W	463 G. L.	2525				S	164	?	588	1482
25		M-3	Morton Estate	12 - 2S - 13W	712 G. L.	270		S	A	179	246	264		
26		M-7	Howard Reeder	14 - 2S - 13W	600 G. L.	306				S	280	293		
27		Water Well No. 1	National Park Service	32 - 2S - 13W	435 G. L.	344				S	206	222		
28		Water Well No. 3	National Park Service	33 - 2S - 13W	492 G. L.	253				S	239			
29		Water Well No. 4	National Park Service	33 - 2S - 13W	431 G. L.	180				S	162			
30	11	Mrs. N. Patterson No. 1	G. F. Mercer et. al.	8 - 2S - 12W	585 D. F.	2010				S	197	200	400	1350
31		N-47	U. S. Geol. Survey	2 - 2S - 12W	533 G. L.	270				S	205	215		
32		0-177	U. S. Geol. Survey	8 - 2S - 11W	530 G. L.	230				S	202	225		

MAP NUMBER	STATE OIL AND GAS BOARD PERMIT NUMBER	WELL NAME OR NUMBER	OPERATOR OR OWNER	LOCATION (section, township, range)	ELEVATION[1]	TOTAL DEPTH (feet)	QUATERNARY	CRETACEOUS	PENNSYLVANIAN	MISSISSIPPIAN	DEVONIAN	SILURIAN	UPPER AND MIDDLE ORDOVICIAN	LOWER ORDOVICIAN AND CAMBRIAN
							SYSTEM/SERIES PENETRATED[2] (depth in feet to top of System/Series)							
LAUDERDALE COUNTY - Cont.														
33		0-178	U. S. Geol. Survey	11 - 2S - 11W	662 G. L.	271				S	244			
34		0-179	U. S. Geol. Survey	30 - 2S - 11W	498 G. L.	211				S	200			
35		0-176	U. S. Geol. Survey	32 - 2S - 11W	480 G. L.	175				S	148	170		
36		0-175	U. S. Geol. Survey	33 - 2S - 11W	485 G. L.	227				S	183	211		
37		0-149	U.S. Geol. Survey	35 - 2S - 11W	515 G. L.	203				S	197			
38		0-106	U. S. Geol. Survey	25 - 2S - 11W	536 G. L.	260				S	185	212		
39		P-163	E. Campbell	4 - 2S - 10W	537 G. L.	[illegible]				S	37	50		
40	30	Shelton Estate No. 2	A. W. T. Davis and J. L. Jaynes, et. al.	9 - 2S - 10W	515 D. F.	549				S	35	50	153	
41	28	Shelton Estate No. 1	A. W. T. Davis and J. L. Jaynes, et. al.	10 - 2S - 10W	510 D. F.	525				S	30	45	138	
42	32	Shelton Estate No. 3	A. W. T. Davis and J. L. Jaynes	10 - 2S - 10W	535 D. F.	550				S	70	88	192	
43		P-20	R. A. Tidwell	12 - 2S - 10W	697 G. L.	163				S	145	153		
44		P-162	U. S. Geol. Survey	24 - 2S - 10W	603 G. L.	199				S	173	184		
45		Q-77	U. S. Geol. Survey	19 - 2S - 9W	535 G. L.	160				S	87	108		
46		Water Well No. 1	Mr. and Mrs. G. H. White	19 - 2S - 8W	515 G. L.	500				S	?	108	176	
47		X-46	U. S. Geol. Survey	5 - 3S - 11W	468 G. L.	163				S	106	126		
48		X-9	U. S. Geol. Survey	2 - 3S - 11W	600 G. L.	300				S	231	265		
49		X-40	U. S. Geol. Survey	14 - 3S - 11W	510 G. L.	260				S	210	235		
50		X-47	U. S. Geol. Survey	14 - 3S - 11W	430 G. L.	196				S	165	190		
51		T-33	Girl Scouts of America	1 - 3S - 7W	576 G. L.	166				S	150	161		
LAWRENCE COUNTY														
1		AY-22 + 00	Tennessee Valley Authority	34 - 4S - 8W	584 G. L.	466				S	427	442		
2		AY-74 + 00	Tennessee Valley Authority	35 - 4S - 8W	575 G. L.	402				S	362	375		
3	21	Connors No. G-130	Reynolds Metal Co.	17 - 5S - 8W	750 D. F.	4500				S	651	667	770	1872
4	1316	G. F. Brackin No. 1	R. M. Landers	32 - 5S - 8W	694 G. L.	1415				S	680	703	805	
5	1883	Love Place No. 1	R. M. Landers	10 - 6S - 9W	685 G. L.	2175				S	735	768	907?	1894
6	2539	Edsel Moors No. 1	Strahan Oil and Gas Co., Inc.	23 - 6S - 9W	563 G. L.	1251				S	760	790	917	
7	2832	Pace No. 1	Strahan Oil and Gas Co., Inc.	25 - 6S - 9W	635 G. L.	1450				S	848	884	1022	
8	821	Dave Rutherford No. 1	Bama Oil and Gas Co.	29 - 6S - 8W	616 G. L.	2200				S	770	790	920	1910
9	2761	Jones, et. al., No. 1	Strahan Oil and Gas Co., Inc.	6 - 7S - 8W	645 G. L.	1610				S	880	920	1130?	
10	919	United States of America No. 1	David [illegible] Brooks	26 - 7S - 8W	1036 G. L.	1815			S	190	1455	1496	1640	

MAP NUMBER	STATE OIL AND GAS BOARD PERMIT NUMBER	WELL NAME OR NUMBER	OPERATOR OR OWNER	LOCATION (section, township, range)	ELEVATION[1]	TOTAL DEPTH (feet)	QUATERNARY	CRETACEOUS	PENNSYLVANIAN	MISSISSIPPIAN	DEVONIAN	SILURIAN	UPPER AND MIDDLE ORDOVICIAN	LOWER ORDOVICIAN AND CAMBRIAN
							SYSTEM/SERIES PENETRATED[2] (depth in feet to top of System/Series)							
LAWRENCE COUNTY - Cont.														
11	B-283	Rob Jacobs No. 1	Fidelity Oil and Gas Co.	11 - 7S - 7W	645 G. L.	1500				S	797	824	979	
12	B-327	W. R. Jackson No. 1	Mid-Southern Petroleum Co.	30 - 7S - 6W	635 D. F.	2001				S	890	930	980	1957
13	754	Shirley Smith No. 1	Frank Burt and S. L. Bass	29 - 7S - 6W	670 G. L.	1605				S	917	943	983	
14	201	Shirley Smith No. 1	R. M. Landers	29 - 7S - 6W	660 D. F.	1603				S	875	900	960	
15	1587	Core Test No. 2	Murphy Oil Corp.	17 - 8S - 9W	965 G. L.	908			S	250				
LIMESTONE COUNTY														
1		B-025-31	Geol. Survey of Alabama	17 - 1S - 4W	757 G. L.	103				S	90	93	95	
2		B-025-15	Geol. Survey of Alabama	28 - 1S - 4W	835 G. L.	83				S	60	A	65	
3	B-334	Carter No. 1	Shaw, Johnson and Thompson	35 - 2S - 5W	740 G. L.	520				S	120	A	125	
4		B-025-28	Geol. Survey of Alabama	8 - 2S - 4W	765 G. L.	103				S	80	A	85	
5		B-025-16	Geol. Survey of Alabama	21 - 2S - 4W	773 G. L.	103				S	75	A	80	
6	835	G. C. Bridges No. 1	G. W. Jones and Sons	10 - 2S - 3W	867 D. F.	2506				S	38	A	47	1050
7		Athens C. T. -6	U. S. Geol. Survey	4 - 3S - 4W	711 G. L.	82				S	73	A	75	
8		Limestone Terrane Test Hole No. 9	Geol. Survey of Alabama	32 - 3S - 4W	680 G. L.	154				S	143	A	145	
9		B-025-25	Geol. Survey of Alabama	35 - 3S - 4W	618 G. L.	103				S	A	A	75	
10		Glaze No. 1	Shaw, Johnson and Thompson	7 - 3S - 3W	691 D. F.	331				S	95	A	100	
MADISON COUNTY														
1		MT-135	U. S. Geol. Survey	3 - 2S - 2W	825 G. L.	140				S	95	100		
2		MT-150	U. S. Geol. Survey	15 - 2S - 2W	820 G. L.	227				S	A	A	115	
3		MT-136	U. S. Geol. Survey	23 - 2S - 2W	808 G. L.	186				S	140	155		
MARION COUNTY														
1	553	Miller-Childers Unit No. 1	Warrior Basin Oil Corp.	12 - 9S - 15W	455 D. F.	4458	S	A	A	10	1450	1577	1940	2608
2	1060	Maxine Murray No. 1	Mrs. Mary Taylor Maury	19 - 10S - 15W	469 G. L.	1763		S	240?	350?				
3	B-211	Hamilton No. 1	A. M. Oil, Gas and Pipeline Co.	23 - 10S - 14W	438 D. F.	2393			S	255	1720	1862	2193	
4	2829	L. Burleson No. 10	Galaxy Energies, Inc.	22 - 10S - 12W	644 K. B.	3500			S	382	1810	1848	2184	3014
5	1609	C. A. Lewis No. 1	Willard McKinney	28 - 11S - 15W	474 D. F.	2173		S	280?	850	2125?			
6	B-331	J. F. Clarke No. 1-A	Seaboard Oil Company	28 - 11S - 14W	380 G. L.	2686		S	35	?	2098	2265	2588	
7	408	Arthur Ritch No. 1	H. L. Cullet	27 - 11S - 14W	403 D. F.	4710			S	?	2045	2200	2561	3215
8	1838	H. W. Mathews No. 25-1	McMoRan Exploration Co.	25 - 11S - 14W	644 D. F.	2310		S	174?	1120				

MAP NUMBER	STATE OIL AND GAS BOARD PERMIT NUMBER	WELL NAME OR NUMBER	OPERATOR OR OWNER	LOCATION (section, township, range)	ELEVATION[1]	TOTAL DEPTH (feet)	QUATERNARY	CRETACEOUS	PENNSYLVANIAN	MISSISSIPPIAN	DEVONIAN	SILURIAN	UPPER AND MIDDLE ORDOVICIAN	LOWER ORDOVICIAN AND CAMBRIAN
							SYSTEM/SERIES PENETRATED[2] (depth in feet to top of System/Series)							
MARION COUNTY - Cont.														
9	386	Howard-Mays-Hobson No. 1	Benedum-Trees Oil Company	7 - 11S - 13W	420 G. L.	3510	S	A	18	?	1975	2071	2412	3032
10	943	F. N. B. Trustee No. 2	E. H. Woods	27 - 11S - 12W	787 D. F.	2115		S	110	1050				
11	738	F. N. B. Trustee No. 2	Walter Pearson and Associates	7 - 11S - 11W	[illegible]37 D. F.	1641	S	A	14	645				
12	1828	H. W. Mathews et. al. No. 1	McMoRan Exploration Co.	12 - 12S - 14W	711 D. F.	2400		S	200?	1345				
MORGAN COUNTY														
1	B-264	English No. 1	Albany-Decatur Oil and Gas Co.	6 - 6S - 4W	547 D. F.	4130				S	350	372	410	1790
WINSTON COUNTY														
1	16	J. J. Henderson No. 1	G. L. Reasor	30 - 9S - 10W	950 D. F.	3128		S	66	565	1905	1935	2210	31[illegible]
2	2284	[illegible]I. Batchelor No. 32-14	Energy Explorations, Inc.	32 - 9S - 10W	922 K. B.	3220		S	?	?	1941	1971	2262	3116
3	B-152	Woodard No. 1	Woodward Oil and Gas Co.	6 - 10S - [illegible]0W	731 D. F.	2982		S	9	615	1735	1760	[illegible]	2915
4	1167	Marwin Corp. No. 1	Mt. Carmel Drilling Co.	1 - 10S - 10W	836 D. F.	1534			S	680				
5	617	W. A. Gamble No. 1	Great Southern Oil Co.	20 - 10S - 10W	909 D. F.	3604			S	860	[illegible]054	2092	2390	3216

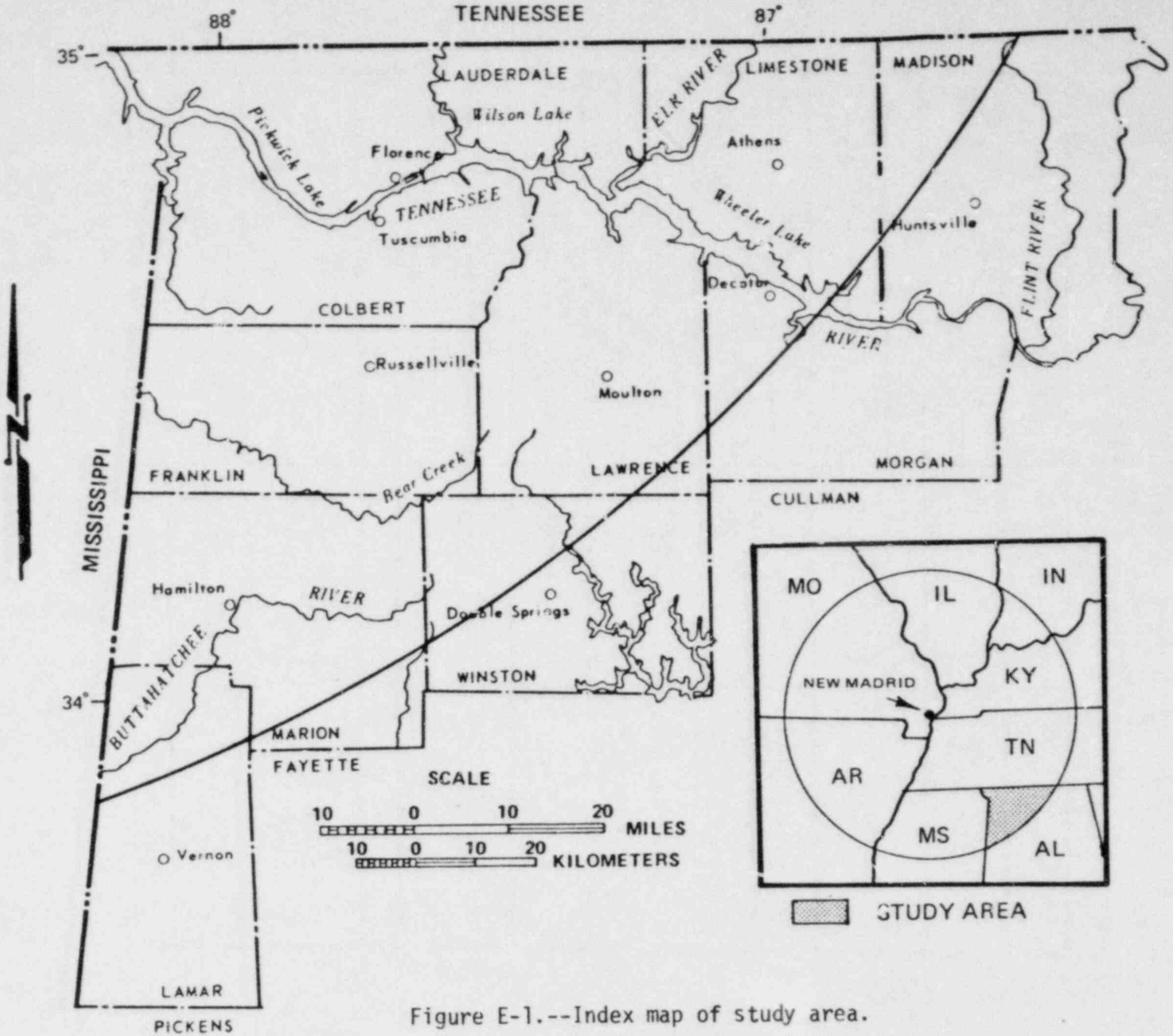


Figure E-1.--Index map of study area.

SYSTEM	SERIES	UNIT	
QUATERNARY		ALLUVIAL AND LOW TERRACE DEPOSITS	
		HIGH TERRACE DEPOSITS	
CRETACEOUS	UPPER	EUTAW FORMATION	
		TUSCALOOSA GROUP	GORDO FORMATION
			COKER FORMATION
PENNSYLVANIAN	LOWER	POTTSVILLE FORMATION	
? ?		PARKWOOD FORMATION	
MISSISSIPPIAN	UPPER	BANGOR LIMESTONE	
		FLOYD SHALE	HARTSELLE SANDSTONE
			PRIDE MOUNTAIN FORMATION
		TUSCUMBIA LIMESTONE	
	LOWER	FORT PAYNE CHERT	
		MAURY FORMATION	
DEVONIAN		CHATTANOOGA SHALE	
		ROSS FORMATION	
		DEVONIAN UNDIFFERENTIATED	
SILURIAN		SILURIAN UNDIFFERENTIATED	
ORDOVICIAN	UPPER	RICHMOND, AYSVILLE, EDEN AND NASHVILLE GROUPS UNDIFFERENTIATED	
	MIDDLE		
		STONES RIVER GROUP UNDIFFERENTIATED	
	LOWER	KNOX GROUP UNDIFFERENTIATED	
CAMBRIAN	UPPER		

Figure E-2.--Geologic units in the study area.

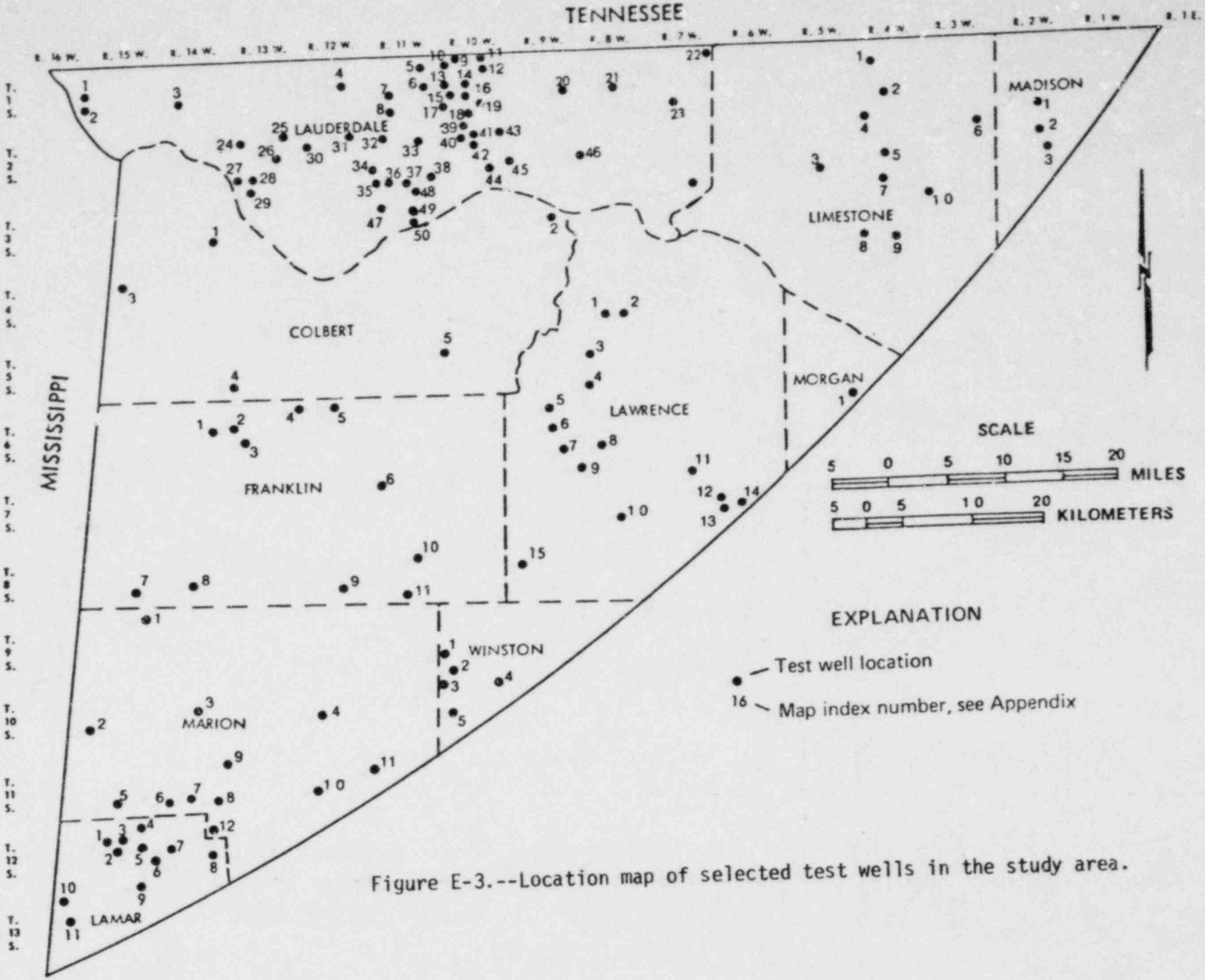


Figure E-3.--Location map of selected test wells in the study area.

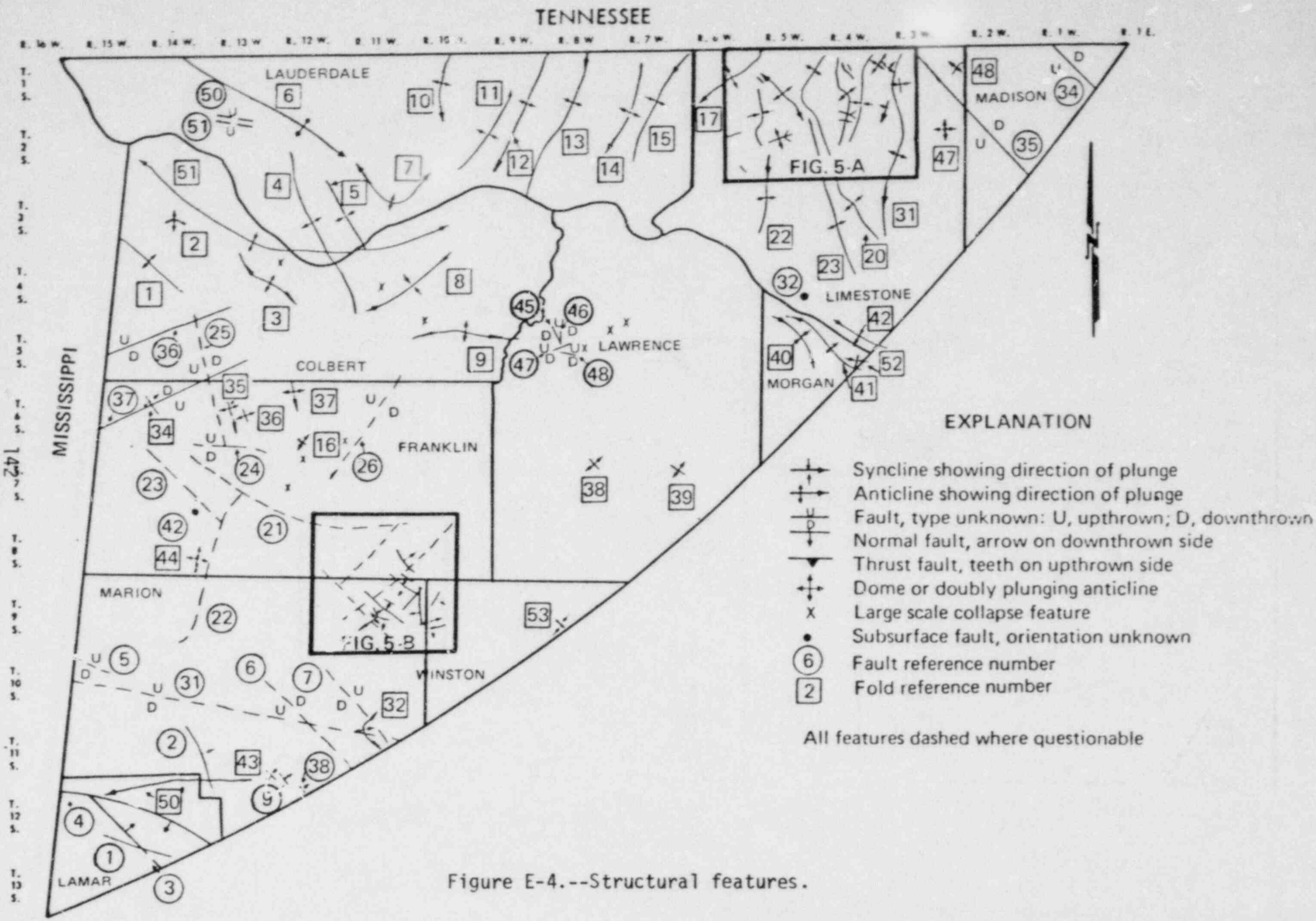
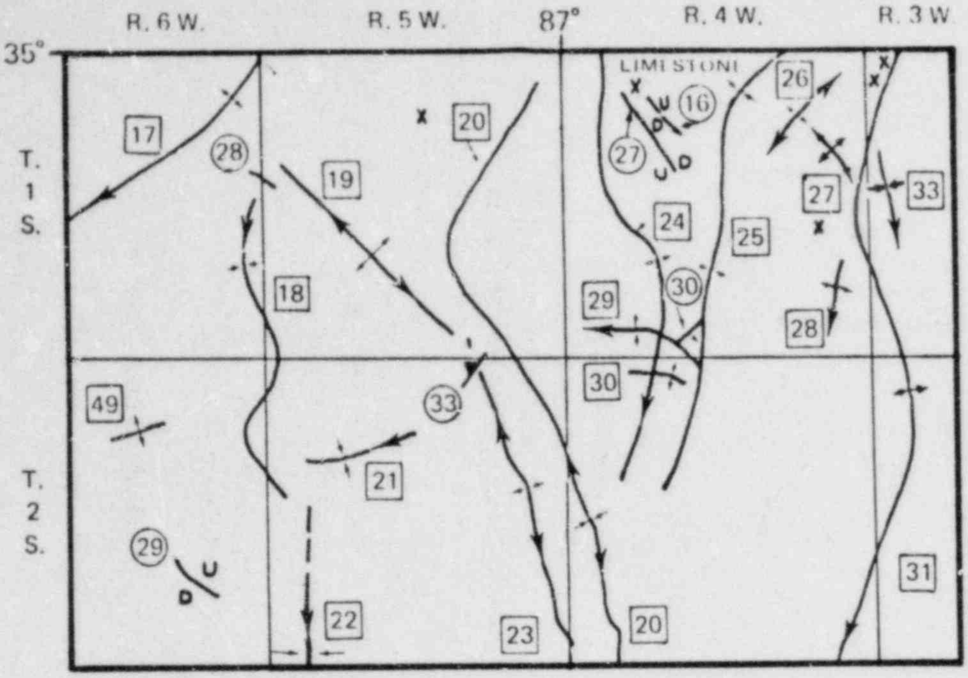
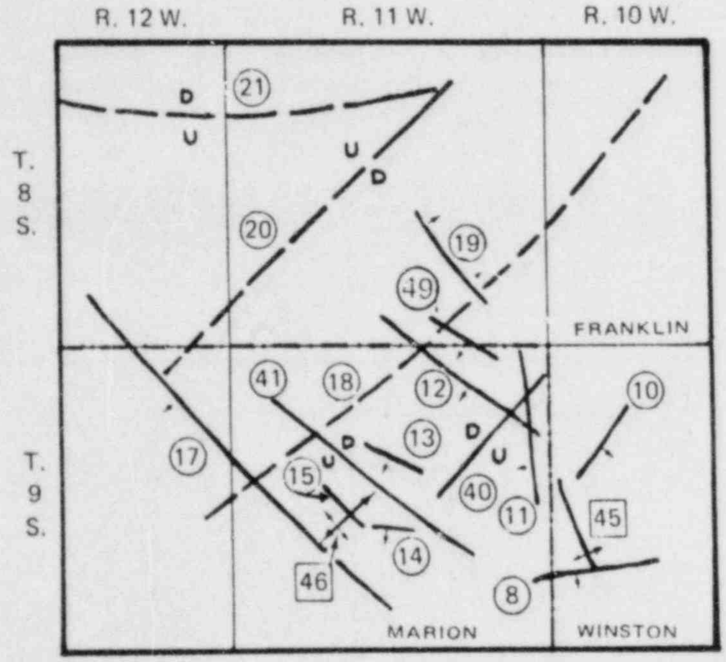
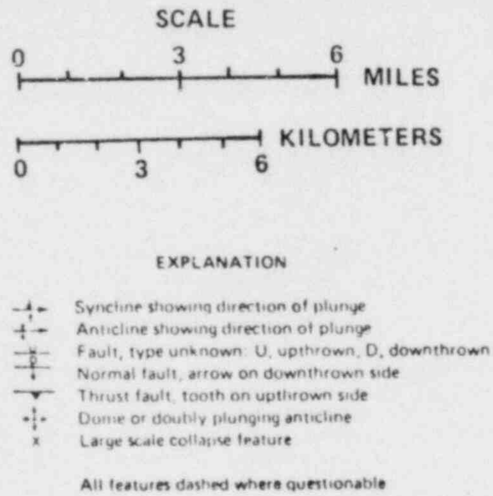


Figure E-4.--Structural features.



A. - Structural features, north central Limestone County, Alabama.





B. - Structural features, parts of Franklin, Marion, and Winston Counties, Alabama.

(21) - Fault reference number

[40] - Fold reference number

Figure E-5.--Structural features in parts of Limestone, Franklin, Marion, and Winston Counties, Alabama.

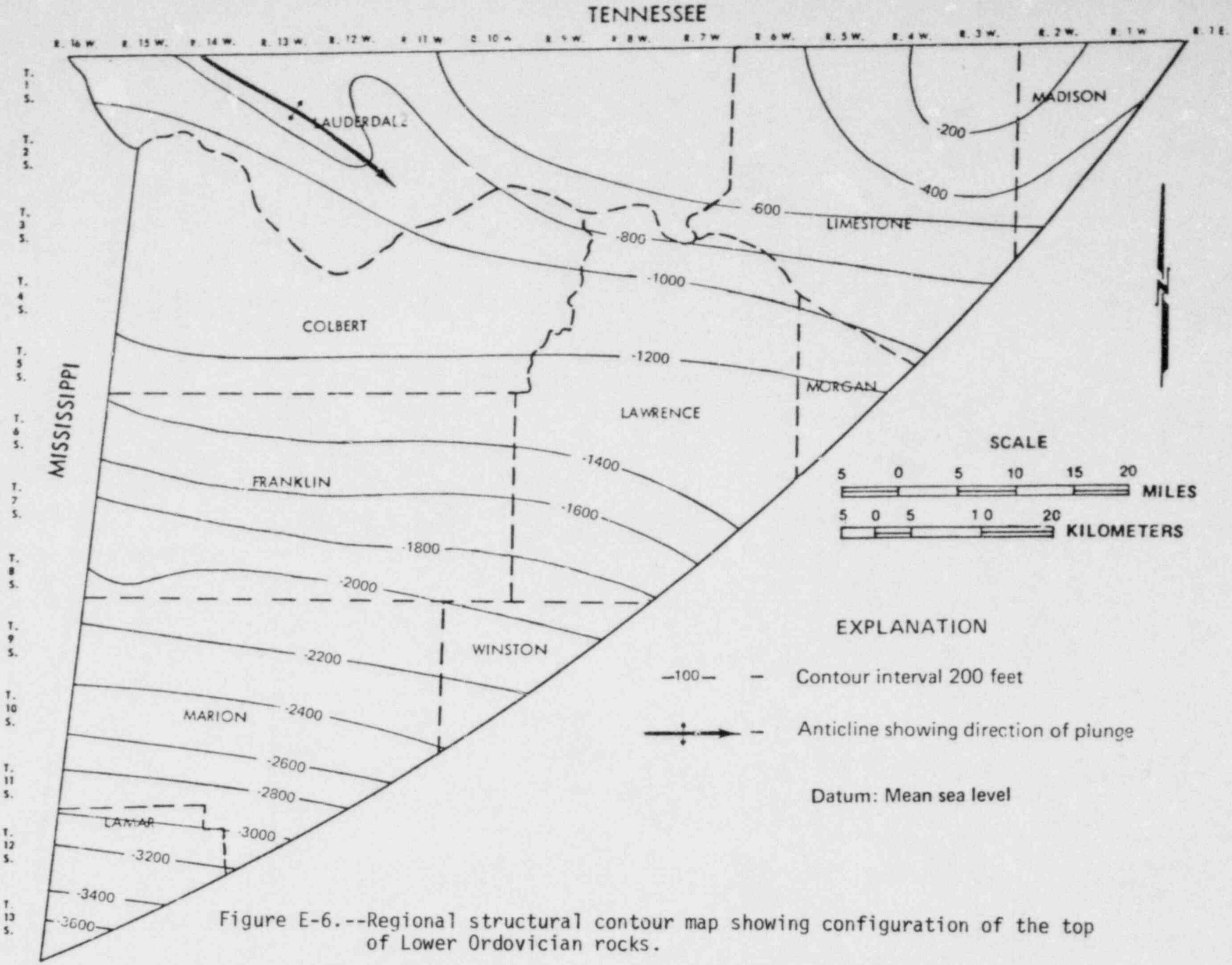


Figure E-6.--Regional structural contour map showing configuration of the top of Lower Ordovician rocks.

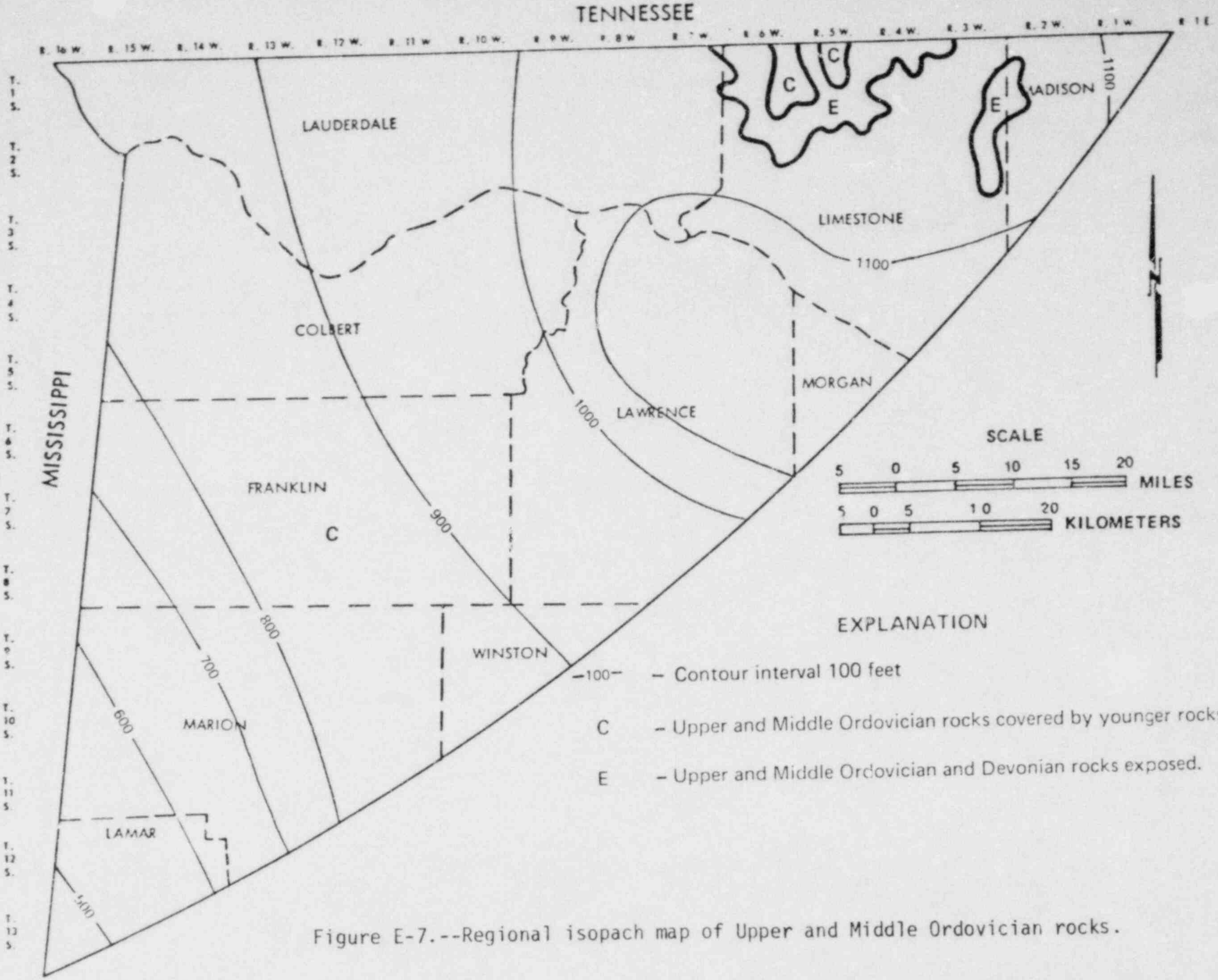


Figure E-7.--Regional isopach map of Upper and Middle Ordovician rocks.

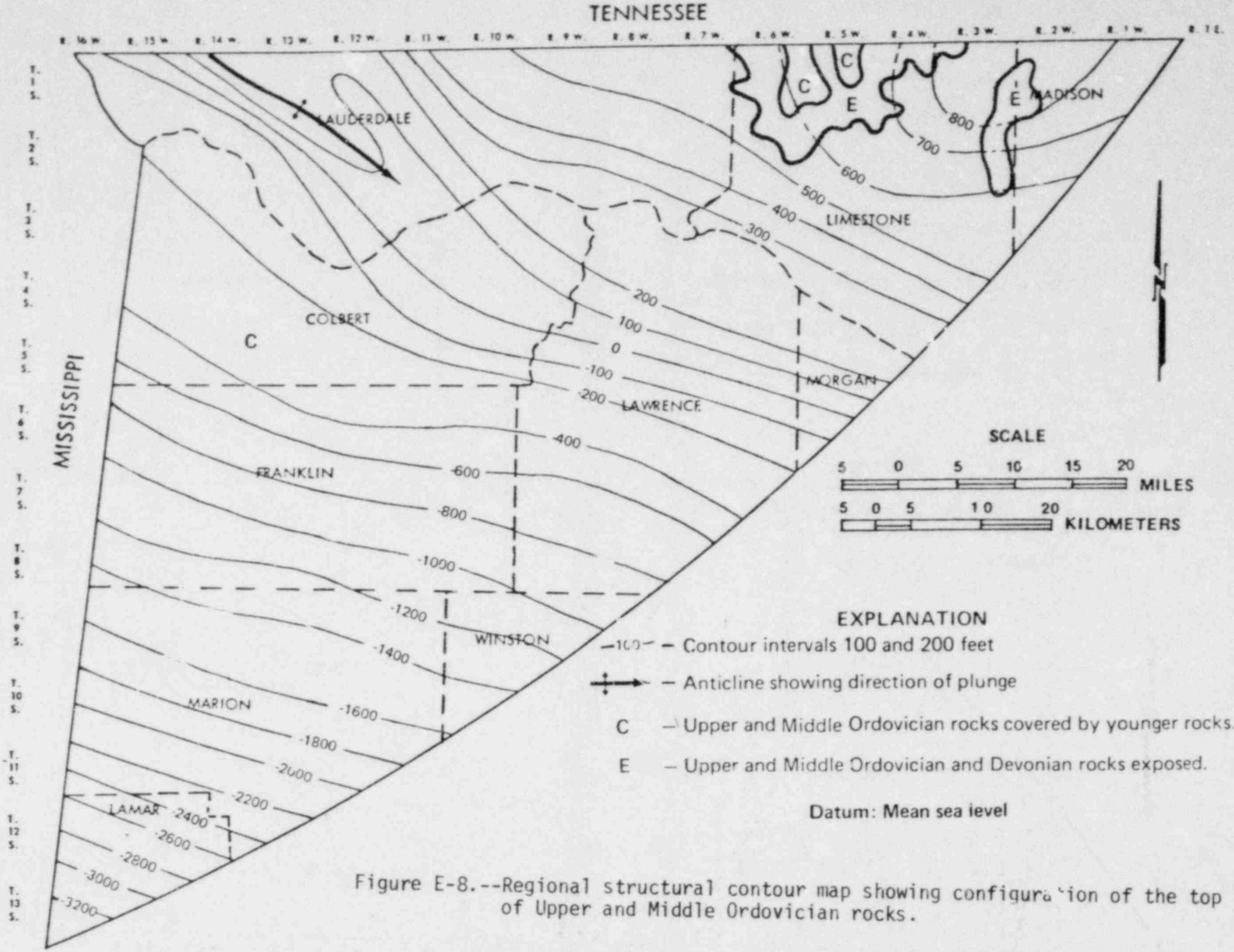


Figure E-8.--Regional structural contour map showing configuration of the top of Upper and Middle Ordovician rocks.

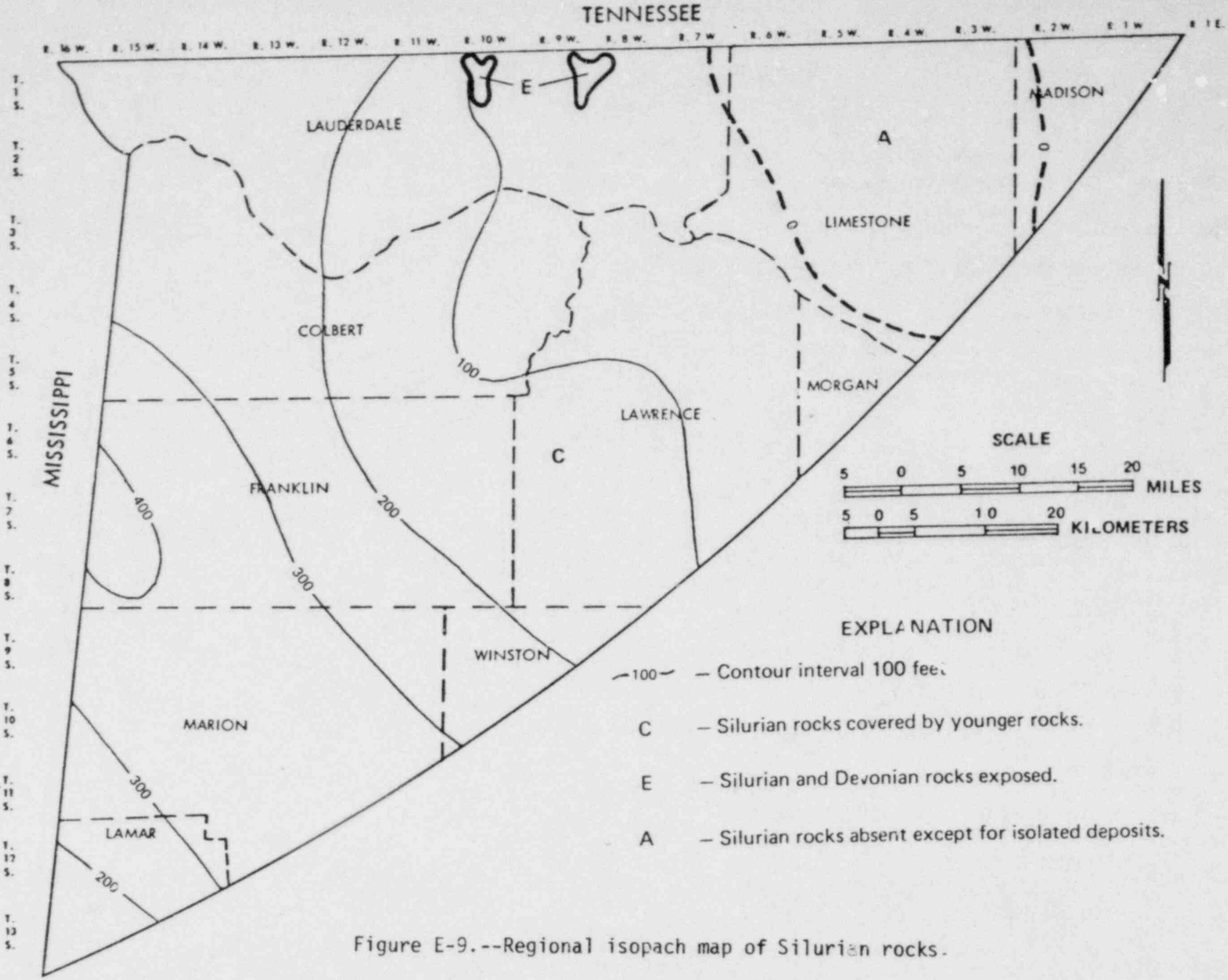


Figure E-9.--Regional isopach map of Silurian rocks.

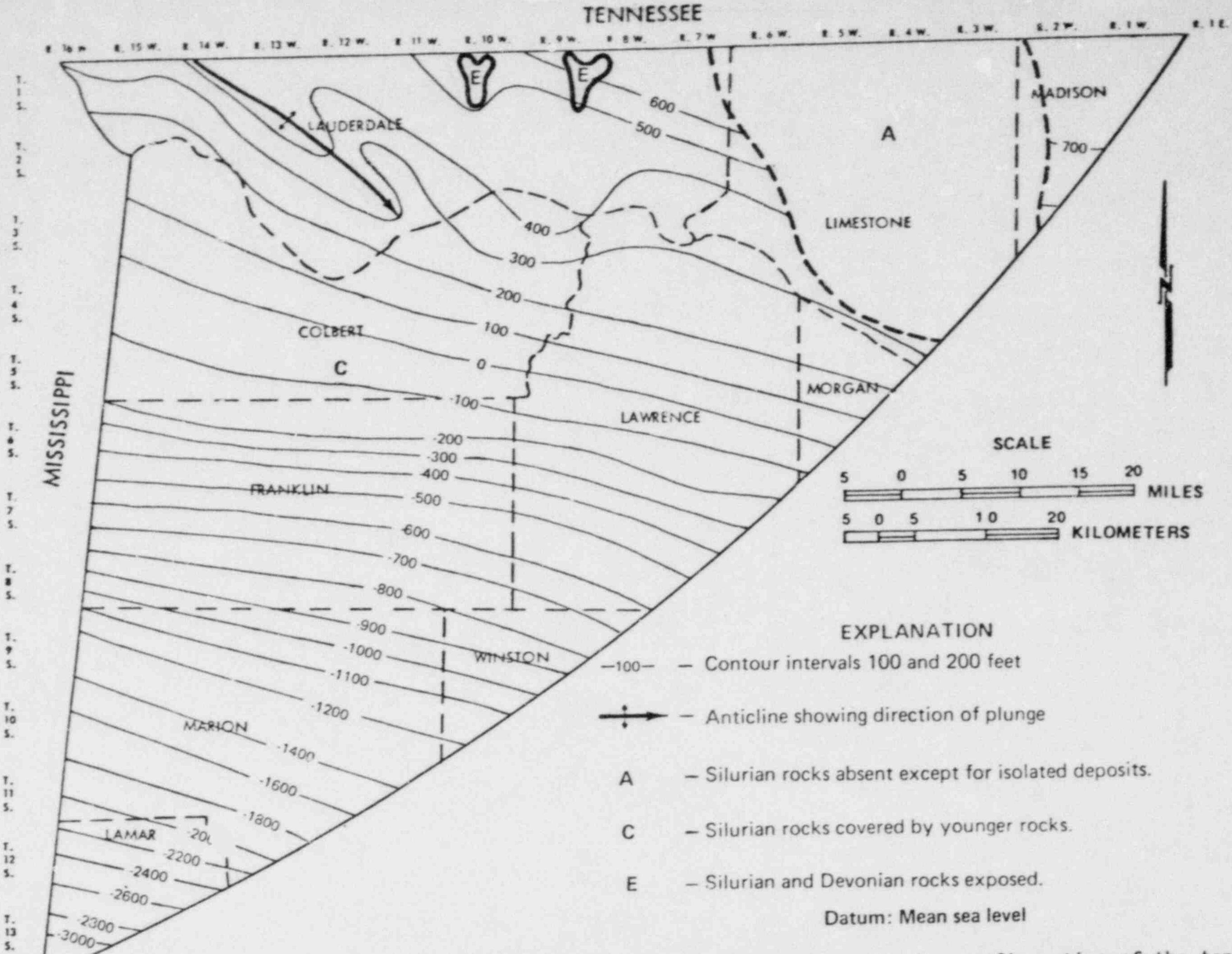


Figure E-10.--Regional structural contour map showing configuration of the top of Silurian rocks.

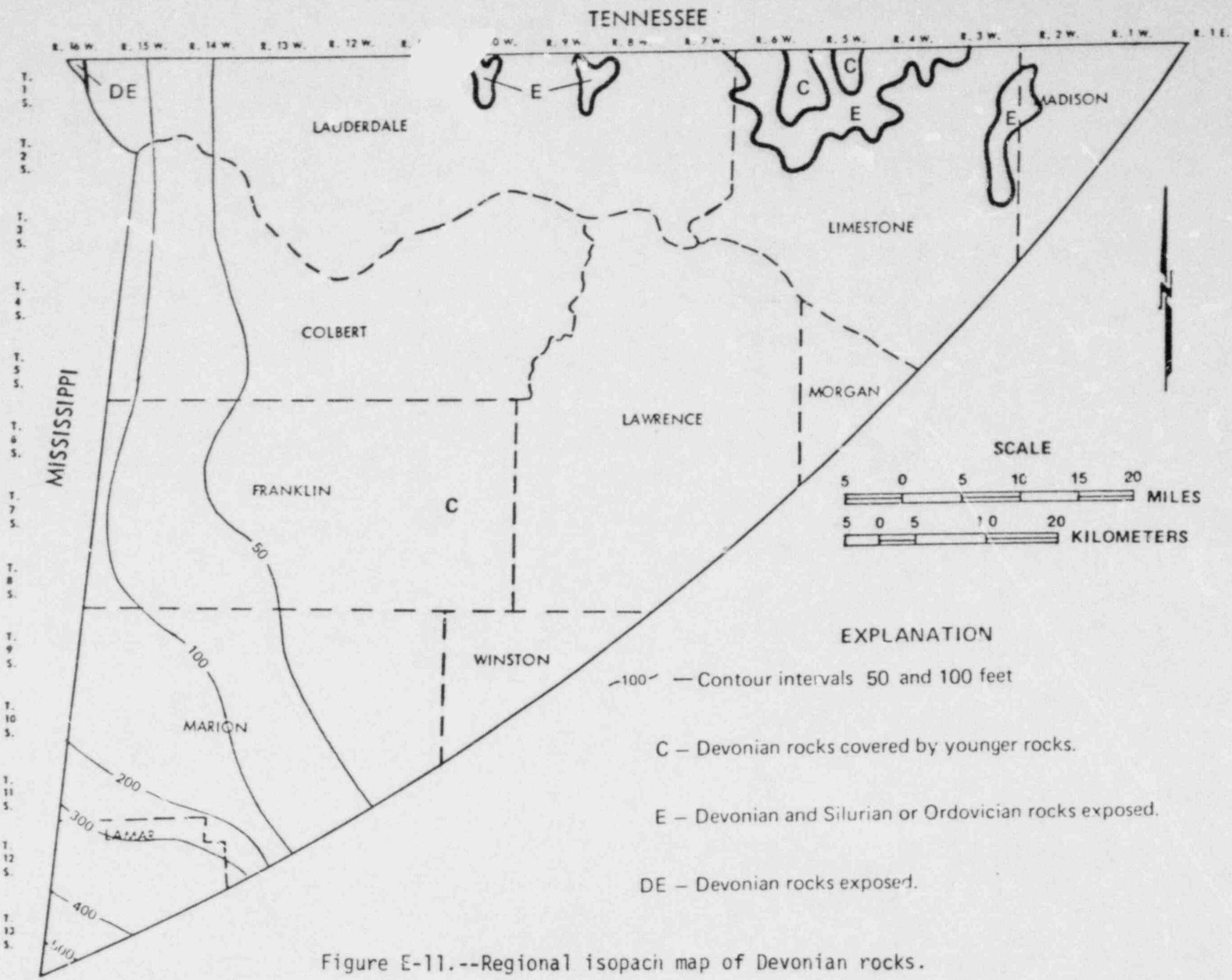


Figure E-11.--Regional isopach map of Devonian rocks.

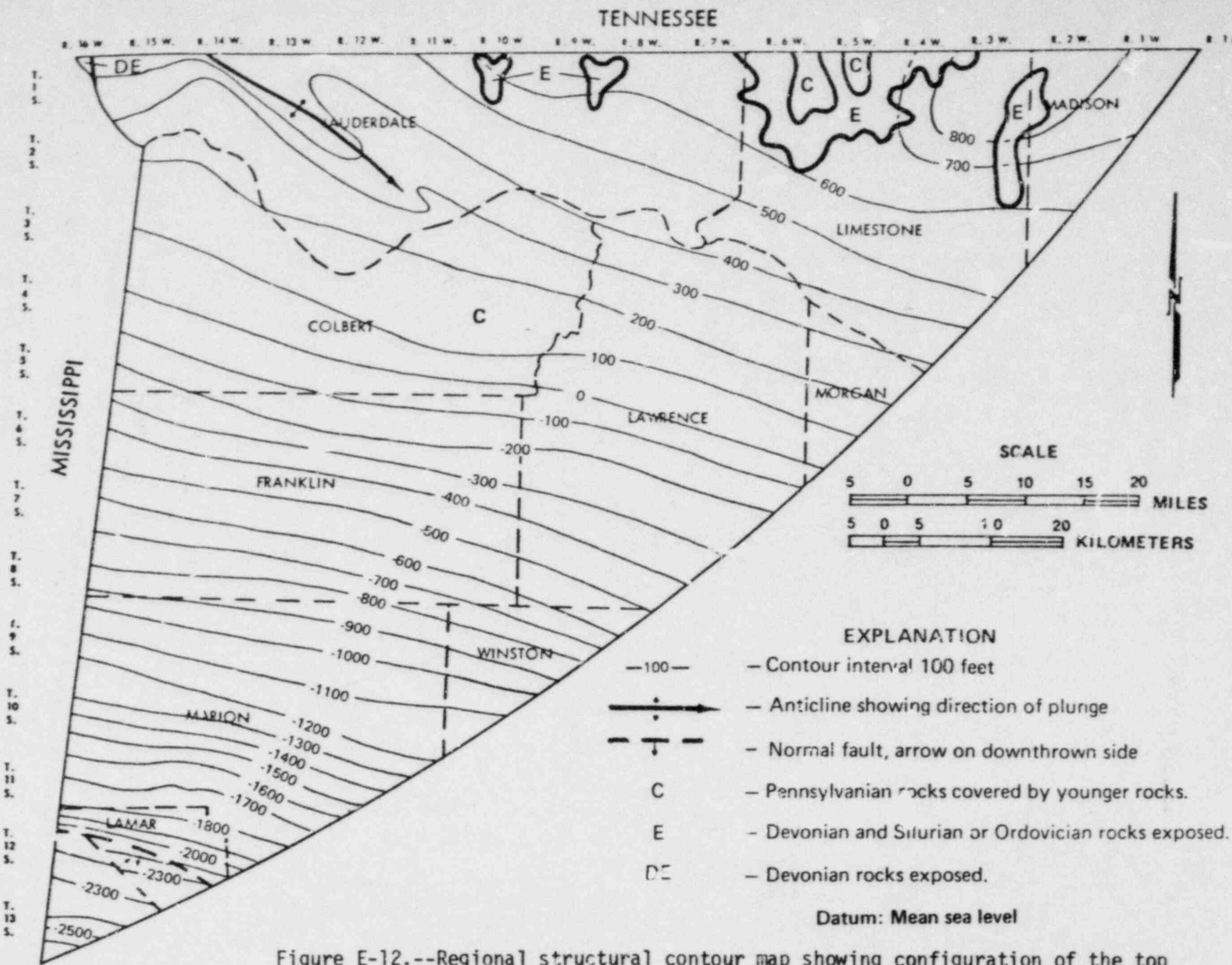


Figure E-12.--Regional structural contour map showing configuration of the top of Devonian rocks.

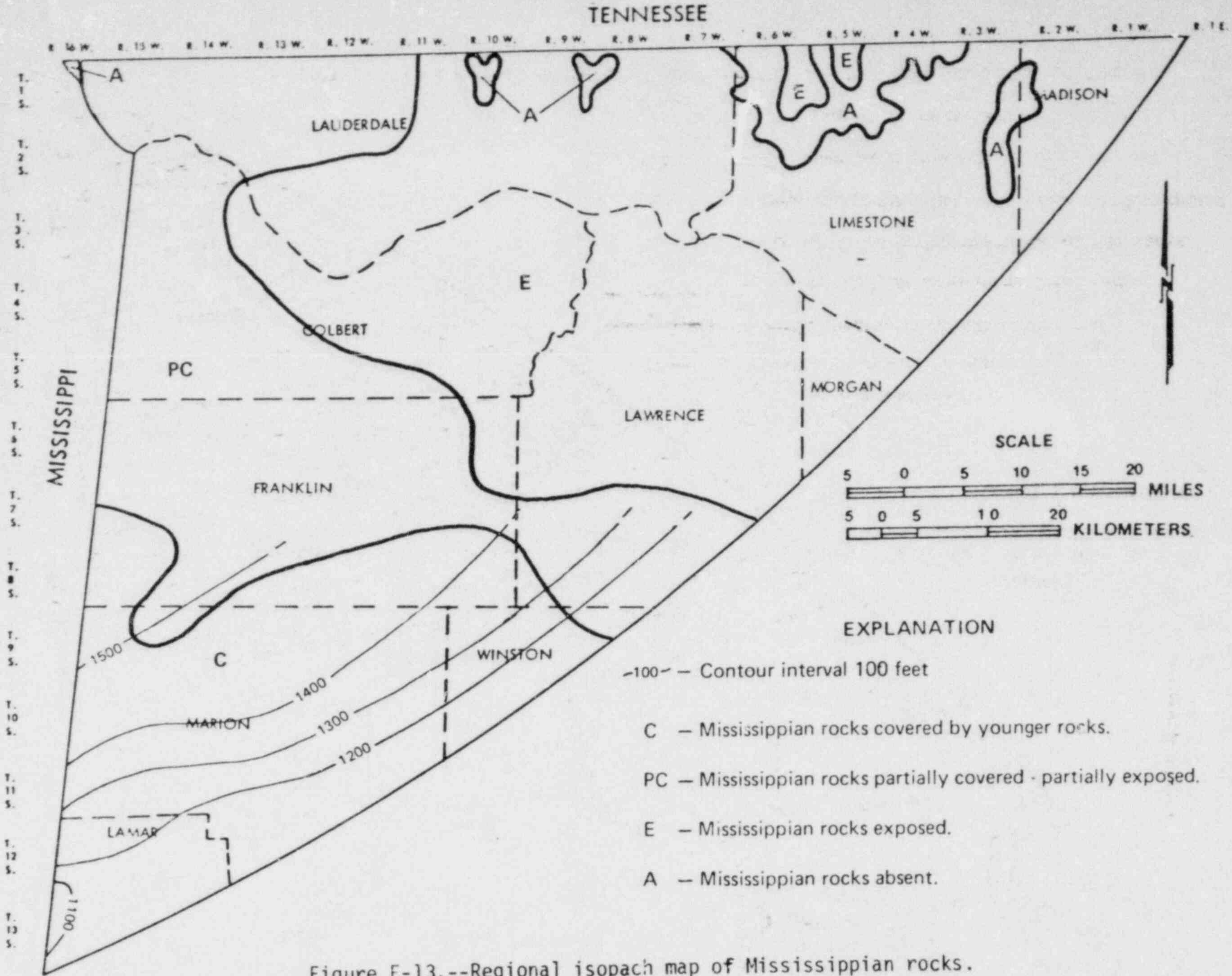


Figure E-13.--Regional isopach map of Mississippian rocks.

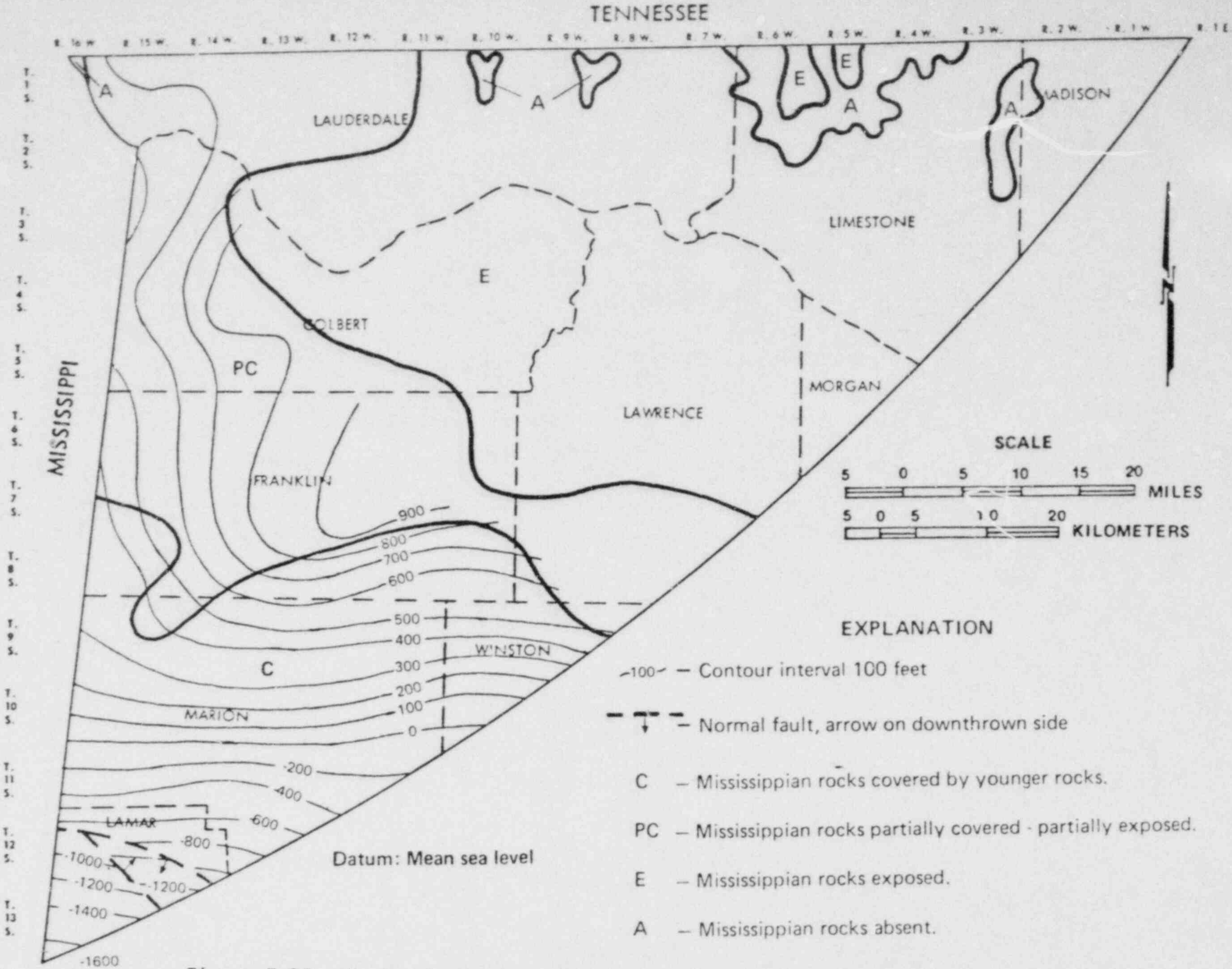


Figure E-14.--Regional structural contour map showing configuration of the top of Mississippian rocks.

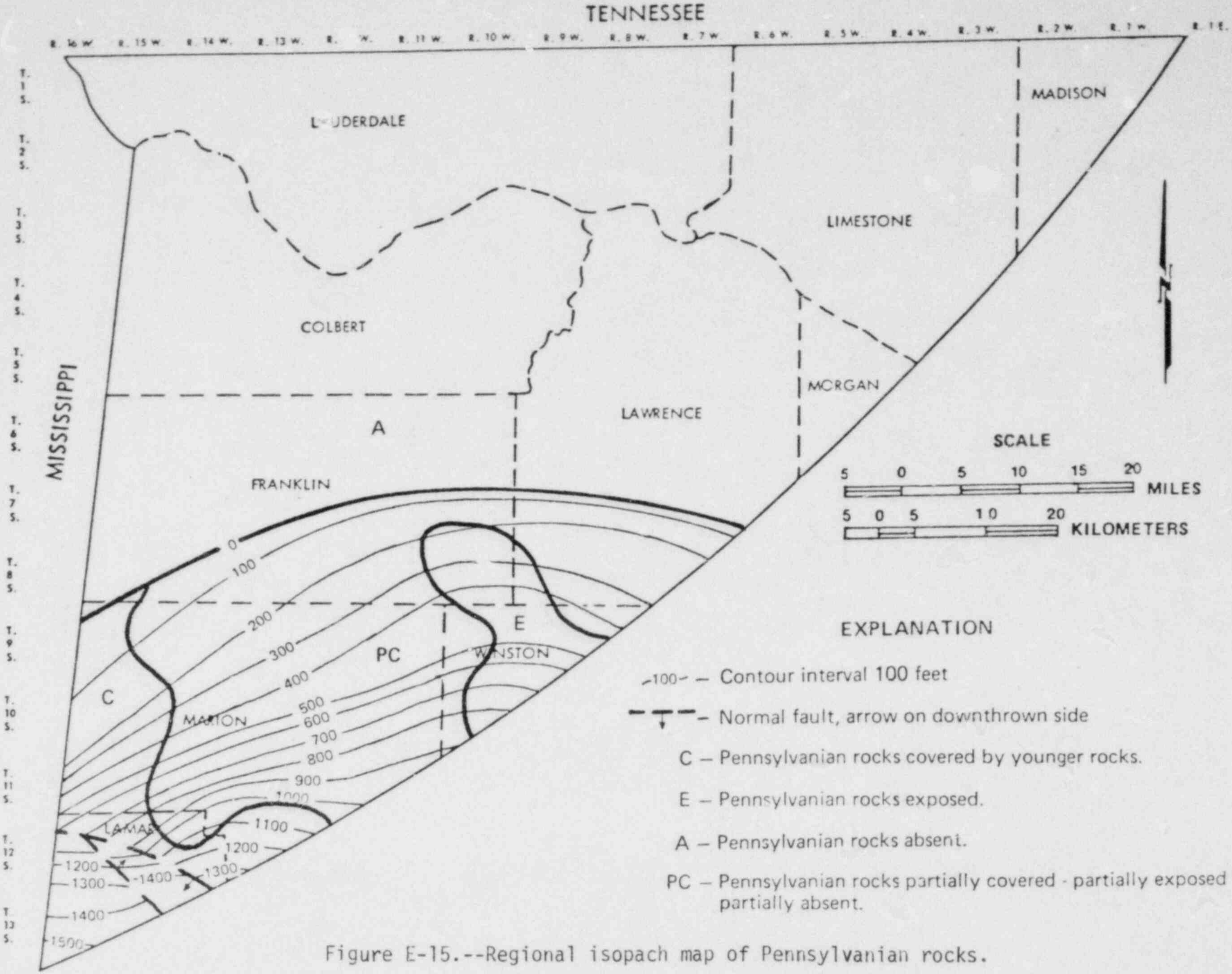


Figure E-15.--Regional isopach map of Pennsylvanian rocks.

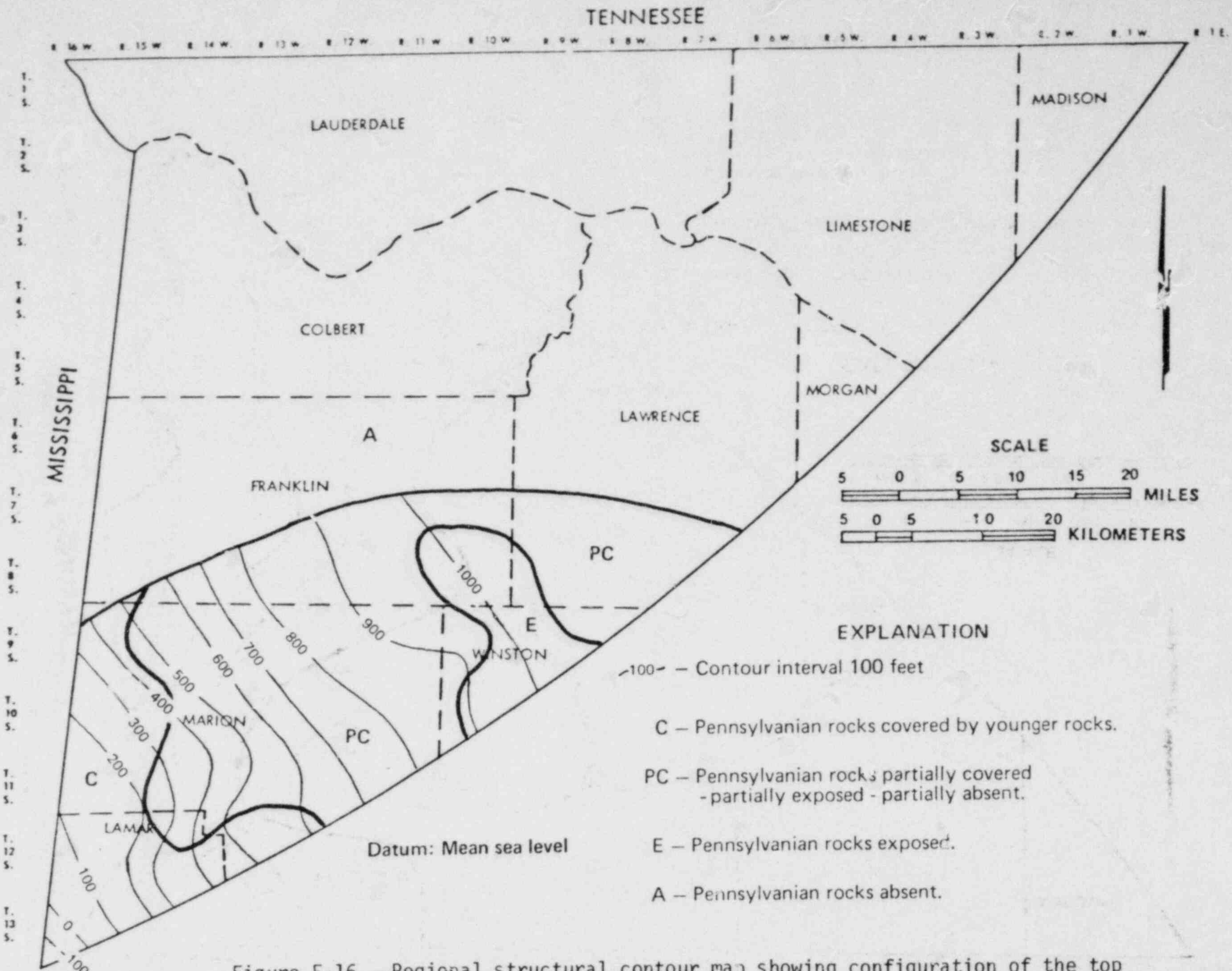


Figure E-16.--Regional structural contour map showing configuration of the top of Pennsylvanian rocks.

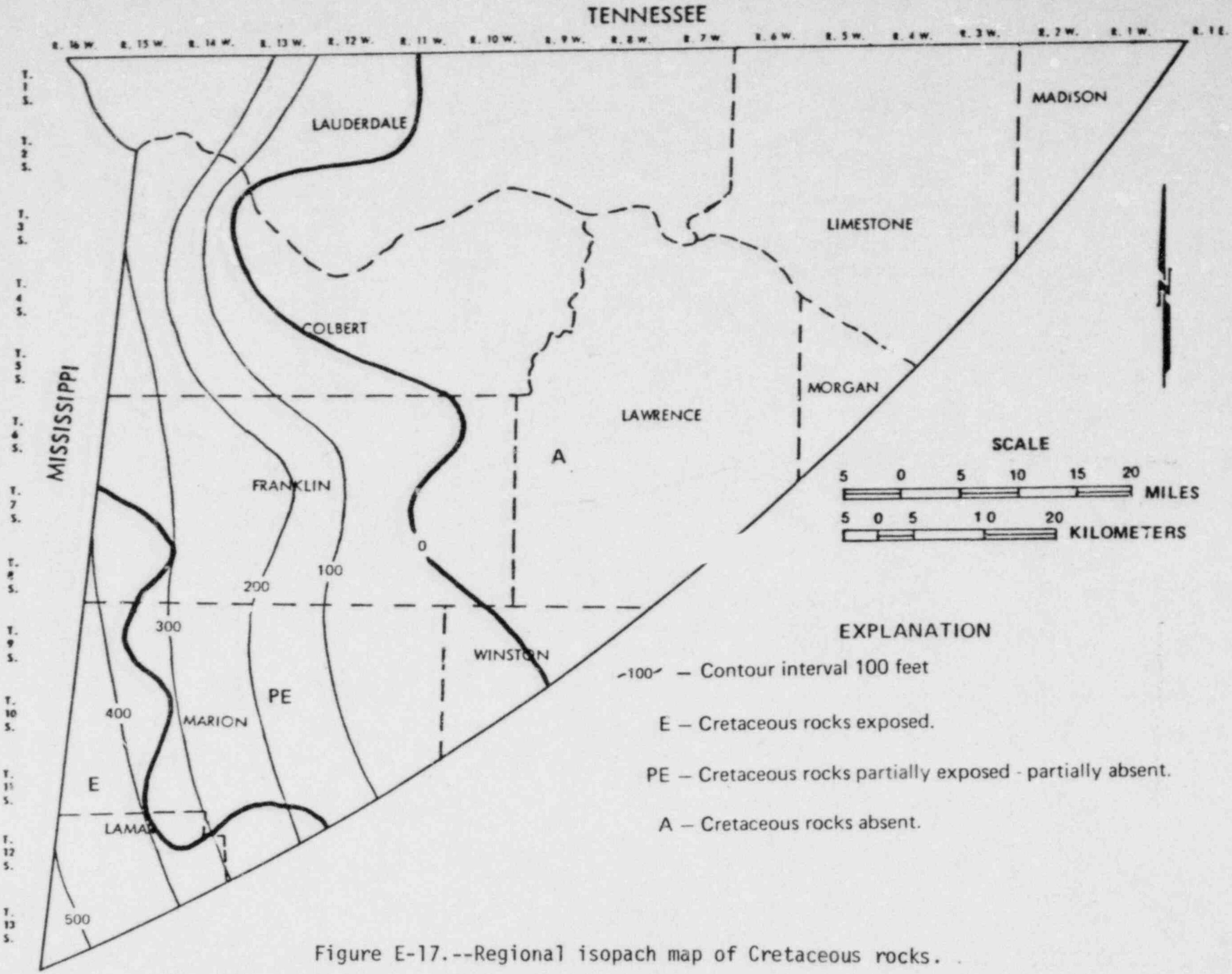


Figure E-17.--Regional isopach map of Cretaceous rocks.

STRUCTURAL GEOLOGIC STUDY OF SOUTHEASTERN MISSOURI

Annual Progress Report - Fiscal Year 1980

Contract No. NRC-04-78-206

Ronald A. Ward
Missouri Department of Natural Resources
Division of Geology and Land Survey

ABSTRACT

Field investigation along the western half of the Missouri portion of Crowleys Ridge has resulted in additional documentation of faulting involving Tertiary and older deposits. Fifteen test-holes were drilled at the Lowe Industry Bloomfield clay plant 5½ miles northeast of Bloomfield at the eastern margin of Crowleys Ridge. The main fault examined strikes N. 65° W. and dips northeast, with 16 feet of displacement. Other faults at this location have similar northwest-southeast strikes. All faults observed appear to be normal; no evidence of strike-slip movement was encountered. From this investigation it is concluded that faulting has not disturbed the overlying Pleistocene colluvial silts and gravels or the Pleistocene loess above them. Documentation has been accomplished by detailed analysis and correlation of test-hole samples traversing the fault zone. The faulting investigated in this area is thus post-Paleocene and pre-Pleistocene and may be temporally related to the emplacement or renewed activity of the "Bloomfield pluton." Recent interest in age determination of the "Bloomfield pluton," heretofore considered Precambrian in age, may help answer questions regarding this matter.

Field reconnaissance of much of the Crowleys Ridge area this year has not demonstrated that any other significant faulting has affected the Plio-Pleistocene and Pleistocene deposits in the area. A thick loess cover over the area partially masks other possible faults.

SUMMARY

1. The major activity this year has been concentrated at the Lowe Industry Bloomfield clay plant in sec. 28, T. 27 N., R. 11 E., Stoddard County, Missouri. Excellent exposure of normal faulting in Cretaceous and Tertiary deposits has been confirmed by drilling 15 test-holes across the major fault, which trends N. 65° W. and dips northeast, with 16 feet of displacement in the Porters Creek Clay (Paleocene). Plane-table mapping of the entire pit area, supported by analysis of company drill records, permitted accurate location of several other faults which generally strike northwest. Faulting does not appear to have affected the

overlying Pleistocene colluvial silts and gravels and the Pleistocene loess deposits above them. In-place Plio-Pleistocene gravels ("Mounds type") were not observed at this location. The faulting may be temporally related to emplacement of the "Bloomfield pluton" if the pluton is much younger than previously thought.

2. Reconnaissance of the Crowleys Ridge area attempted to locate faults affecting Plio-Pleistocene and younger deposits in the area. The only significant fault observed is at the Rock Knob gravel locality. Other faults probably exist but have not been discovered, due to the loess mantle covering the entire area.
3. Visual examination of the Rock Knob gravel locality, sec. 35, T. 27 N., R. 9 E., Stoddard County, Missouri revealed a normal fault cutting McNairy sands (Cretaceous) and overlying Plio-Pleistocene gravels. Displacement of 3 1/3 feet (1 meter) along this fault, which strikes 54° W. and dips 80° to the southwest, may be due to differential subsidence or perhaps a deeper tectonic event.

PURPOSE OF INVESTIGATION

This year's investigation, as well as the previous year's study, has focused on developing increased understanding of the age of faulting along Crowley's Ridge (Figure F-1). Specifically, it has attempted to determine whether faulting affecting Cretaceous and Tertiary deposits also cuts the overlying Pleistocene loess. An additional purpose has been to further document faulting affecting Cretaceous-Tertiary and older deposits in this region. It is to be hoped this work will help answer larger questions concerning the regional tectonic history of the region.

BACKGROUND

General Statement

This report represents the fourth year of investigations by the Missouri Geological Survey. First-year activities included an inventory of information for the Missouri portion of the area within a 200-mile radius around the town of New Madrid. The second year's activity involved making a geologic map (scale 1:62,500) from early drill records (1875 hand-drilled

W.P.A. test-holes) in addition to further field work by the Survey staff. Third-year activity dealt with test drilling along Beech Grove Branch (4 miles northeast of Bloomfield) in order to establish Lower Tertiary faulting and to present evidence for the lack of disturbance in the overlying Plio-Pleistocene and Pleistocene sequence above. This year's activities have concentrated on an area 4 miles north of the Beech Grove Branch site along the eastern edge of Crowleys Ridge, specifically the Lowe Industry Bloomfield clay plant.

Structural Geology

The early work of Farrar and McManamy (1937), Stewart and McManamy (1942), and Grohskopf (1955), first showed faulting existed in the Missouri portion of the Mississippi embayment. Two major fault sets trending northwest-southeast and northeast-southwest have been identified and are similar to the fault system in the Ozark highlands. Investigations by the Missouri Survey for the past two years have dealt primarily with the northwest-southeast fault set. Based on field observations, it is the conclusion of the investigator that the faulting which trends northeast-southwest may be partly due to slumping, the likelihood of which is increased by the fact that the northeast-southwest fault set generally parallels the long axes of Crowleys Ridge and Benton Hills.

The structural implications of faulting as they may relate to the Bloomfield geophysical feature, illustrated in Figure F-2, are only tentative at this time. If the time of emplacement of the inferred pluton is much younger than its suggested Precambrian age, faulting in the area may be genetically related. The answer to this must await further investigation.

Stratigraphy

A brief discussion of the stratigraphy of the entire area is presented to provide the reader with information important to an understanding of this year's investigation.

Figure F-3 is a detailed stratigraphic section of the Cretaceous and Tertiary Systems in southeast Missouri. A more detailed description of the stratigraphy and geologic history will be included in the final report.

Along the Missouri portion of Crowleys Ridge-Benton Hills, the Mesozoic is represented by the Cretaceous McNairy and Owl Creek Formations, but subsurface data suggests that older Cretaceous sediments are present in the extreme southeast corner of the Missouri Bootheel. The McNairy can be divided into two identifiable units: a lower sand unit with a quartzitic boulder bed near the top locally, and an upper unit consisting of alternating sands and clay. The thickness of this formation ranges from 0 to slightly more than 200 feet. Overlying the McNairy is the Owl Creek Formation, mostly sandy clay, with green and brown glauconite disseminated throughout. The Owl Creek is dark gray on fresh surfaces and brownish-blue in weathered exposures. Thickness ranges from 0 to 20 feet.

Overlying the Mesozoic are Cenozoic deposits of the Tertiary System, which are represented by two, possibly three, series: Paleocene, Eocene, and Pliocene (?) (Figure F-3). The Clayton Formation, ranging in thickness from 0 to 10 feet, is the basal Tertiary unit and is lithologically very distinctive. It is green due to the presence of abundant glauconite and is composed of sand, clay, limonite, and some fossilized material. The Porters Creek Clay, lying above the Clayton, ranges from 0 to 200 feet thick. This unit is easily distinguishable from the other formations, because it is a massive clay, fairly uniform throughout, and dark gray on fresh damp surfaces. The clay unit contains many joints, along which there is usually a small amount of iron oxide staining. Boulders of siderite have been observed near the top of the Porters Creek. Above the Porters Creek Clay lies the Ackerman Formation, a clayey unit similar to the Porters Creek, although it is lighter in color and contains some quarz silts and sands. In certain areas small gravels occur at the base. The thickness of the Ackerman Formation ranges from 0 to approximately 40 feet. The "Holly Springs"* Formation stratigraphically overlies the Ackerman and ranges from 0 to approximately 2?0 feet thick. The lithology of this formation is variable: clays, sandy clays, sands, and in some areas, gravels. The clays are usually white to gray, although red and green clays are present, with quartz silt and sand sometimes present. On weathered exposures, iron-staining is common. Near the base highly-polished, black, pink and clear quartz gravels are usually present. As a general rule, the "Holly Springs" can be divided into a lower and an upper unit (Figure F-3). The sands and polished gravels are common to the lower unit, along with some clay balls, whereas the upper

*"Holly Springs" is herein used in an informal sense pending further stratigraphic investigation in Missouri.

unit contains more shaly beds. Overlying the "Holly Springs" are gravels probably equivalent to the "Mounds Gravels" of Illinois Geological Survey usage. They are assigned to the Pliocene, but, as has been suggested by some they may be Pleistocene. The gravels range from 0 to about 60 feet in thickness and occur at higher elevations of the hilltops. Although there is a wide variety of lithologies and colors represented in the gravels, most are brown cherts. There are minor amounts of clays, sands, and pebbles throughout the unit.

The entire upland area is blanketed by three loess formations. There is a well-developed soil (Sangamon) at the top of the basal Loveland Silt (Illinoian). The overlying Roxana Silt is of early Wisconsinan age. The uppermost loess, referred to as the Peoria Loess, is extensively developed. Color, texture, and stratigraphic position are useful criteria for recognizing these units in the field.

PLAN OF INVESTIGATION

The plan of investigation has been to establish whether faulting within the older Cretaceous and Tertiary formations has affected overlying Pleistocene and Holocene deposits. Due to thick loess cover, good exposures of such faulting are rarely developed other than on side-slope positions. Faults exposed in side-slope exposures are commonly believed to result from slumping, or it is believed that slumping cannot be discounted as a possible faulting mechanism.

The exposure in the Bloomfield clay plant mine has afforded an excellent opportunity to view local faulting in other than a side-slope setting; thus, it has been possible to establish that the fault displacements are the result of deeper tectonic events, not the result of slumping. From exposures at the clay plant we have been able to establish the vertical extent of faulting and thus make a statement regarding the age of fault movement. This has been accomplished by field observation and detailed test drilling, with accompanying gamma-ray logging. Company drilling records have been of additional benefit in understanding the geology of the area.

A second site, referred to as the Rock Knob gravel locality, has been investigated. Field observations were made at this location without the aid of drilling, which was precluded by the nature of the deposits at this site and the limitations of Survey-owned drilling equipment.

FIELD AND OFFICE INVESTIGATIONS

Lowe Industry Bloomfield Clay Plant

The Lowe Industry Bloomfield clay plant is in sec. 28, T. 27 N., R. 11 E., Stoddard County, Missouri, three miles northeast of the town of Aquilla (Figure F-2). Physiographically it is on the eastern edge of Crowleys Ridge where the Castor River flows onto the alluvial plane. In this area, there is approximately 200 feet of relief between the alluvial plane and higher elevations on the Ridge. Loess mantles the Ridge covering Tertiary gravels which are exposed only where streams have cut headward at higher elevations.

There have been mining operations at this site for the past three years; however, it was only during the past year that large quantities of clay were removed. The present mined area, with a long axis oriented north-south, is bounded on the north by highway Y and on the west by a north-south unimproved county road; the eastern and southern margins are limited by the Ridge termination. Mining and land reclamation activities of the company have controlled test drilling locations and field observations this year. The company is currently filling the mined area with overburden stripped from the area immediately to the west, which is to be mined next.

The stratigraphy of the site is illustrated in Figure F-5. The lowest identified unit is the unexposed Upper Cretaceous McNairy Formation. It was not sampled in detail in drilling. It is best described by variable subunits of brownish-gray sandy clay, lignitic in part, and medium- to fine-grained white to orange sand, with brown-black clay. Overlying the McNairy, the Upper Cretaceous Owl Creek Formation has been partially exposed in the pit area. It is a yellowish-brown and light olive-gray sandy clay, with minor amounts of glauconite. The unit is fossiliferous in part and locally 6½ feet thick.

The Clayton Formation, the youngest unit of the Tertiary (Paleocene) represented, lies above the Owl Creek. The unit is 8 feet thick and is described as a green to brown sandy, very glauconitic clay. Due to the presence of limonite, color may vary to yellowish-brown. Fossils are abundant and well-preserved. An argillaceous carbonate layer, characterized by very pale brown color, with dark green glauconite specks throughout, occurs at the top of the Clayton and defines the pit floor of the mining operation. Also representing the Paleocene is the overlying Porters Creek Clay, a dark gray clay with a characteristic conchoidal fracture; an increase of sand and glauconite occurs at the base. The clay is highly absorbent and is mined for use in the production of "Kitty Litter" and pesticide carrier. In the mined area, from south to north, the thickness varies from less than 10 feet to more than 90 feet. Eocene deposits overlying the Porters Creek Clay may be represented locally by remnants of the Ackerman Formation, a silty sandy clay often having the appearance of weathered Porters Creek Clay.

An erosional unconformity exists at the top of the Porters Creek Clay and what may be remnants of the Ackerman Formation. Colluvial material derived from a higher elevation and composed of brown to yellowish-brown silts and rounded gravels assumed to be reworked loess and Tertiary gravels was deposited on this surface. The gravels are typical "Mounds type" material, an in-place example of which can be found a half mile northwest of the Gravel Hill Church. Thickness of the colluvial unit averages 5 to 10 feet and is assumed to be Pleistocene in age. Sangamon paleosol is developed in the colluvial unit and in what may be in-place Loveland loess. An average of 15 feet of Wisconsinan age silts and loesses, Roxanna and Peoria, respectively, overlie the Sangamon paleosol.

Access to drilling records of the Bloomfield clay plant was granted with restrictions. From them it was determined that at least one significant normal fault existed, trending N. 65° W., downfaulted to the northeast, with approximately 16 feet of displacement. This has been verified from this year's drilling activities and from field observations at the plant site. Other, lesser faults are exposed within the pit north of the major fault. They generally strike northwest, but one in the extreme northern end of the pit strikes N. 60° E. and dips 65° to the southeast. The early work of Farrar and McManamy (1937) first showed faulting existed in the area. They described a fault with 30 feet of displacement to the south, in sections 29 and 30, T. 27 N., R. 11 E., directly west of the clay plant. The fault strike was uncertain but was indicated on their map to be N. 75° W. It is assumed to be part of the same fault system investigated this year.

The major fault within the pit has been studied in detail (refer to Figures F-4 and F-5). It has been determined that displacement along this fault is 16 feet and that movement occurred sometime after deposition of the Porters Creek Clay but antedated deposition of the overlying Pleistocene colluvial silt and gravel unit. As illustrated in Figure F-5, the main fault comprises two closely spaced parallel faults dipping 65° northeast. It is noteworthy that the angel of dip diminishes toward the upper boundary of the Porters Creek. A minor antithetic fault, with 12 inches of displacement, dips into the main fault. No evidence from this year's study suggests strike-slip movement along any of the observed faults.

It appears from the evidence seen locally that no faults penetrate the colluvial unit and overlying loess deposits. Figure F-6 illustrates the structural relationship of the materials above the main fault to the underlying deposits. No displacement corresponding to the major fault displacement can be observed within the overlying materials. Because of the placement of spoil materials, the area immediately above the fault could not be viewed as a whole; however, the same general area was inspected two years before, and no offset could be observed then.

The significance of Tertiary faulting with respect to the location of the geophysical feature known as the "Bloomfield High," illustrated in Figure F-2, is worthy of mention. At this location, there are both gravity and magnetic anomalies, which have been interpreted as indicating a buried mafic or ultramafic pluton (Hildenbrand, et al., 1977). The pluton is believed to be embedded within the basement complex, suggesting a Precambrian age. However, the presence of possible igneous materials from a well drilled on the southeastern flank of the "high," suggests a possible shallow emplacement and much younger age, perhaps Tertiary (Hildenbrand, et al., 1977). Certainly the observed faulting at this year's study site, as well as information obtained from last year's investigation of the area 4 miles south, may have significant relationship to the "Bloomfield pluton."

Another point of interest is the parallelism of the Castor River channel to the general fault trend at the study site. It is suggested that the channel may have developed over earlier fault-weakened strata in the area. If this is the case, faulting at the study site may continue northwestward across Crowleys Ridge.

Rock Knob Gravel Locality

The gravel pit at Rock Knob is 7½ miles northwest of Bloomfield, Missouri (Figure F-2) on Crowleys Ridge (sec. 35, T. 27 N., R. 9 E.). At this location one can see an example of normal faulting affecting Plio-Pleistocene gravels ("Mounds type") overlying Cretaceous sands of the McNairy Formation. From the considerable time spent this year investigating gravel exposures on Crowleys Ridge, it appears that this site offers the only clear evidence for exposed faulting affecting deposits of this age. However, this certainly does not preclude the possibility that other faults affect deposits of this age but have not been revealed because of the thick loess mantle covering the area.

Stratigraphically, the oldest deposits exposed at Rock Knob include sands and quartzites of the McNairy Formation (Cretaceous). Before deposition of Plio-Pleistocene sands and gravels in the area, much relief, indicated to have been more than 50 feet, developed on the McNairy surface. Ancient channels, the bluffs of which were formed by the resistant McNairy quartzites, flowed through the area. Deposition of the Plio-Pleistocene sands, gravels, and minor clays on the erosion surface appears to have had a multiple history.

A fault with 3 1/3 feet (1 meter) of displacement, strikes N. 54° W. and dips 80° southwest. Plio-Pleistocene gravel ("Mounds type") overlying McNairy sands are displaced along the fault, which could not be traced further than 25 feet from the location of the outcrop studied. It is unknown whether the fault is the surface expression of a fault at depth or merely the result of differential subsidence, or "paleo-slump" relating to the high relief on the ancient McNairy surface. Loess cover is absent in the immediate area of the fault and therefore cannot be used to determine time of faulting.

No further formal study of the site is planned at present.

PROPOSED PROGRAM FOR 1980-81

The 1980-81 program will concentrate on the following activities:

1. Test drilling of two or more 400- to 500-foot holes on opposite sides of the major fault at the Lowe Industry Bloomfield clay plant (sec. 28, T. 27 N., R. 11 E.) along the eastern flank of Crowleys Ridge. The test holes will be sampled in detail and gamma-ray logged for purposes of correlation.

2. Using drilling information, establishment of whether the faulting is the result of solution collapse.
3. In addition, also using drilling information, establishment of whether recurrent movement has taken place and of the attitude of the fault plane with depth.
4. A final report on the "Structural Geologic Study of Southeastern Missouri," as conducted by the Missouri Geological Survey for the past five years.

PERSONNEL

The principal investigator was aided by Mark Reising, Geologist I working on contract. Pat Cullen worked on the project as a geologic technician along with Kim Haas, who was responsible for laboratory analyses of field samples. Ira Satterfield and Tom Thompson offered suggestions and advice on matters relating to the project. Robert Hansman provided editing assistance and Sharon Lemasters provided her typing skills. Drafting was done by Bill Ross.

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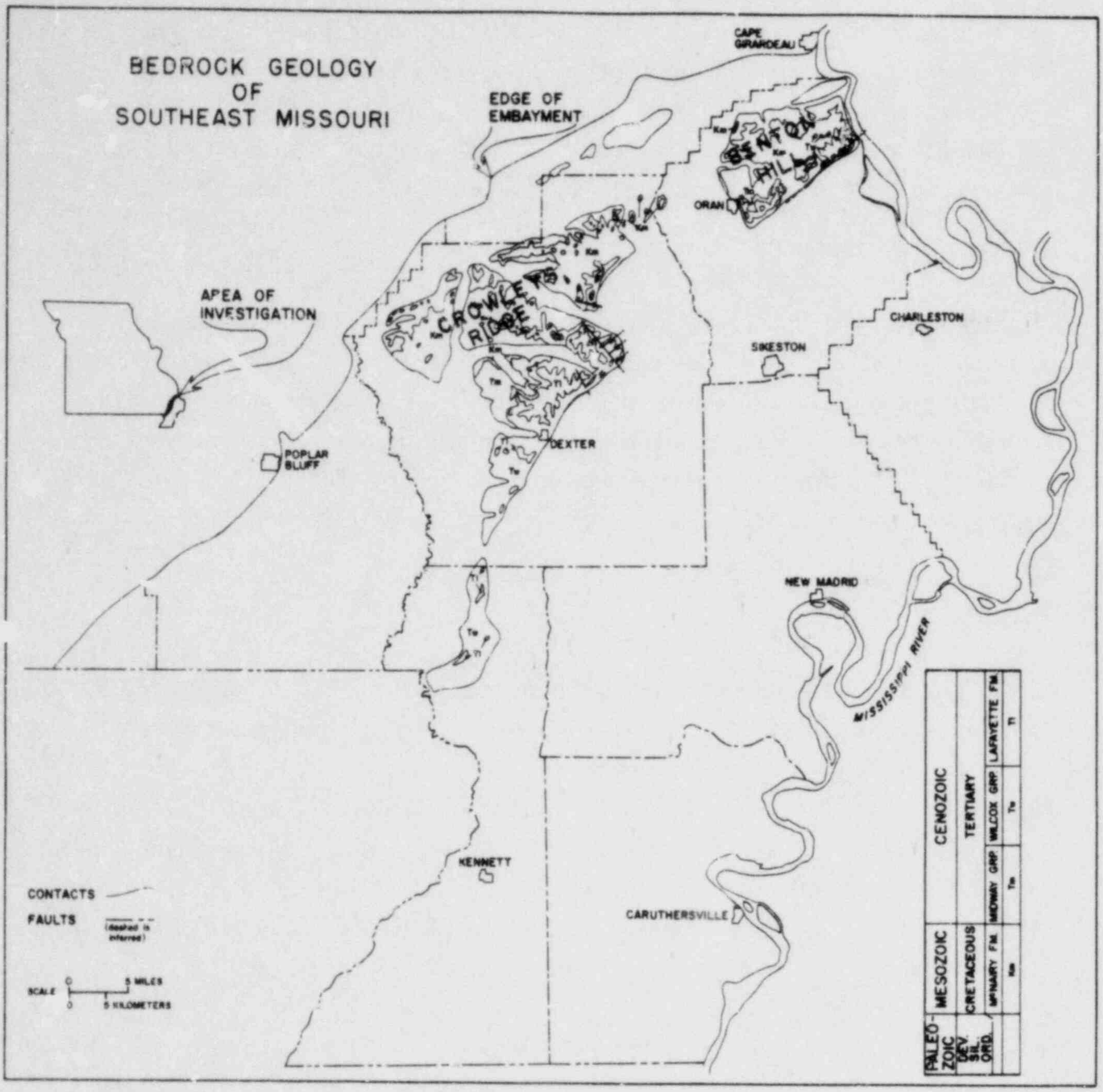

Figure F-1

A generalized geologic map of the Crowleys Ridge - Benton Hills area, southeastern Missouri lowlands, with emphasis on Mesozoic and Cenozoic geology. This year's field investigation concentrated on Crowleys Ridge.

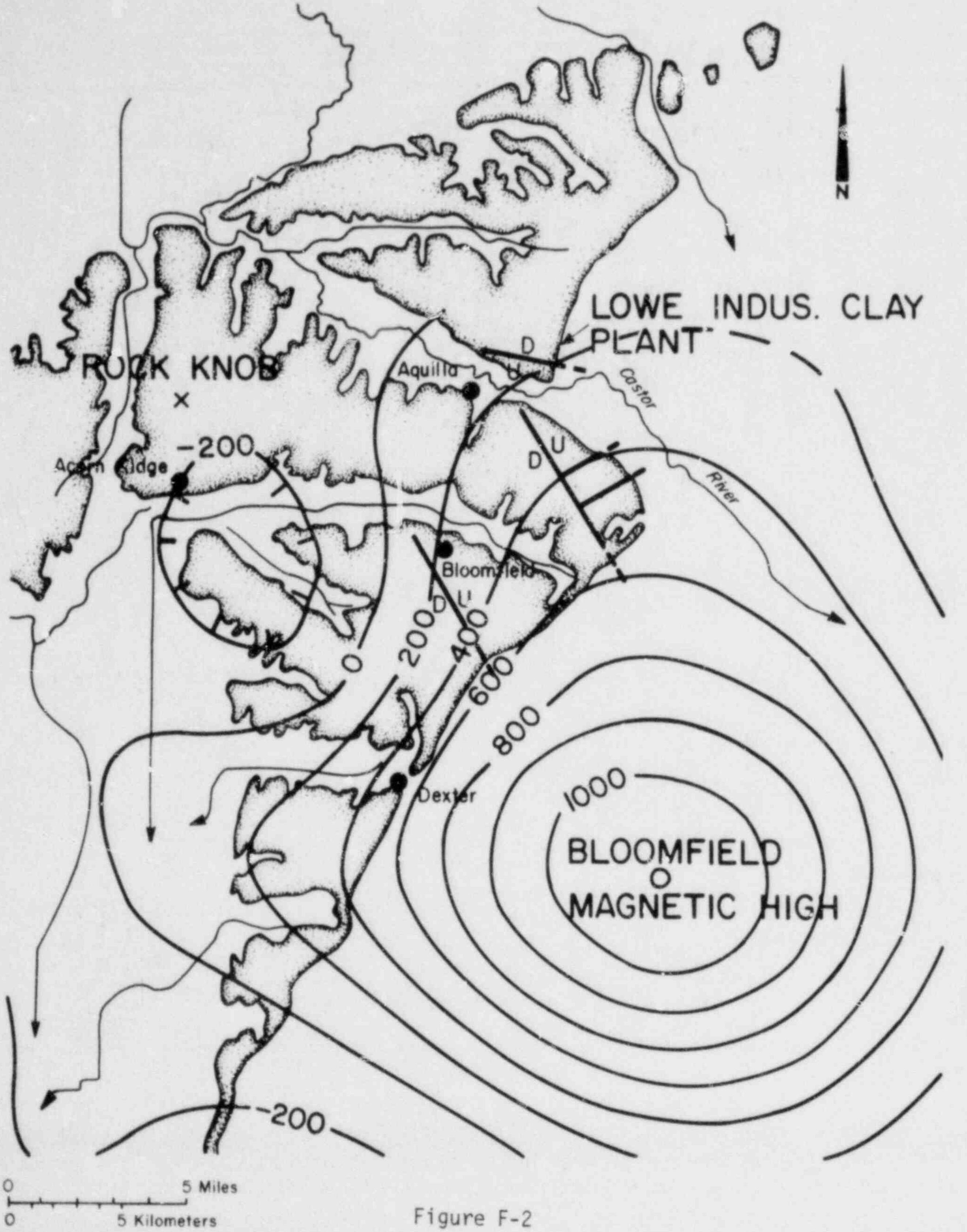

Figure F-2

Eastern half of Crowleys Ridge, site of this year's field investigation. Note location of Lowe Industry clay plant study site and associated faulting relative to "Bloomfield Magnetic High" and parallelism of faulting to Castor River channel. Total magnetic field intensity data taken from Hildenbrand, et al. (1977). Magnetic intensity contours 200 gammas.

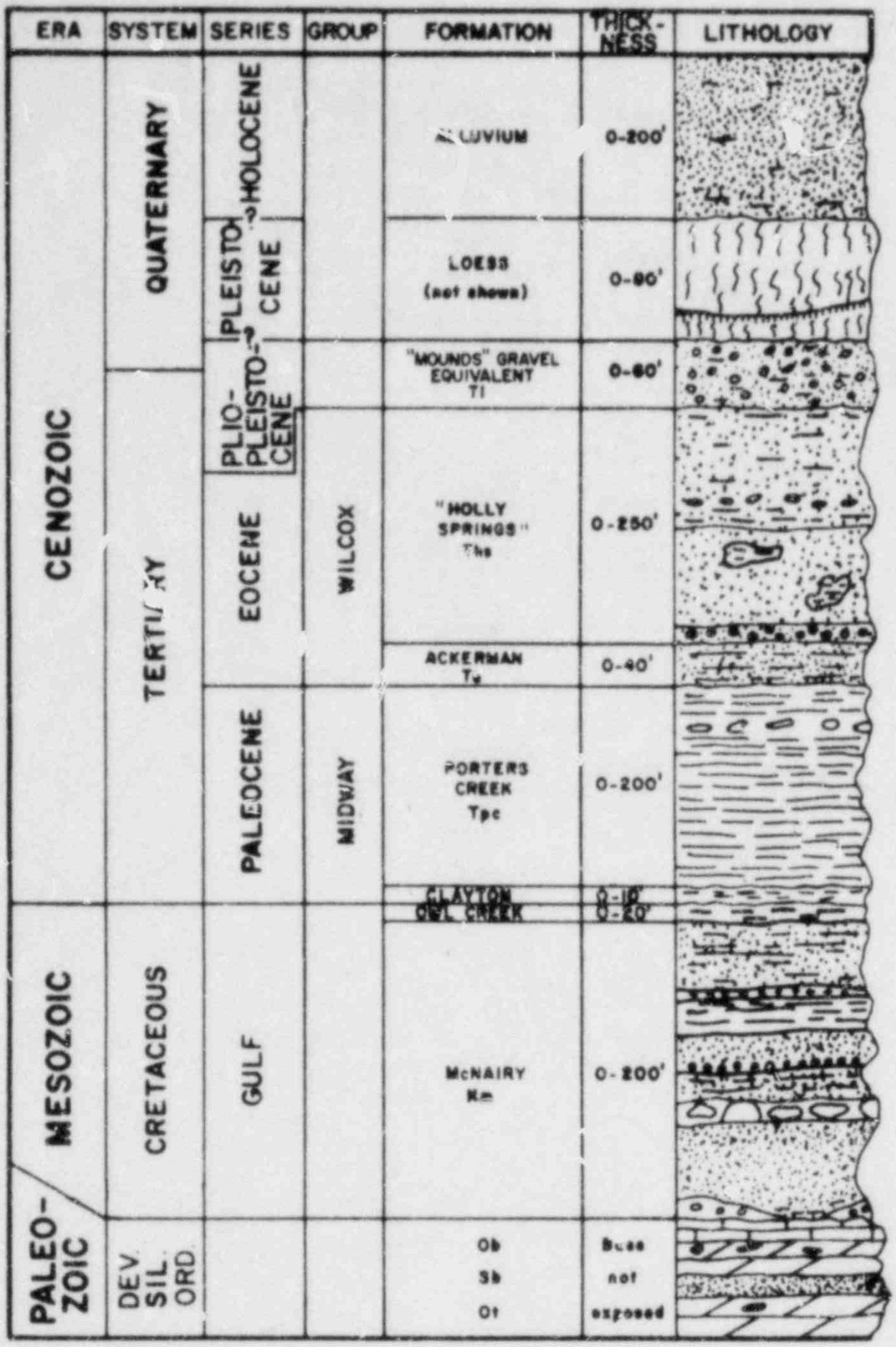

Figure F-3

A detailed stratigraphic section of the units exposed in the prominent ridges of Missouri's Bootheel, with emphasis on the Gulf (Cretaceous), Paleocene, Eocene, and Pliocene (Tertiary) Series.

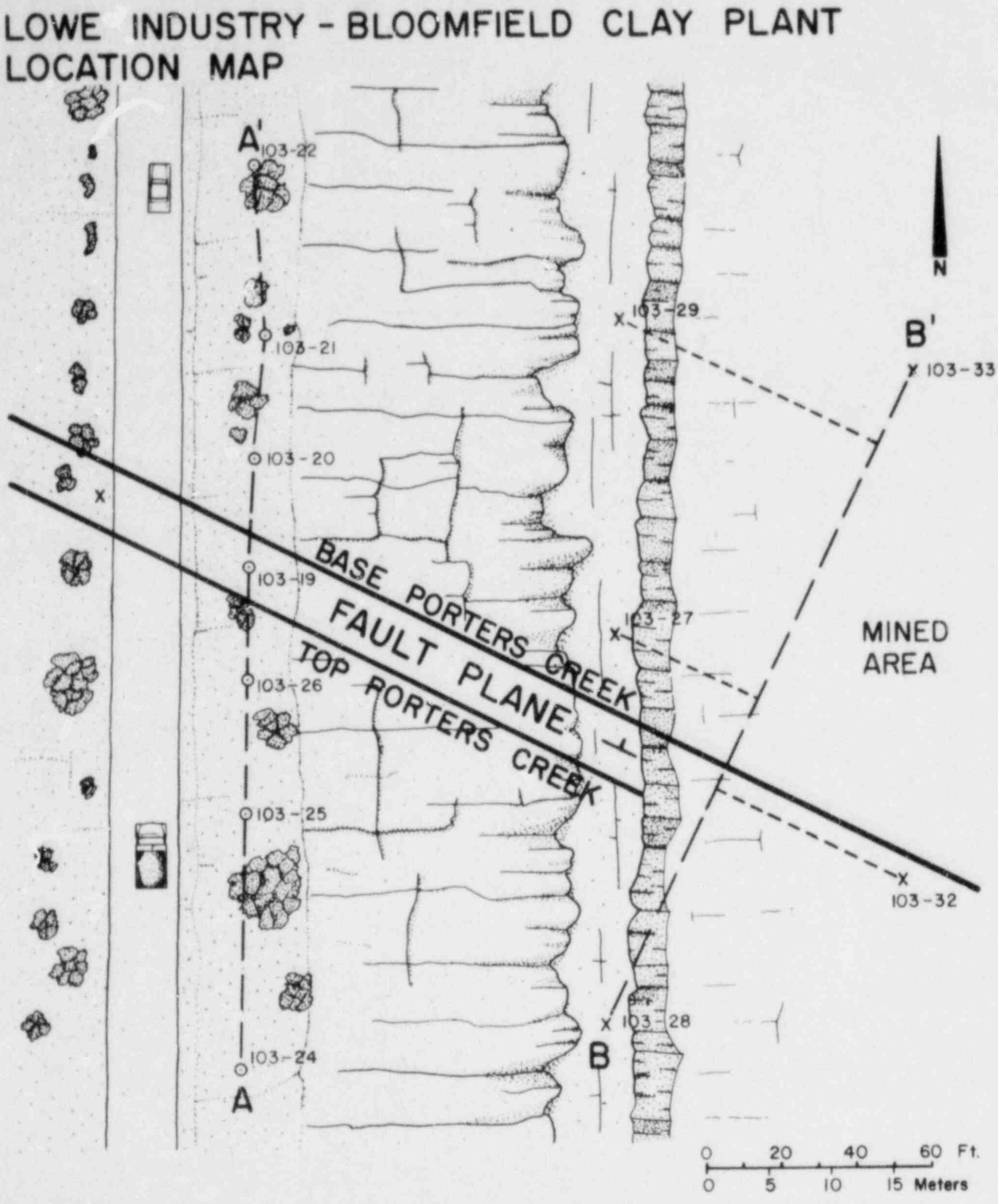

Figure F-4

Plan view of portion of Lowe Industry Bloomfield clay plant mining area. Location of test holes shown for cross sections A-A' and B-B'. Major fault-plane location illustrated for unmined portion of Porters Creek Clay; fault plane dip to northeast.

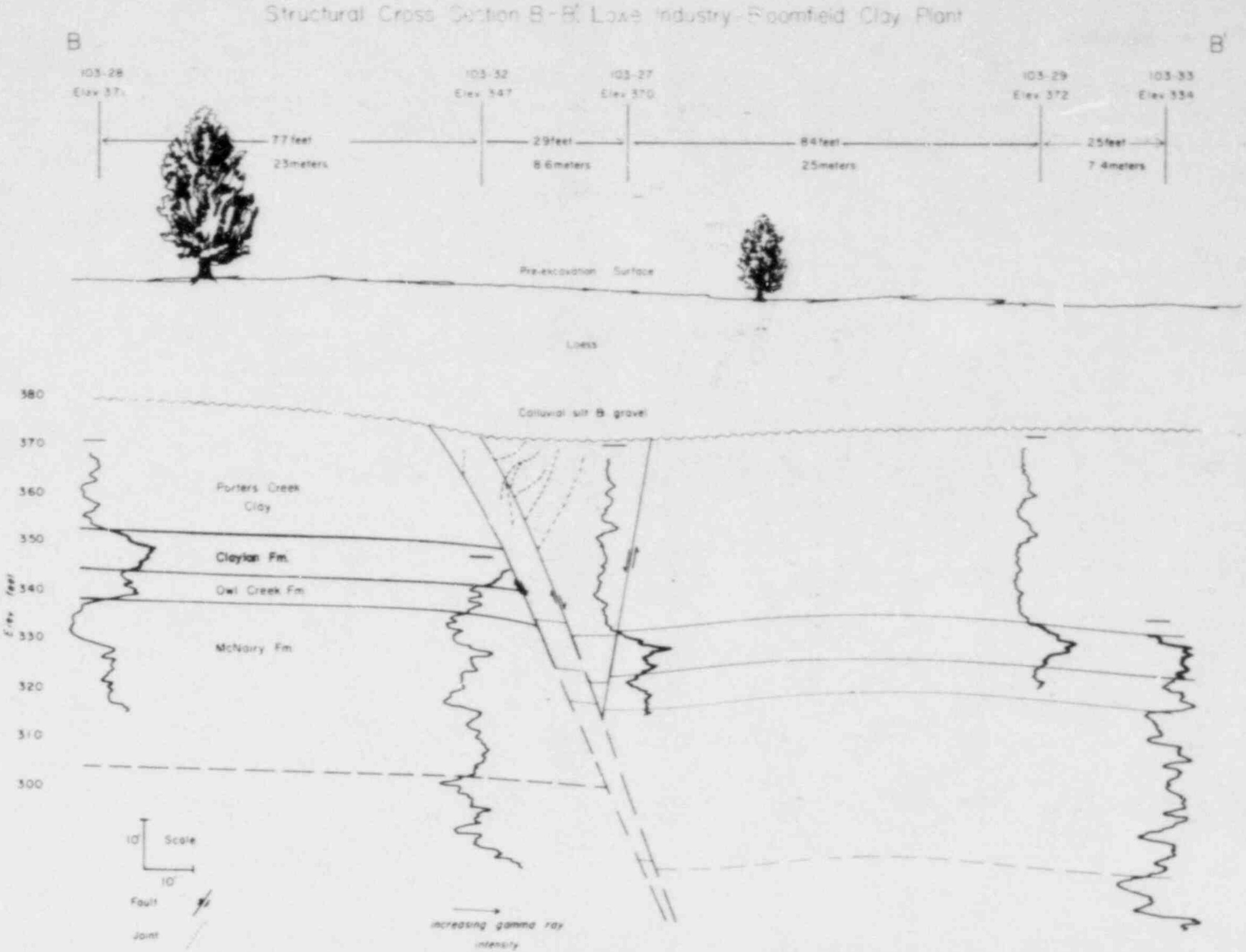

Figure F-5

Cross section B-B' located on fig. F-4. Gamma-ray log traces shown for each of the 5 test holes drilled. Correlation of Tertiary and Cretaceous units demonstrate the presence of a major fault with 16 feet of displacement. Faulting does not penetrate Pleistocene age units overlying erosional unconformity on the Porters Creek Clay.

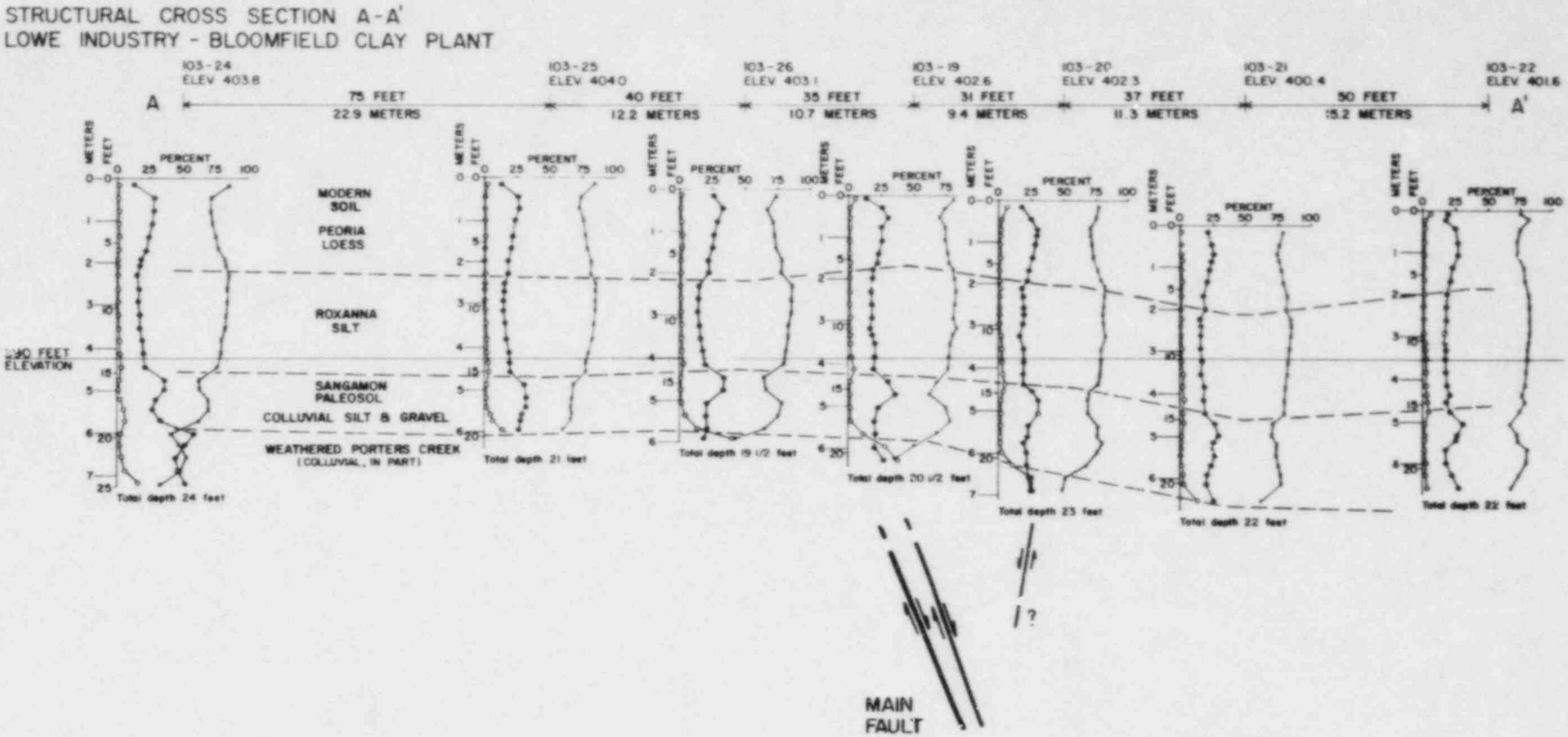

Figure F-6

Cross section A-A' located on fig. F-4. Particle-size data shown for 7 test holes traversing major fault; lateral correlations demonstrate absence of fault offset in Pleistocene units. Suggestion of fault-scarp development and depositional thickening on the downfaulted side of underlying fault is indicated.

A STUDY OF INDIANA FAULT LOCATIONS, DISPLACEMENTS, ATTITUDES AND AGES IN SOUTHWESTERN INDIANA

Annual Progress Report - Fiscal Year 1980

Contract No. NRC-04-77-164

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ABSTRACT

Faulting extending from Kentucky into Spencer and Perry Counties, Indiana, was investigated in detail by using subsurface data, primarily geophysical logs of petroleum tests in Spencer County and extensive surface field surveys in Perry County. Faults in these counties are similar to those of the Wabash Valley Fault System investigated in previous years in Posey and Gibson Counties. They are high-angle normal faults trending north-northeastward. The maximum vertical displacement observed was about 130 feet. Twenty miles of detailed surface mapping of the Mt. Carmel Fault in Monroe and Lawrence Counties shows the fault to be high angle, normal, and more complex than previously thought. Four or more associated faults are present in some areas, and drag-fold structures, small horsts and grabens, and jointing are evident. Preliminary tectonic comparisons between the Mt. Carmel Fault and other faulting in southwestern Indiana show several significant differences.

OBJECTIVES

The objective of this study is determining the location, extent, attitude, displacement, and other geologic and seismic aspects of faulting in southwestern Indiana to help characterize the tectonic processes in that region.

WORK PERFORMED

Wabash Valley Fault System in Posey and Gibson Counties

All subsurface datum points from about 6,000 wells were compiled and posted on mylar base maps on a scale of 2 inches to the mile for two structural horizons, the top of the Cypress Formation (Mississippian) and the top of the Springfield Coal Member of the Petersburg Formation (Pennsylvanian), by the beginning of fiscal year 1980. Much additional time was spent during the year in checking all point data, making final structural interpretations, and drafting the maps for publication by the Indiana Geological Survey in its Miscellaneous Map Series.

Data were gathered and recorded for three other structural horizons, the base of the West Franklin Limestone Member of the Shelburn Formation (Pennsylvanian), the base of the Menard Formation (Mississippian), and the top of the Renault Formation (Mississippian). Final construction of one or more structural maps showing faults on these beds will be undertaken during the coming year.

During the past year, two deep-coal tests that served as stratigraphic control for rocks of Pennsylvanian age for this study were drilled in northern Posey County by the Indiana Geological Survey. Neither test hole encountered faulting, but the extensive coring and detailed lithologic descriptions obtained from these tests aided our correlations of Pennsylvanian strata in nearby faulted areas.

Previously reported faulting in Vanderburgh County, adjoining Posey County on the east, was not confirmed by our studies. No repeated or missing stratigraphic section was found in geophysical logs of wells drilled near the postulated faults, and steepening of dip, present in some areas, is insufficient evidence in itself to support the mapping of faults.

Spencer County faulting

Extensions of northeastward-trending faults mapped by Johnson and Smith (1968) and by Goudarzi and Smith (1971) in Kentucky were investigated in Spencer County, Indiana, by subsurface mapping. Two faults that extend across the Ohio River from Kentucky into southern Spencer County were mapped on top of the Cypress Formation and have tentatively been named Little Hurricane Island Fault and Africa Fault (Figures G-1 and G-2). Recognition of the Little Hurricane Island Fault was based on subsurface mapping, which showed 40 feet of structural reversal on top of the Cypress Formation. No wells that cut the fault were examined. The normal fault is interpreted to trend N. 40° E.; its upthrown side is to the northwest.

The Africa Fault is a high-angle normal fault about 5 miles long and trends north-northeastward from Kentucky through T. 8 S., R. 6 W., Spencer County, Indiana, and back into Kentucky (Figure G-1). Vertical displacement of about 80 feet was observed in one well that was drilled through the fault.

No surface expression of either fault was observed because of deposits of thick alluvium and other unconsolidated surface materials.

Perry County faulting

Two faults, tentatively named the Deer Creek Fault and the German Ridge Fault, were mapped in southern Perry County by using both surface and subsurface data (Figures G-1 and G-3). The Deer Creek Fault as mapped in Indiana is an extension of a fault mapped in Kentucky by Bergendahl (1965). Structure maps on top of the Glen Dean Limestone (Mississippian) show anomolously steep dips near both faults. Structure maps were constructed by using subsurface data and data from surface outcrops to confirm the faulting.

Mapping revealed that the Deer Creek Fault has a length of about 4 miles. It has vertical displacement of about 130 feet as measured on outcrop exposures of the Negli Creek Limestone (Mississippian). Outcrop expressions of the fault itself are rare, although one prominent drag feature mapped is probably fault related.

The German Ridge Fault trends northward from the Ohio River for about 6 miles (Figure G-1). Vertical displacement ranges from 30 to 60 feet. Two apparent drag features with steep dips up to 34° were found cropping out. Additional faulting postulated in the county by previous investigators was not substantiated by our study.

Mt. Carmel Fault

The Mt. Carmel trends southward about 50 miles from Morgan County to Washington County (Figure G-4). Twenty miles of the fault was mapped during the year. As many as four accessory faults were mapped near the main fault plane. Small grabens, one of which paralleled the main fault for 8 miles in Lawrence County, were mapped on the west side of the main fault. Small antithetical faults and tilted blocks were mapped near the fault, and many conjugate and feather joints were observed. Slickensides were recorded with striations dipping more than 30° on fault surfaces, which indicates lateral movement on the Mt. Carmel Fault.

The Lee le Anticline is a long asymmetrical anticline that is parallel to the Mt. Carmel Fault, is as much as 3 miles wide, and has five domal structural closures. Its strata dip toward the fault, possibly as the result of reverse drag. Surface mapping shows that beds of the anticline dip as much as 3° E. toward the Mt. Carmel Fault. Normal drag features with dips as great as 30° W. were observed in direct association with the fault.

Wells drilled through the main fault have an indicated vertical displacement on the fault at depth that is less than the total displacement observed at the surface. This may be because not all of several fault planes were penetrated by the well, or it may indicate a significant decrease in dip angle on the fault with depth.

The northwesterly extent of the Mt. Carmel Fault is not known, but previous mapping has indicated that it passes beneath glacial drift in Morgan County and that shallow drilling would be necessary to determine its northerly extent.

PRELIMINARY RESULTS

Our mapping in the past 3 years of the study of the Wabash Valley Fault System has been completed in Posey and Gibson Counties on two marker beds. The faults have now been mapped on a scale of 2 inches to the mile by using all available data. The main characteristics of the faults of the Wabash Valley Fault System in Indiana are as follows:

1. The faults are all high-angle normal faults trending N. 15° to 30° E. with vertical displacements as much as 450 feet. The faults are downthrown either to the east or to the west, producing horsts and grabens and tilted fault-block structures.
2. The faults occur in zones. There are as many as five or more individual faults with more than 20 feet of vertical displacement. The fault zones become less complex with depth.
3. Our investigations indicate that the faults are all post-Pennsylvanian to pre-Pleistocene in age.
4. The fault displacements are consistent with depth in rocks of Pennsylvanian and Mississippian age, and although deeper data are sparse, we infer that faulting reaches basement rocks.
5. If fault dips observed in shallow rocks are similar to dips on the faults at depth, migration of faults mapped in rocks of Pennsylvanian and Mississippian age suggests that three or more major fault zones may be present in basement rocks in Posey and Gibson Counties.

The faults mapped in Spencer and Perry Counties are similar to those of the Wabash Valley Fault System. They are high-angle normal faults trending northward to northeastward and dipping westward or eastward. Maximum vertical displacement on any fault in these two counties is about 130 feet.

Subsurface data are sparse near the faults in Perry County, but locations of the faults were confirmed by detailed surface mapping. The faults in Spencer County were mapped only by using subsurface data, mainly electric logs from petroleum tests.

Detailed maps of the 20 miles of the Mt. Carmel Fault mapped thus far show complex structures not previously recorded. Some structures are being mapped for the first time; these include complex drag features and folding near the fault. Structural relationships of the Leesville Anticline, which parallels the Mt. Carmel Fault on the west, are being investigated. We note that two separate tectonic events may have produced the folding and faulting associated with the Mt. Carmel Fault but withhold final tectonic analysis at this time.

A fault plane called the Heltonville Fault was traced in several sections in northern Lawrence County about 1 mile west of the main Mt. Carmel fault plane. Dips on the Heltonville and other accessory faults range from 60° to 65° in horst and graben features.

Integrated mapping of the Mt. Carmel Fault by using both surface and subsurface data was expedited by computer-generated base maps from the INDIMAP program, although primary compilations are on U.S. Geological Survey topographic maps and Indiana Geological Survey base maps.

FUTURE WORK

Fieldwork to be finished in the final year of the project includes detailed mapping of more than 30 miles of the Mt. Carmel and Georgetown Faults. Because the northerly extent of the Mt. Carmel Fault is covered by glacial drift, a shallow drilling program will be undertaken to determine the extent of the faulting under the drift.

We propose the drilling of at least four test holes to stratigraphic markers of Mississippian age with the Survey's truck-mounted drilling rig. We anticipate the test holes will average about 200 feet in depth. Integration of information from this drilling with the sparse drilling data already available should add considerably to our knowledge of the location and displacement of the northern part of the Mt. Carmel Fault.

Seismic data on the Mt. Carmel Fault from past geophysical studies by faculty and students of the Department of Geology, Indiana University, will be integrated with data from our mapping. If additional geophysical studies appear feasible from the results obtained, they will be undertaken by using Survey equipment.

In preliminary work on the Mt. Carmel Fault, we have not attempted to relate tectonically the structural framework of the Mt. Carmel area with the more complex faulting of the Wabash Valley Fault System. Significant differences between the two areas of faulting are apparent: the nearly opposite trend of the Mt. Carmel Fault compared with that of the Wabash Valley Fault System; the parallel anticlinal structure on the west side of the Mt. Carmel Fault (including widespread dipping of beds toward the fault) compared with structures associated with the Wabash Valley Fault System; and the obvious difference that the Mt. Carmel Fault is a single major fault with associated accessory faulting, while the Wabash Valley Fault System contains numerous faults that may be bifurcations or splinters of major fault zones in basement rocks. Similarities are also apparent between the Mt. Carmel Fault and the Wabash Valley Fault System, and complete gathering of data and mapping of the faulting will aid in a more complete tectonic analysis.

Final reports on the results of the study and detailed maps will be prepared.

REPORTS AND MAPS OTHER THAN THOSE FOR NRC

In press:

Ault, C.H., D.M. Sullivan, and G.F. Tanner

1980 - Faulting in Posey and Gibson Counties, Indiana: Indiana Acad. Sci. Proc. for 1979, v. 89.

In editorial process:

Sullivan, D.M., C.H. Ault, and J.N. Stellavato

1980 - The Wabash Valley Fault System in Indiana and its economic implications: Kentucky Oil and Gas Assoc. Proc.

In preparation:

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Tanner, G.F.

1980 - Movement, drag features and complexity of the Mt. Carmel Fault, Indiana (abs): Announcement of fall meeting of the American Geophysical Union, p.

Tanner, G.F., J.N. Stellavato, and J.C. Mackey

1980 - Map of Posey County, Indiana, showing faulting and elevations of top of Cypress Formation (four parts): Indiana Geol. Survey Misc. Map

Tanner, G.F., J.N. Stellavato, and J.C. Mackey

1980 - Map of part of Gibson County, Indiana, showing faulting and elevations on top of Cypress Formation (two parts): Indiana Geol. Survey Misc. Map

Associated paper published using data from this project:

Ault, C.H. and D.D. Carr

1980 - New exploration and evaluation of minable coal resources in complexly faulted area containing old petroleum production (abs): Am. Assoc. Petroleum Geologists Bull. v. 64, p. 672.

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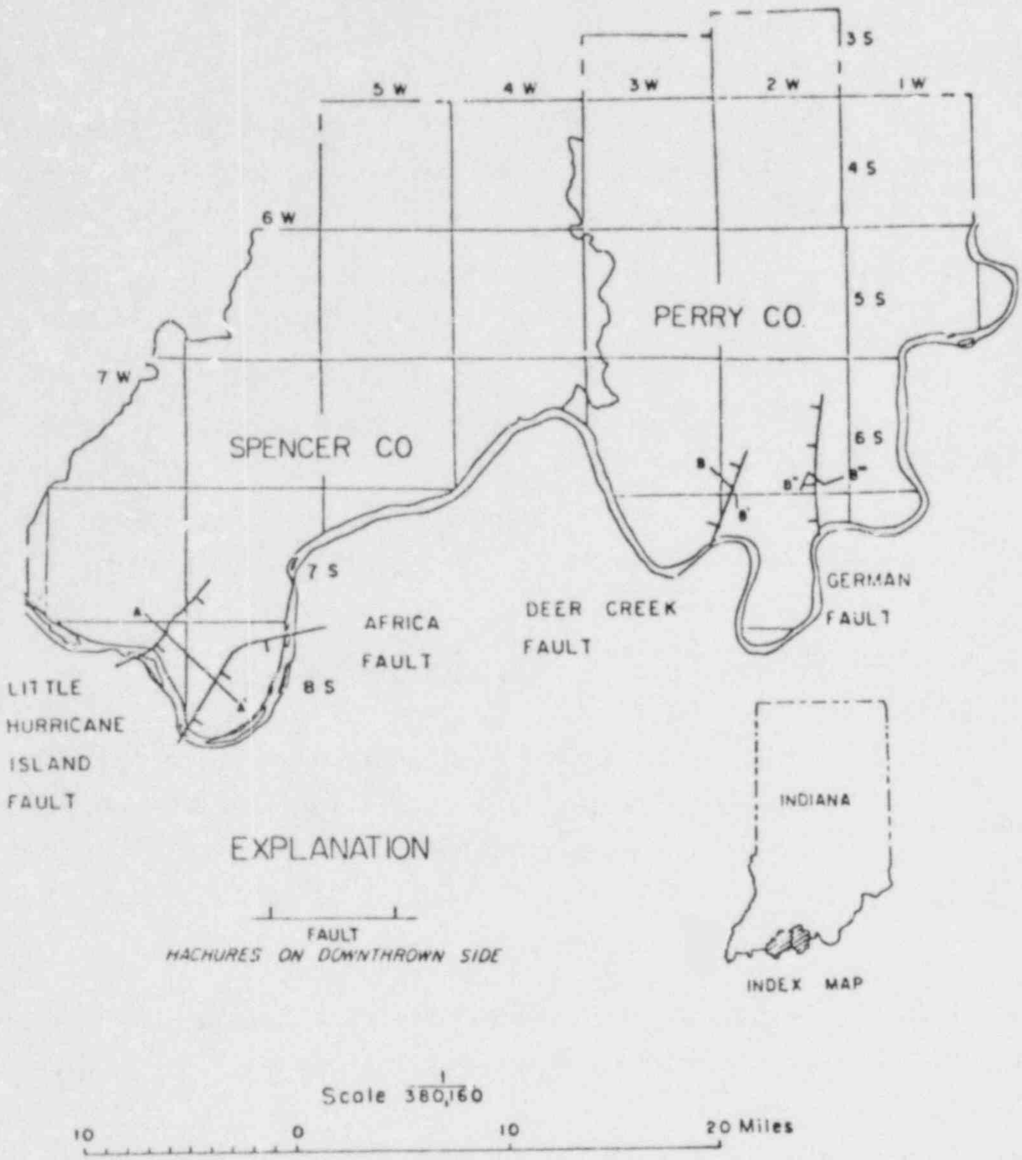

Fig. G-1. Map of Spencer and Perry Counties showing faulting and lines of cross section. (See figs. G-2 and G-3.)

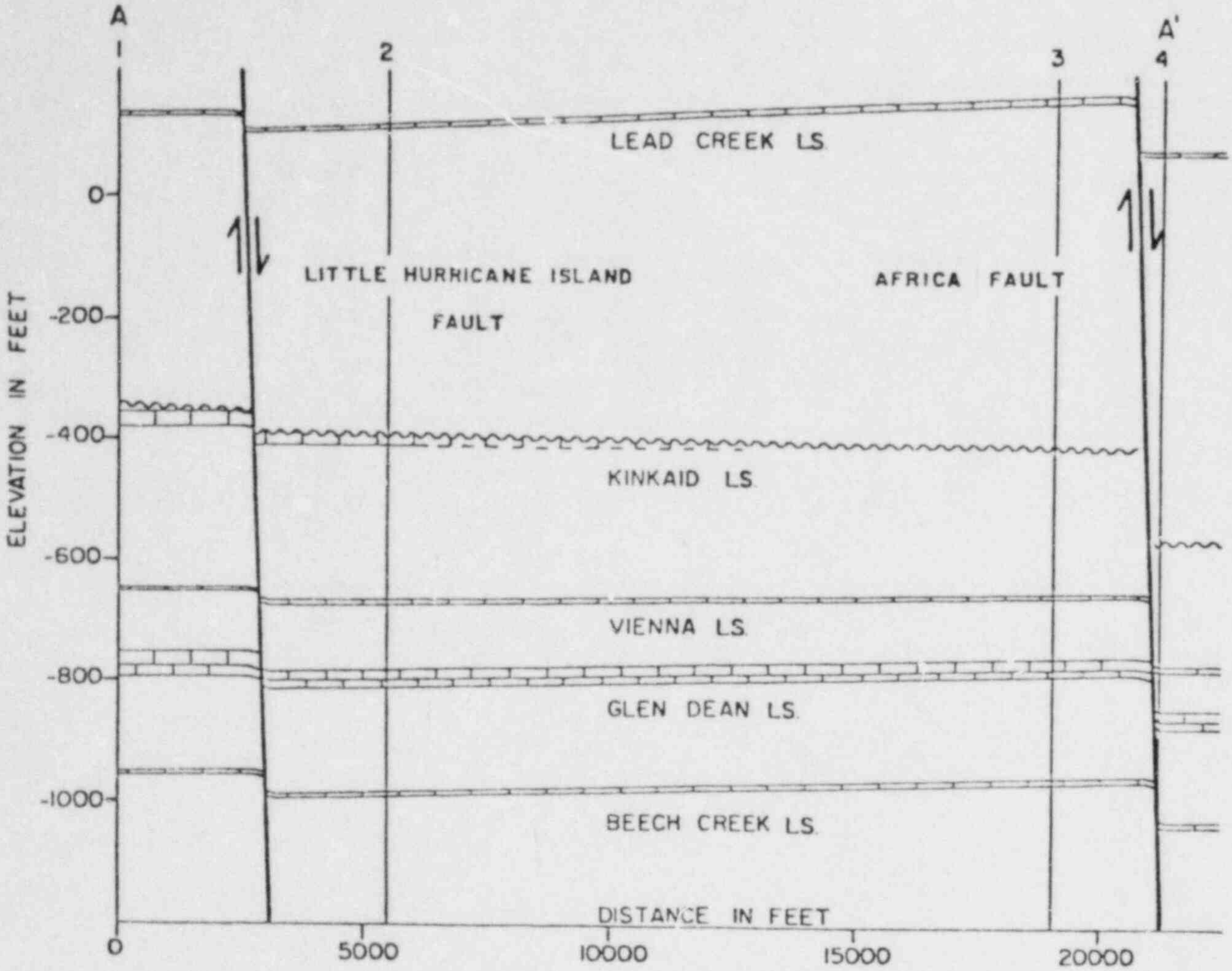

Fig. G-2. Cross section showing faults in Spencer County. (See fig. G-1 for line of section.)

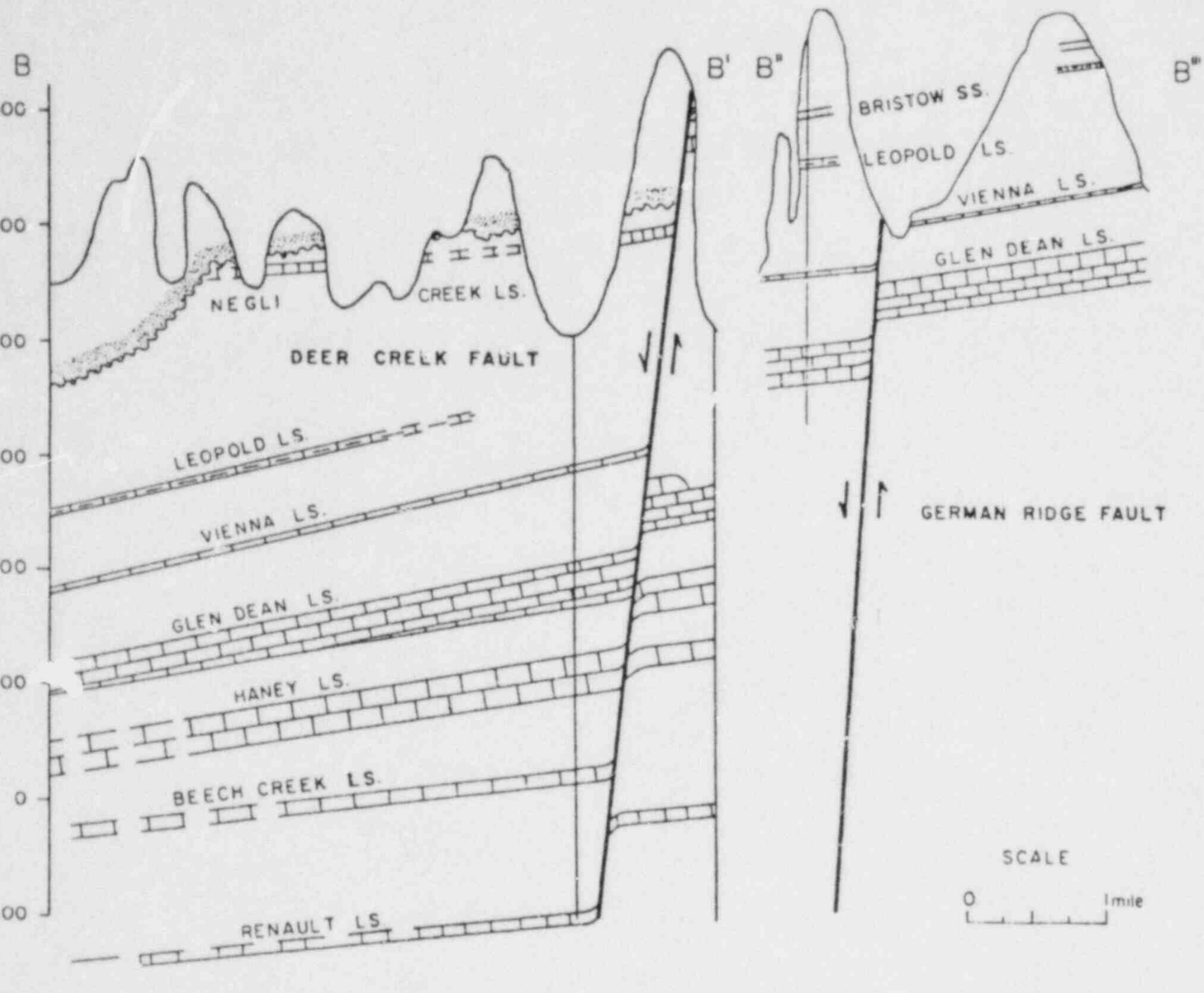

Fig. G-3. Cross sections showing faulting in Perry County. (See fig. G-1 for line of section.)

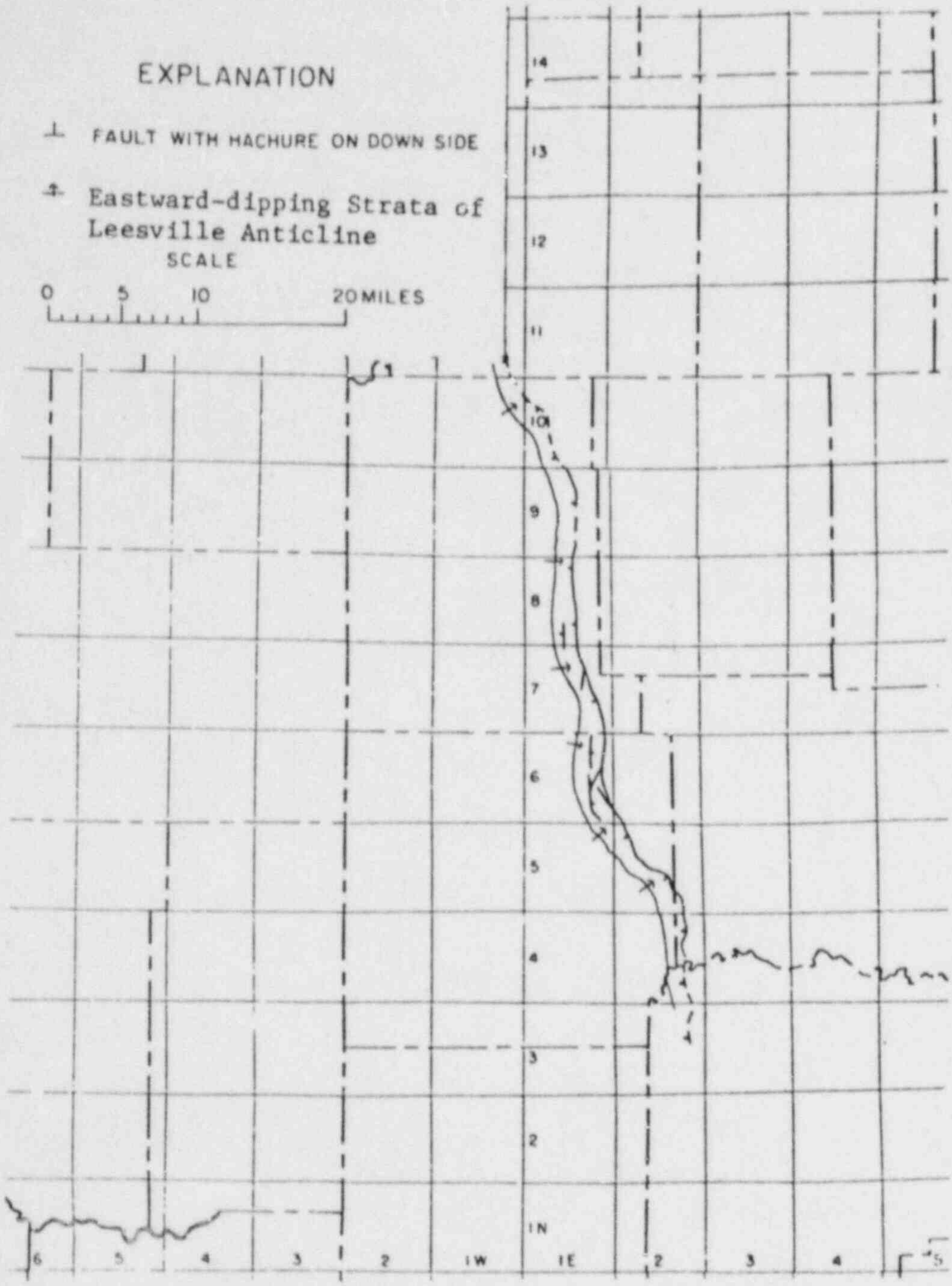

Fig. G-4. Map showing the Mt. Carmel Fault and eastward-dipping strata of the Leesville Anticline.

PALEOZOIC GEOLOGY OF THE NEW MADRID AREA

Annual Progress Report - Fiscal Year 1980

Contract No. NRC-04-76-321

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Illinois State Geological Survey*

SUMMARY

Since Precambrian time zones of weakness have been repeatedly but infrequently reactivated. The latest occurrence of major tectonic activity (perhaps Early Cretaceous) not only affected the old fault zones (and it appears that all the major folds and many of the minor anticlines are associated with basement faults), but also created a vast new feature that does not have any Paleozoic antecedent, the Pascola Arch. The severe erosion and subsequent Tertiary subsidence of the Pascola Arch provide the basis for my belief that this structure alone is the locus of present-day major earthquake activity. Until that time in the geologic future when old established zones of weakness are reactivated regionally, only the relatively young Pascola Arch will continue to be the focal point of high intensity earthquake activity.

INTRODUCTION

Within a two hundred mile radius of New Madrid, Missouri, the tectonic framework has been interpreted from the Paleozoic sedimentary record. Begun as an investigation of the nature of recent seismic activity in the region, the study has incorporated the stratigraphic and structural geologic parameters relating to earthquake activity.

Well cuttings from selected deep tests drilled in the area were studied to determine their lithology and the presence of microfossils, igneous intrusives and metabentonites. To better understand tectonic events leading to interruptions in the sedimentary record, the magnitude and extent of unconformities were appraised by detailed stratigraphic correlation, based partly on geophysical logs. Samples of igneous intrusives and crystalline basement rocks were collected for age dating by radiometric methods, in addition to age dates obtained from private and published reports.

*Work done under auspices of the Kentucky Geological Survey

A great amount of information was obtained from the files of state geological surveys and universities, and I gratefully acknowledge the help and criticism from the following individuals:

Dr. Kenneth Anderson, Missouri Division of Geological Survey and Water Resources; Jerry Carpenter and Andrew Hreha, Indiana Geological Survey; William Caplan, Arkansas Geological Commission; Alvin Bicker, Jr., Mississippi Bureau of Geology; Dr. Robert Hershey and Dr. Ned Luther, Tennessee Division of Geology; Jack Kidd, Geological Survey of Alabama, and all the members of the New Madrid Study Group. I assume sole responsibility for the interpretation of the data and the conclusions presented in this report.

GEOLOGIC FEATURES

The geologic complexity of the region is illustrated by the number of named elements of tectonic importance to the study area (Figure H-1).

Ozark Uplift

The oldest tectonic element recognized in the area is the Precambrian Ozark Uplift. It is believed that the igneous rocks exposed in the St. Francois Mountains of southeastern Missouri portion of the uplift represent a major petrogenic epoch of relatively short duration in late Precambrian time (Tolman and Robertson, 1969). Precambrian marine invasion of the Ozark Uplift area is documented by the presence of stromatolitic limestones with a minimum age of 1,400 m.y. (Stinchcomb, 1976); the next sediments to onlap the St. Francois Mountains are Upper Cambrian in age.

Although subject to infrequent marine incursion, the Precambrian terrain of the Ozark Uplift was the dominant topographic feature throughout the Paleozoic.

The topographically lower region surrounding the Ozark Uplift contained numerous hills and ridges, and relief on some of these features exceeded 500 feet. Some of the ridges of crystalline rock were probably accentuated by bordering faults, and these faults probably affected later faulting of overlying sediments. Within the study area no other Precambrian sediments have been identified beyond the St. Francois Mountains and the sedimentary rock-crystalline rock contact is sharp without any appreciable weathering profile noted in outcrop or the subsurface. Debris transport must have kept the region clear of weathered products.

Mississippi Embayment Rift

A major tectonic event which probably occurred at the end of Precambrian time opened a rift extending from northeastern Arkansas into southern Illinois. The rift zone flanked the eastern edge of the Ozark Uplift, and affected crustal rocks for about 100 miles to the east. The edges of the rift zone were probably step-faulted parallel to the central graben, and total displacement to the center of the rift probably exceeded 5,000 feet. With one anomalous exception, no well has penetrated basement within the Mississippi Embayment Rift, and the nature of the sediments in the bottom of the rift zone is unknown. Marine waters probably entered the graben from the south or southwest, and Lower Cambrian sediments are probably present in the deep portions.

The anomalous exception mentioned is the Big Chief #1 Taylor well in Gibson County, Tennessee, which encountered Precambrian basement at 6,900 feet. The radiometric age date of the igneous cuttings from this well have the unusual value of 680 m.y. (Robert Hershey, personal communication). The isopach of Pre-Knox strata (Figure H-2) shows the anomalously thin sedimentary interval above the basement in this well. This interval contained neither basal sands nor shale; instead dolomite of presumed Upper Cambrian age is resting directly on the crystalline basement.

Two possible explanations of the shallow basement depth and lack of clastic Pre-Knox sediments in the #1 Taylor are related to the interpretation of the formation of the rift zone. The well may have penetrated an upthrown block, or horst, created by rift-associated faulting. But the forces causing rifting were tensional and thus not likely to have produced an uplifted block of crystalline rock near the center of spreading. The other explanation might be the formation of extrusive igneous plugs or cones, which stood well above the surrounding landscape and were preserved long enough to be buried under sedimentary cover. Such extrusion would probably have been contemporaneous with rifting, and the dating of these rocks at 680 m.y. would indicate that the rift was latest Precambrian.

Rough Creek Graben

During rifting in the Mississippi Embayment area the eastern block containing the Nashville Dome began to rotate toward the southwest. This rotation created two zones of weakness producing the Rough Creek Graben extending eastward from the northern end of the Mississippi Embayment Rift. The Rough Creek Fault and the Pennyrile Fault Zones mark the northern and southern borders of this graben, respectively, which was down-dropped several thousands of feet. The graben narrows in width from about 35 miles on the west to about 15 miles in the east. The bounding fault zones curve toward each other at the eastern end of the graben, and may connect in the subsurface in the vicinity of eastern Grayson and Edmonson Counties. The two fault zones were reactivated repeatedly during the Paleozoic Era, allowing the Rough Creek Graben to deepen and acquire a thick accumulation of sediments. (Whether the bordering faults of the Mississippi Embayment Rift were similarly reactivated in the Paleozoic is unknown because erosion has removed most of the post-Ordovician sediments in that area).

In the Texas Gas Exploration #1 Shain well in Grayson County, Kentucky, a thick Middle Cambrian marine shale section was encountered beneath the Upper Cambrian Eau Claire formation (Figure H-3, well #4). A total of 2,360 feet of shale with thin arkosic streaks and a few thin beds of oolitic limestone were cut at the bottom of this test, which stopped in the sedimentary section. The shale contains linguloid brachiopods and a few trilobite fragments, which provide a means of dating the formation. An agnostid trilobite was identified by Christina L. Balk as the genus Baltagnostus, which occurs near the top of the Middle Cambrian. Additional specimens examined by Michael E. Taylor of the USGS were also assigned a questionable Middle Cambrian age. No Mt. Simon Sandstone was present in this well, and the Eau Claire Formation rests directly on the unnamed Middle Cambrian shale.

In wells penetrating the crystalline basement north of the Cottage Grove and Rough Creek Fault systems the Mt. Simon Sandstone of Upper Cambrian age is the oldest sedimentary unit found.

Lower and Middle Cambrian sediments lap on to the Nashville Dome from the Appalachian Basin, but they thin and disappear in north-central Tennessee, where Lower Knox dolomite of Late Cambrian age rests directly on the basement. The Nashville Dome segment of the Cincinnati Arch may have begun to take form in early Cambrian time, as it seems to have prohibited

Lower and Middle Cambrian sedimentation to the east of the Rough Creek Graben (Figure H-4).

Reelfoot Basin

Although none have yet been identified on the surface or in the subsurface, Lower Cambrian sediments are presumed to exist in the bottom of the Embayment Rift, and in the Rough Creek Graben. One can only speculate as to the lithology and thickness of any Lower Cambrian sediments there, but they would most likely be arkosic sands derived from the exposed crystalline terrain, and could be several thousands of feet thick in the deepest portions of the rift system.

The Reelfoot Basin (Schwalb, 1969) occupies a portion of the trough of the Embayment Rift and contains an accumulation of Cambrian and Ordovician sediments estimated to have been 12,000 feet thick. Two wells within the basin, The Texas Pacific #1 Farley in Sec. 34, T. 13 S., R. 3 E., Johnson County, Illinois, (Figure H-5, well #4; Appendix H-1) and the Benz #1 Merritt Estate in Sec. 3, T. 4 S., R. 1 E., Lake County, Tennessee, (Figure H-6, Well #5; Appendix H-1) penetrated sediments believed to be Middle Cambrian or older.

During Middle to Late Paleozoic time depocenters shifted northward, yet remained south of the Cottage Grove and Rough Creek Fault Systems. Later uplift exposed the rocks in the center of the Reelfoot Basin, and a vast amount of sedimentary section was removed by erosion; therefore the thickness of the total accumulation of sediments in the basin can only be estimated.

The Arkoma Basin

Trending westward from the Mississippi Embayment Rift, the eastern portion of the Arkoma Basin in northeastern Arkansas is a younger feature than the Reelfoot Basin. Lack of data on deep wells, and the absence of basement tests in the central eastern portion of the Arkoma Basin prevents the reconstruction of the early history of this region. Although they thin westward into the Arkoma Basin, Knox strata are lithologically similar to those of the Reelfoot Basin. Likewise, Middle and Upper Ordovician strata in the Arkoma Basin are lithologically similar to but much thinner than those in the Illinois Basin. Only portions of the Silurian, Devonian, and Mississippian Systems are present in the Arkansas portion of the Arkoma Basin, and these sediments are also very thin compared to the preserved record of these systems in southern Illinois. From their northern erosional limit Pennsylvanian strata thicken southward and westward into the Arkoma Basin. These sediments are believed to have the same easterly and northeasterly source as those of the Illinois Basin. If, during Pennsylvanian time, the Illinois Basin was connected to the Arkoma Basin, so probably was the Reelfoot Basin. The maximum thickness of Pennsylvanian strata into Illinois Basin (about 3200 feet in Union County, Kentucky) is probably represented by over 10,000 feet of Pennsylvanian sediments in Arkansas.

Warrior Basin

The Warrior Basin of Alabama and Mississippi appears to have a similar history to that of the Arkoma Basin in that the sediments of the early Paleozoic are lithologically similar to but thinner than those in the Reelfoot Basin, and the Pennsylvanian section thickens dramatically from the Illinois Basin southward to near the southern end of the Warrior Basin where more than 10,000 feet are preserved. Late Pennsylvanian or post-Pennsylvanian tectonism produced extensive faulting and folding as well as weak metamorphic alteration of the sediments in the southern Warrior Basin and the southern Arkoma Basin of Arkansas. The line of demarcation between the rocks exhibiting metamorphic alteration to the south and unaltered rocks to the north is called the Ouachita Front in Arkansas. It trends from west to east where it is buried beneath the sub-Cretaceous unconformity and takes a more southerly trend toward Mississippi and Alabama.

Pascola Arch

Extending from extreme northwestern Tennessee into southeastern Missouri is the site of the buried Pascola Arch (Grohskopf, 1955). Uplift of this arch effected southern closure to the Illinois Basin, domed the sediments of the Reelfoot Basin, thereby exposing them to subaerial erosion. The uplift, which exposed pre-Lamotte sediments at its crest, affected an area of over 15,000 square miles (Figure H-7). Erosional debris in the form of gravel and boulders which were deposited in an arc extending from the northeast to the south around the arch, have been dated as Upper Cretaceous Tuscaloosa Formation (Marcher and Stearns, 1962). Uplift of the arch was undoubtedly accompanied by faulting, and perhaps by the emplacement of plutons (Hildenbrand, Kane, and Stauder, 1977). Uplift along the Pascola Arch cannot be dated closer than post-Pennsylvanian and pre-Upper Cretaceous. Erosion effectively planed the northern part of the Mississippi Embayment before downwarping allowed renewed sedimentation. Upper Cretaceous and Tertiary strata of both marine and nonmarine origin then filled the depression. These sediments cover most of the Paleozoic rocks that were involved in the uplift of the Pascola Arch, and thoroughly mask the buried structure.

Post-Pennsylvanian Reactivation

Probably at the same time that the Pascola Arch was uplifted many of the earlier-formed faults and uplifts were reactivated throughout the region. The Rough Creek Fault system was displaced with some reverse movement, especially along its western portion where as much as 3000 feet of vertical movement is recorded by Devonian beds being elevated on the south of the zone into contact with Pennsylvanian sed[illegible]. In a graben in Union County, Kentucky, rock as young as those of early Permian age are present. Activity of the fault was not as pronounced to the east, where the zone has the appearance of a tensionally stressed anticline. Here horsts expose Mississippian rocks, and graben blocks preserve Pennsylvanian rocks. Last displacement of the Rough Creek system is down to the north, a reversal compared to earlier movement. In westernmost Kentucky, the south side of the Rough Creek Fault system dips very steeply into the Moorman Syncline (Rough Creek Graben), and may indicate an additional fault in the crystalline basement along the axis of the syncline with sufficient throw to accommodate the steep dip observed at the surface.

As much as 4000 to 5000 feet of sediment is believed to have been eroded from above the present surface of western Kentucky and southern Illinois; the exposed portion of the fault was therefore deeply buried when the last movement took place. Small compressional features now exposed within the Rough Creek Fault system are interpreted to be the result of squeezing of internal blocks as the north and south side of the zone tilted away from each other.

Northeastward and eastward trending block faulting in the Fluorspar District of southern Illinois and western Kentucky, as well as the Wabash Valley Faults, which have a more northerly trend at the western end of the Rough Creek system, are dated as post-Pennsylvanian. Renewed movement along the LaSalle Anticlinal Belt in Pennsylvanian time probably continued beyond that period (Clegg, 1965). The DuQuoin Moncline, Salem and Louden Anticlines, Cottage Grove Fault system and Ste. Genevieve Fault all experienced Pennsylvanian or post-Pennsylvanian tectonic activity.

A vast system of primarily NE-SW oriented erosional valleys marks the regional unconformity between Pennsylvanian and older strata in the Illinois Basin. The valley courses do not seem to have been affected by pre-existing structures except for perhaps the DuQuoin monocline.

It would appear that regionally there was rather gradual reactivation of many older faults and folds during Pennsylvanian time. A more violent and widespread adjustments of the basement rocks resulted in greatly increased accentuation of these features in post-Pennsylvanian time. I would propose that the formation of the Pascola Arch, and the pronounced reactivation of all the basement-related features occurred during the Mesozoic Era, probably early in Cretaceous time. However, the lack of Triassic and Jurassic sedimentary rocks in the region does not preclude major displacements having occurred earlier in the Mesozoic.

Following this latest period of major tectonic activity there has been widespread erosion in the Illinois Basin area, while downwarping of the Mississippi Embayment area has allowed the accumulation of sediments in that southward-deepening trough. The most recent major difference in tectonic regime between the Mississippi Embayment and the Illinois Basin has been stability or uplift to the north and subsidence to the south. Current seismic activity seems to be most active in the area of subsidence.

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APPENDIX H-1

List of Wells Used in Cross Sections

Wells in Figure 3

			Total Depth
1.	Humble Oil Company #1 Pickell	Sec. 21-13S-2W Union County, IL	8,492'
2.	Texas Pacific Oil Company #1 Farley	Sec. 34-13S-3E Johnson County, IL	14,284'
3.	Exxon #1 Duncan	Sec. 5-M-22 Webster County, KY	15,200'
4.	Texas Gas Trans. #1 Shain	Sec. 10-L-36 Grayson County, KY	13,551'
5.	Benz Oil #1 Nunnally	Sec. 16-F-46 Metcalfe County, KY	6,114'

Wells in Figure 4

1.	Texas #2614 Brown (Indiana Farm Bureau)	Sec. 20-5N-2E Lawrence County, IN	6,806'
2.	E. I. DuPont #1 WAD FEE	Sec. 10-U-44 Jefferson County, KY	5,954'
3.	Langford Oil and Gas #1 Knight Bros.	Sec. 6-P-35 Breckinridge County, KY	6,065'
4.	Texas Gas Exploration #1 H. Shain	Sec. 10-L-36 Grayson County, KY	13,551'
5.	Benz Oil Co. #1 Nunnally	Sec. 16-F-46 Metcalfe County, KY	6,114'
6.	Houghland & Hardy #2 S. Goad	Sec. 12-A-43 Macon County, TN	5,048'
7.	E. I. DuPont #1 FEE	Sec. 16-3S-35E Davidson County, TN	5,574'
8.	Texaco #1 B. Haynes	Sec. 10-7S-39E Wilson County, TN	5,756'
9.	Gordon Street #1 R. Holden	Sec. 13-10S-37E Rutherford County, TN	5,631'
10.	Staufer Chemical Co. #1 FEE	Sec. 16-12S-28E Maury County, TN	6,473'
11.	California Co. #1 E. W. Beeler	Sec. 4-15S-29E Giles County, TN	5,750'

Wells in Figure 4 (Cont'd.)

12.	Shenandoah Oil Corp. #1 F. W. Smith & Occidental Pet.	Sec. 26-9S-2W Cullman County, AL	8,270'

Wells in Figure 5

1.	Union Oil Company #1 Cisne Comm.	Sec. 3-1S-7E Wayne County, IL	11,614'
2.	Texaco Oil Company #1 Cuppy	Sec. 6-6S-7E Hamilton County, IL	13,051'
3.	Texas Pacific Oil Company #1 Streich	Sec. 2-11S-6E Pope County, IL	14,942'
4.	Texas Pacific Oil Company #1 Farley	Sec. 34-13S-3E Johnson County, IL	14,284'

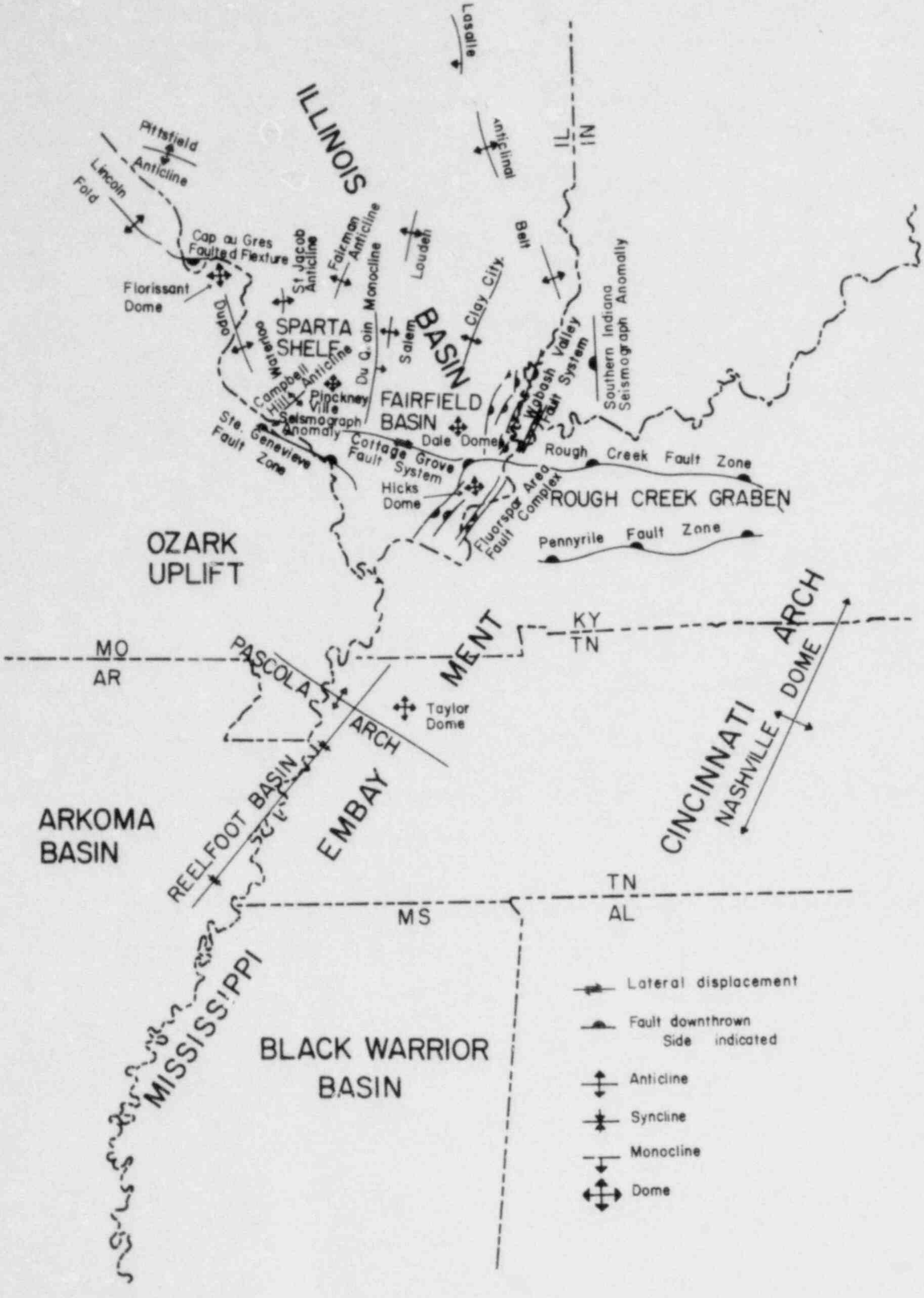
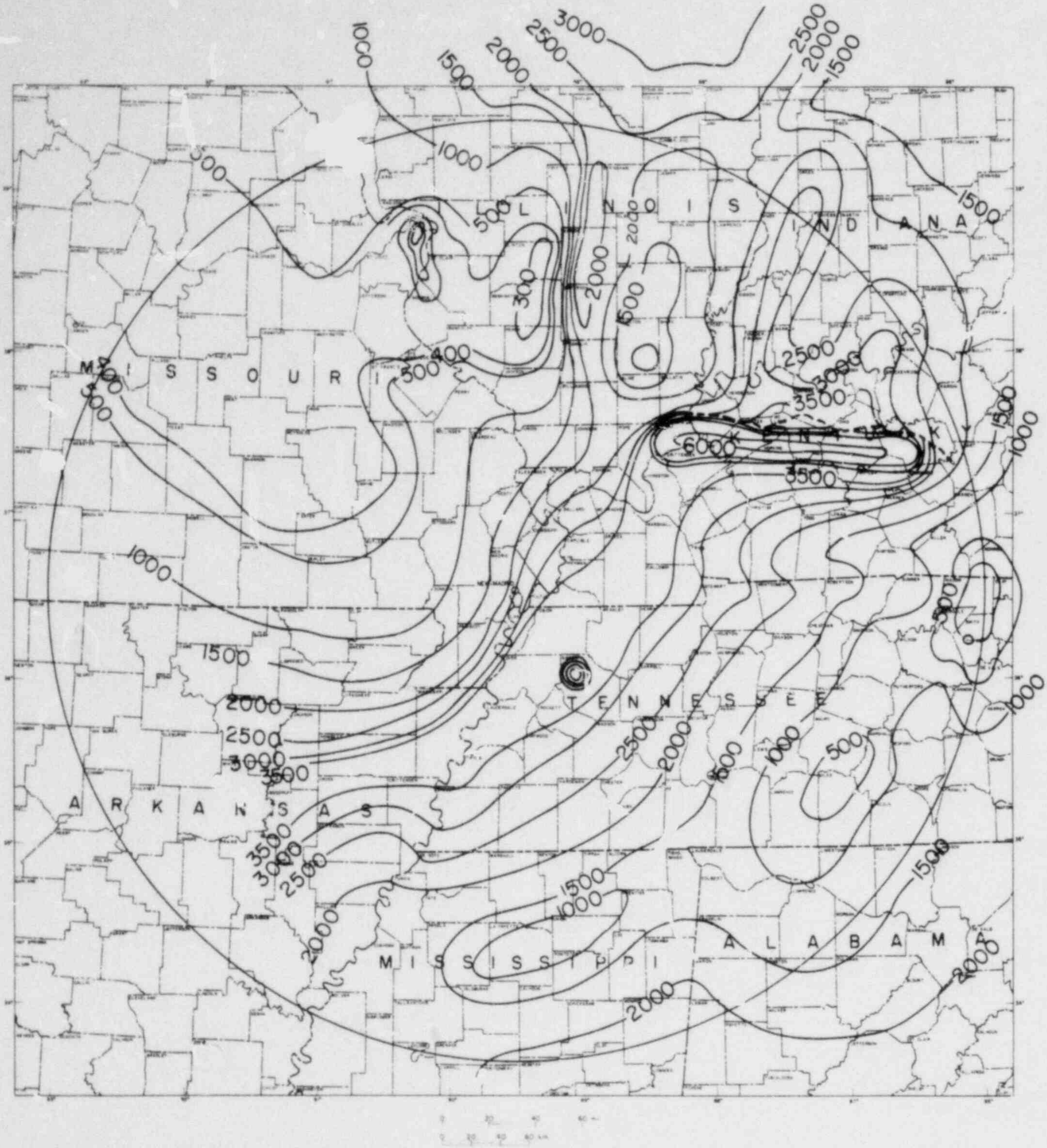


Figure H-1. Major structural features, including those inferred from seismograph exploration, of the New Madrid study area.



COMPILED BY HOWARD SCHWALB
PRELIMINARY DRAFT 7-79
REVISED 11-80

VARYING ISOLITH INTERVAL
SEE LINE VALUES

Figure H-2. Thickness of Pre-Knox Strata.

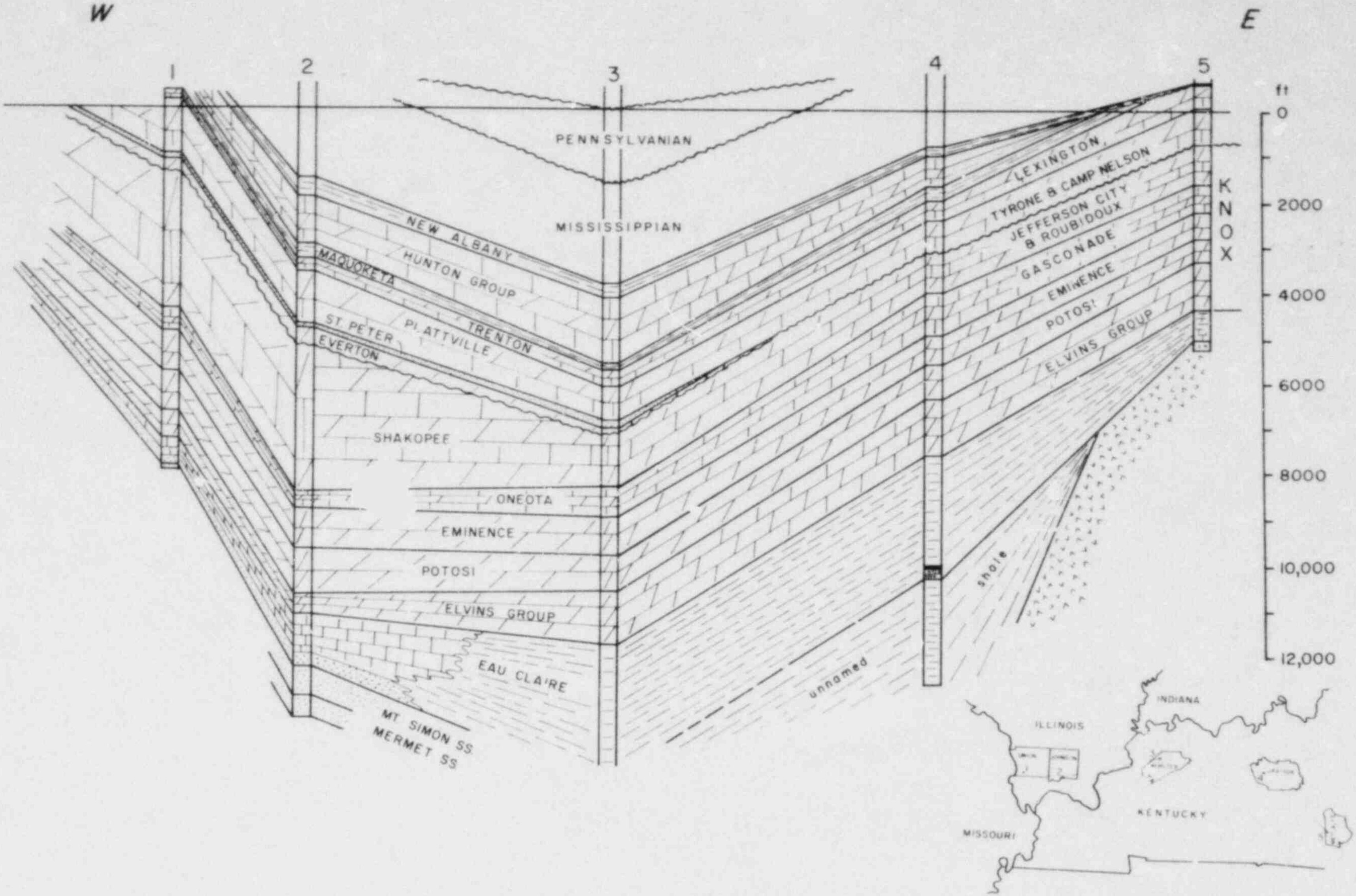


Figure H-3. East-west cross section south of Rough Creek Fault Zone and Cottage Grove Fault System.

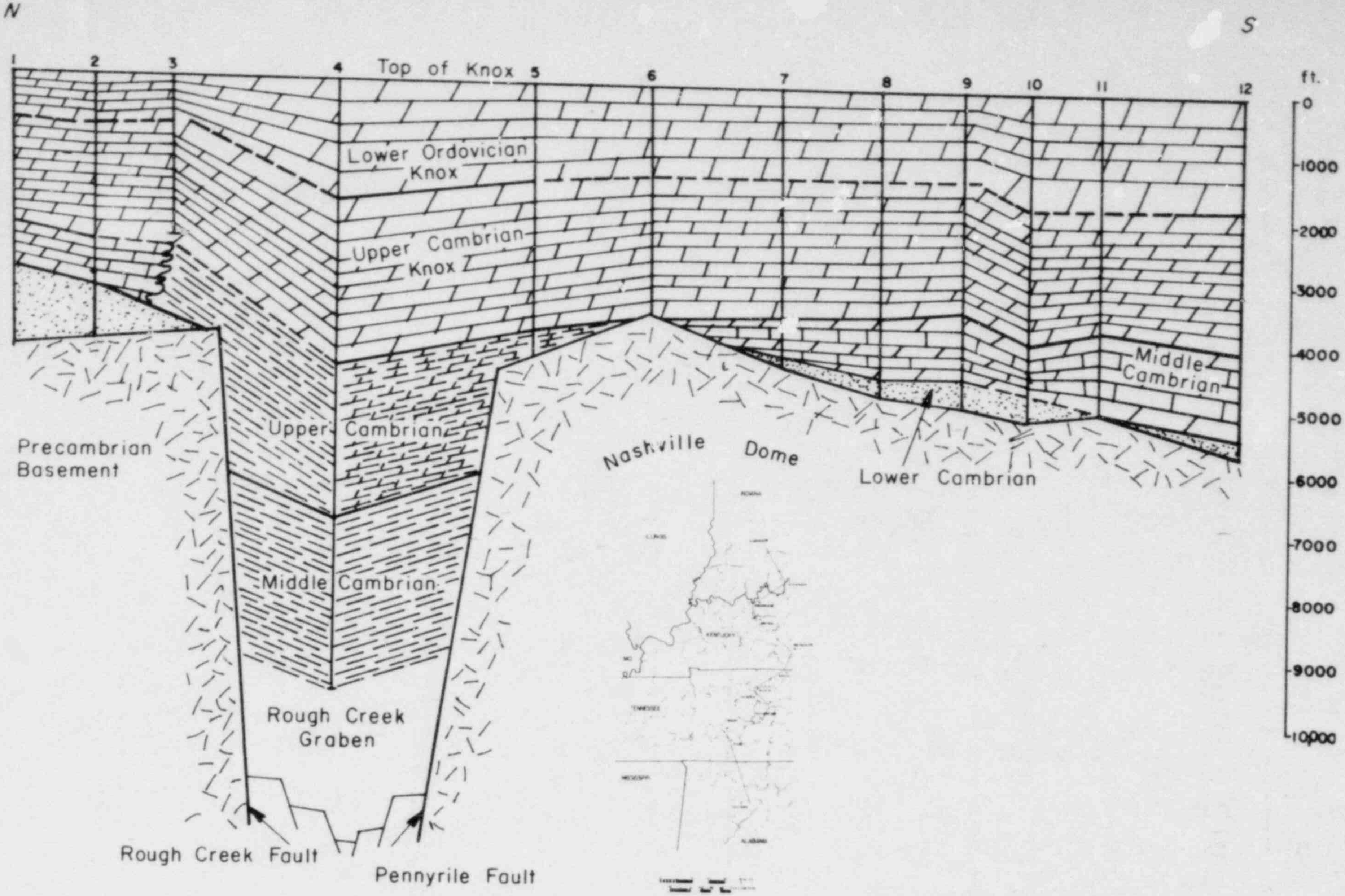


Figure H-4. North-south cross section, east of the study area.

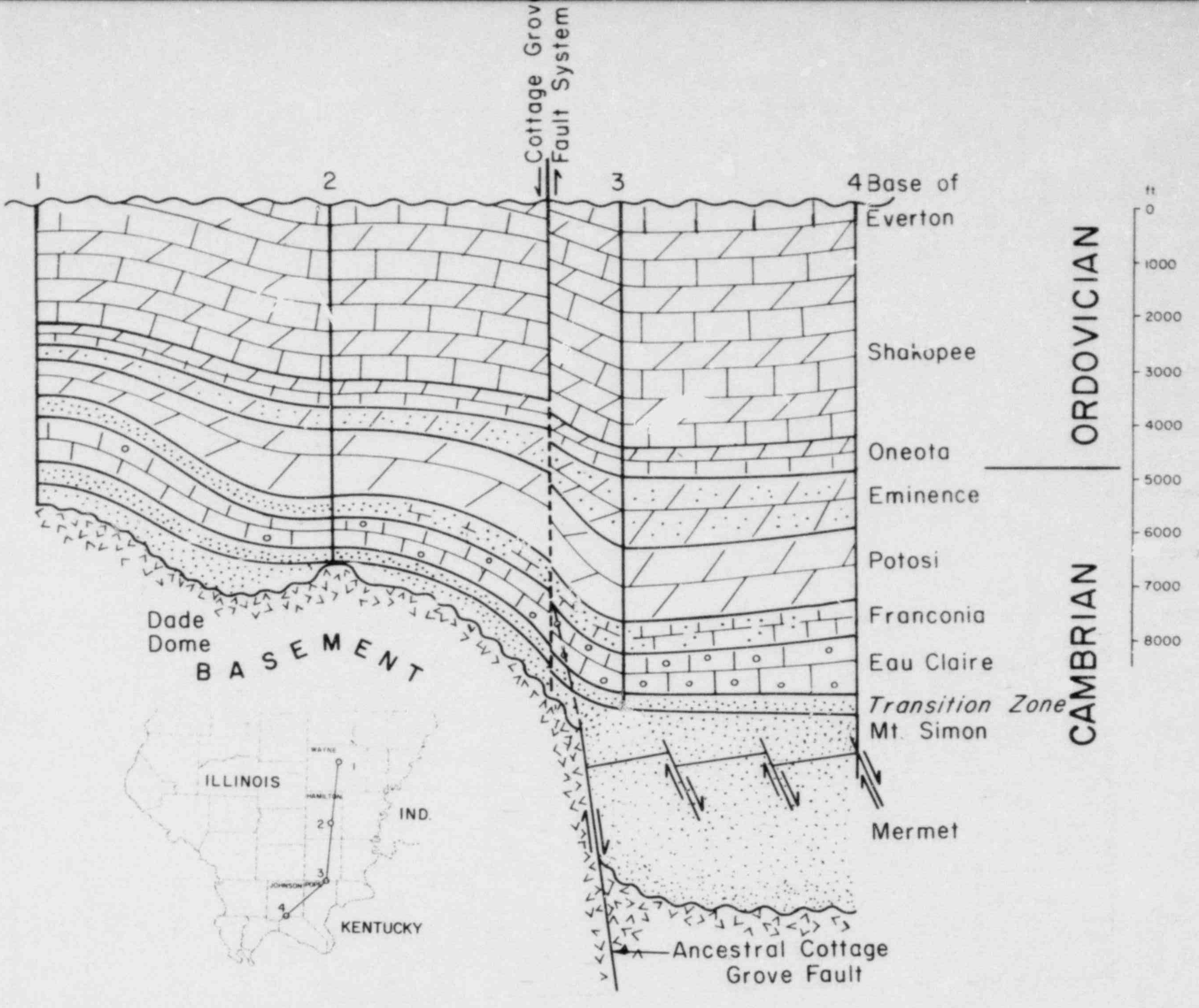


Figure H-5. North-south cross section of sub-Everton strata.

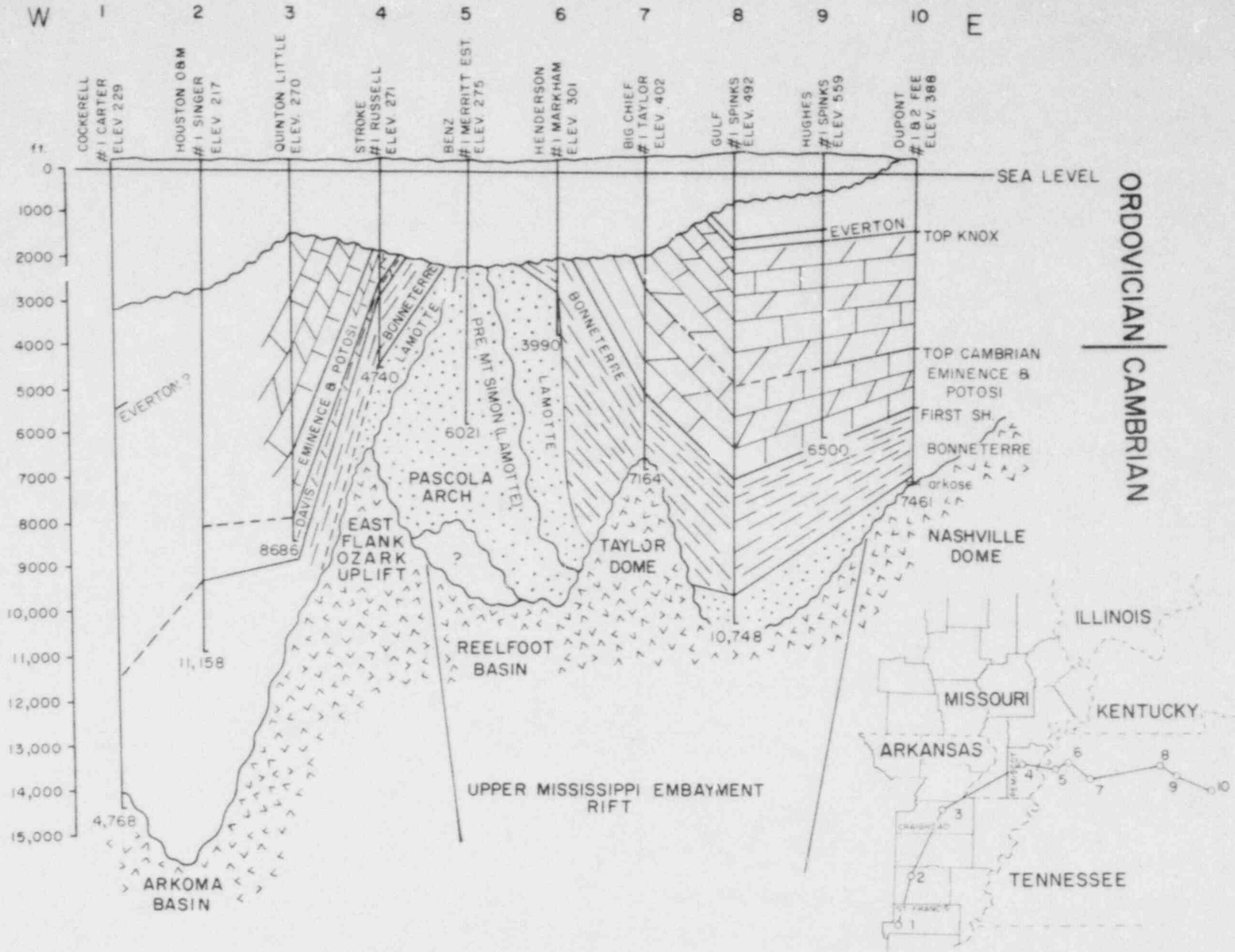


Figure H-6. East-west cross section from Arkansas to Tennessee.

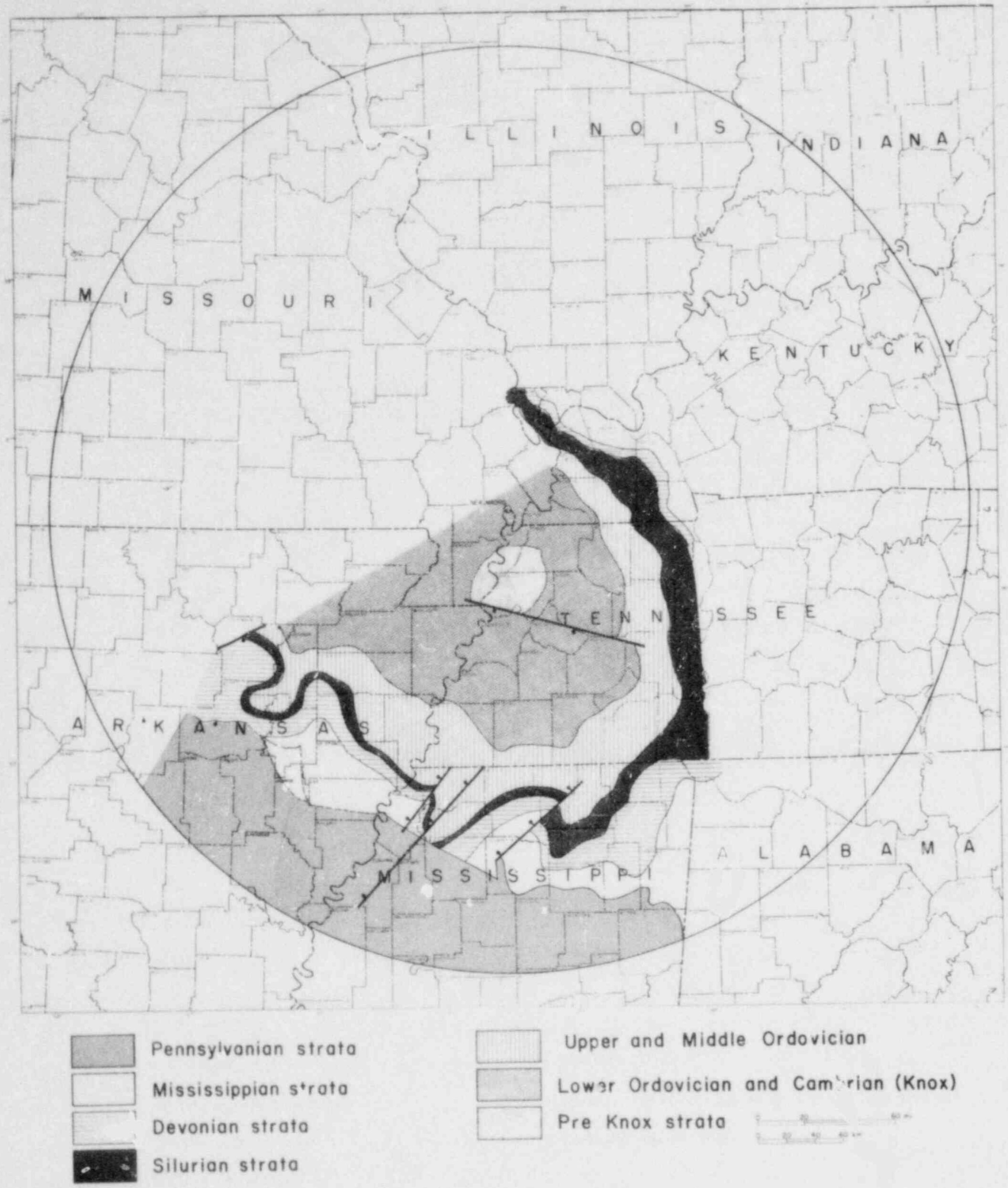


Figure H-7. Paleozoic Subcrop of Pascola Arch area.

MEMPHIS AREA REGIONAL SEISMIC NETWORK

Annual Progress Report - Fiscal Year 1980

Contract No. NRC-04-78-214

Arch C. Johnston
James E. Zollweg
Tennessee Earthquake Information Center
Memphis State University

ABSTRACT

During Fiscal Year 1980 the installation of the Memphis Area Regional Seismic Network (MARSN) was completed. MARSN consists of seven short-period vertical instruments sited in the lower Mississippi embayment between 34.5° N. and 35.5° N. Data are centrally recorded at the Tennessee Earthquake Information Center in Memphis, Tennessee on visual pen and ink recorders and on Develocorder. A digital recording system is under development.

Although MARSN detected 80 regional and near-regional events during the first year of operation, no locatable events occurred within the net proper. This contrasts with the active New Madrid seismic zone immediately north and several small events detected near Clevaland, Mississippi and Pine Bluff, Arkansas to the south.

Current plans call for expanding the network to ten stations and developing a radio-telemetry portable aftershock network. Only a long period of continuously seismic monitoring of the lower Mississippi embayment will answer the question of whether this region is truly aseismic.

INTRODUCTION AND PURPOSE

The Memphis Area Regional Seismic Network (MARSN) was established for the purpose of reliably detecting and accurately locating any earthquakes which occur in the lower Mississippi embayment. To the north the now-familiar pattern of epicenters reported by St. Louis University ends apparently rather abruptly at about latitude 35.5° N. Historical reports of mostly non-instrumental locations indicate a diffuse and very low level seismicity for the lower Mississippi embayment and Gulf coastal plain.

Zollweg (1976) has examined the pre-1960 seismicity of the embayment between 34.5° N. and 35.5° N. and concluded that most of the events attributed to this zone in fact occurred further north. The microseimicity of the region has remained largely unknown until the MARS Network was installed in

1979. This seven-element network of short-period vertical seismometers has been in operation for nearly a year. No events between 34.5° N. and 35.5° N. have been detected. The minimum magnitude detection threshold has yet to be precisely determined but is between m_b= 1.0-1.5. Of course a much longer period of time will be needed to establish the true seismicity or aseismicity of the region.

Included in this report are descriptions of the MARS Network in its present configuration and planned improvements for the next several years. Also field research activities by the Tennessee Earthquake Information Center (TEIC) in the lower Mississippi embayment region are summarized (see Appendix I-1). These have consisted principally of microearthquake surveys and investigation of a large slope failure in Village Creek State Park, Arkansas.

For reference purposes pertinent FY 79-80 data on the MARS Network station descriptions and operational status are compiled in Appendix I-2 (a) and I-2 (b).

THE MARS NETWORK

FY 79-80 MARSN station locations and telemetry routes are shown in Figure I-1; coordinates, dates of installation and instrumentation for each site are given in Appendix I-2 (a). Originally MARSN was to be a six-element network; a seventh station (EBZ) was added in May, 1980. Briefly, each station except SFTN consiss of a short-period (T_0≈1 sec) vertical seismometer, either a Kinemetrics SS-1 or a Geotech S-13, a TEIC-built preamplifier-voltage controlled oscillator and a radio-telemetry link that utilizes 5-element Yagi antennas and a Monitron T21F/R21F transmitter-receiver pair in the FM 216-218 MHz range. Where AC line power is not available transmitters are powered by either a set of five Edison Carbonaire batteries or an automobile battery trickle-charged by a solar panel. Station SFTN is a Mark Products L-15 borehole seismometer (T_0≈0.125 sec) emplaced at a depth of 143 meters in an abandoned U.S. Geological Survey water-test well.

Several of the MARSN stations require radio relay installations to reach central receiving sites. Pickwick Lake, Alabama (PWLA) must be relayed twice, Pleasant Grove, Mississippi once via LGAR, and, until the Forrest City receiving site is completed this year, station OLY must repeat once at WLA. The network is noticeably elongated east-west as a consequence of the desire to provide southerly azimuth control for the St. Louis University coverage of the New Madrid seismic zone, and also the need to have some sensitive stations sited on hard rock. Final station calibrations are not yet complete, but the 10Hz magnifications of the embayment stations on pen and ink recorders (WLA, LGAR, PGM, EBZ) are in the $5X10^4$ to 10^5 range; OLY and PWLA, the two hard-rock sites, are $2\text{-}5X10^6$. For film records off the Develocorder (10X viewer) these magnifications will increase by a factor of four.

There are two central-receiving sites for the MARSN; one atop a tall downtown Memphis building is completely installed and at present transmits all seven MARSN stations to TEIC via a leased phone line. The second site at Forrest City, Arkansas is scheduled for completion in Fall, 1980. It will reduce the necessity of multiply-repeating several Arkansas stations and enable MARSN to expand coverage to areas such as Pine Bluff and Strawberry (Figure I-1) which have experienced recent seismic activity.

TEIC also operates a long-period broadband three-component instrument (MET) currently located on the Memphis State University campus. A concrete pier and vault have been prepared in the basement of the TEIC building to house this facility. When the station is moved later this contract year, the one-second galvanometers presently in use will be replaced with MARSN-funded 100-second galvanometers. This reinstallation (The station's new code is MPH) should considerably improve the operating characteristics of MARSN's single long-period station, but the site will still suffer from the high cultural noise level ever-present within the city of Memphis.

An additional project undertaken with MARSN funding is the design and development of a radio-telemetry portable aftershock network (PAN). The purpose of PAN is to provide TEIC the capability of responding to a major quake (or swarm) in the New Madrid seismic zone in a much more comprehensive fashion than simply deploying portable seismographs in the area. A five-element array consisting of seismometers, amp/VCO's, antennas and transmitters has been assembled. In the next step five permanent tower sites strategically located to provide coverage of the main zone of New Madrid seismicity will be instrumented by TEIC in 1981. The five-element array could then be deployed, transmit to the closest tower and the signals relayed to either TEIC in Memphis or to a central recording site utilizing slow-speed magnetic tape in Ridgely, TN.

When PAN is fully implemented it will provide for the first time an extended aftershock coverage capability. Moreover, the original plan could be easily upgraded to include digital recording and permanent stations at each of the PAN tower sites.

ACTIVITIES RELATED TO THE MARS NETWORK

During FY79-80 no earthquakes of magnitude 3.5 or greater occurred within or close to the region of coverage of the MARS network which would have warranted aftershock monitoring with deployed portable instruments. Indeed it was a quiet year overall for the New Madrid seismic zone, the largest event on the main trend of activity being the 08 July 1979 earthquake near Charleston, Missouri (m_{bLg}= 3.5 USGS; m_b= 3.1 SLU).

Our field activities were necessarily primarily concerned with the MARS Network itself--all seven telemetered stations were installed in FY79-80. Nevertheless, several field investigations were carried out as reported below.

Saint Francis Sunklands, Arkansas Microearthquake Survey

The Saint Francis sunklands, a subsidence feature in northeastern Arkansas apparently formed, or at least was deepened and expanded, during the 1811-1812 New Madrid earthquakes (Fuller, 1912, pp. 64-75). Herrmann et al., (1978) have determined that subsidence in this area of up to two meters is consistent with an estimate of static surface displacements based on a theoretical model of the faulting which produced these events. The sunklands lie at the southwestern terminus of the distinct linear trend of microearthquake epicenters located by the Saint Louis University New Madrid network (Stauder et al., 1976).

In order to determine the seismicity and seismic characteristics of this region and in particular to ascertain if microearthquakes do occur further south along this seismic trend, a four-element array of portable seismographs was operated in the Trumann-Marked Tree, Arkansas area from March 3 to April 11, 1980. Since 1967, 23 earthquakes have been instrumentally located here. Figure I-2 shows the distribution of these events and the station sites used in this investigation. Three Sprengnether MEQ-800's (two on loan from Saint Louis University) were deployed in conjunction with Judd Hill Plantation (JHP), a station of the permanent St. Louis network (see Figure I-1).

As a cost-saving measure each portable station was operated by a student volunteer selected from a senior physics class at Trumann High School. The performance of these operators was variable from one operator who returned nearly complete records to another who returned almost none. Operator negligence was not the only difficulty encountered. Severe rains caused damage at two of the sites and a third, St. Francis Floodway (SFF), had to be moved when flooding and resulting loss of equipment appeared imminent. The mix of bad weather, station failures, and operator problems were responsible for a total station up-time of just under 40 percent. However, during the entire investigation period there was at least one station operating at any one time.

No earthquakes originating within the sunklands array were recorded during this project, although four near-regional events (from the New Madrid zone to the north) were detected. Individual array stations recorded possible minor quakes but lack of correlation on other stations led to these being discounted. Extremely small ($m_b \leq 0$) would have gone undetected because of the low magnifications (10-20k at 10 Hz) required in station operation. The Marked Tree area, especially the proximity of Highway 63 and intense farming activity made higher gains impossible.

The negative result of this project coupled with the lack of earthquakes down to $m_b \approx 1.5$ in the MARSN region indicates that the NE-SW trend of New Madrid seismicity does end rather abruptly at about 35.5° N. This observation is difficult to reconcile with evidence presented by Hildenbrand and others (1977, 1980) for a clearly-defined rift structure in the magnetic basement extending to at least 34.5° N. latitude in the embayment. These considerations have a direct bearing on the question of seismic risk assessment: Should the southern extent of the earthquake source zone for the Mississippi embayment be limited at 35.5° N. latitude on the basis of seismicity or should it extend to about 34.5° N. based on evidence for structural continuity of the basement rift? Succeeding years of observations from the MARS Network will be important in the resolution of this problem.

Slope Failure: Village Creek State Park, Arkansas

Village Creek State Park is located 50 km southwest of the microearthquake Saint Francis sunklands area. On April 28, 1980 two seismic events registered on the permanent MARSN station WLA at Wittsburg Lake, Arkansas. These events, separated by 28 minutes and equivalent to an m_b of roughly 1.5 and 1.1 respectively, were coincident in time (± 2 hours) with a major landslide reactivation occurring 3.7 km away at Lake Austell in Village Creek State Park. The slide formed a graben approximately 100 meters in length, 40 meters in width and up to 15 meters deep. On May 2, a portable seismograph was installed 30 meters from the graben on the south abutment of the dam.

To determine if further deformation is occurring, a transit survey of both horizontal and certical components is being conducted by the Arkansas Conservation Commission in conjunction with TEIC. A preliminary report on the slide (MacFarland, 1980) has shown continued horizontal and vertical movement. Figure I-3 is an idealized cross section of the slide as it appeared in June. Four major down-dropped blocks can be seen, as well as three pressure ridges near the toe of the slide. One of these ridges has completely blocked the stream which ran parallel to the graben itself.

A third resurvey of the slide area has shown that the area of deformation as well as the magnitude of movement are increasing. Much of the south abutment as well as the south side of the dam itself are deforming horizontally.

Since the large movements of April 28, three more episodes of movement have been noted. Each of these occurred after several days of heavy rains. Unfortunately, none of these episodes has been correlated with seismic events on either WLA or the portable station at Lake Austell. In an effort to provide a definite correlation in event of future movements, a five-station micro-network is tentatively planned around Lake Austell. With station distances not exceeding 300 meters, any movement at the slide should show correlation. The Lake Austell micro-network will be telemetered to the MARSN tower at Forrest City, Arkansas and thence to Memphis via leased phone line. Telemetry should improve record return and provide for more immediate interpretation of further seismicity at Lake Austell.

PROPOSED PROGRAM

As previously discussed MARSN will be expanded to ten telemetry stations by 1981. One of these, Pine Bluff, is of particular interest for it will monitor the inferred intersection of the buried Ouachita foldbelt and the New Madrid rift zone. In the twentieth century at least eight quakes of MMI IV or larger have occurred in this general region. This year the MARS Network detected, but was unable to accurately locate, three events (m_b<2.0) from the Pine Bluff area. We intend to monitor this region for several years to ascertain if a more ambitious effort in the Ouachitas is warranted.

In addition to supplementing the number of stations in the MARS Network, the addition of horizontal components at at least one site, and hopefully more, is planned. Accurate S-wave arrival times and studies of the anelastic attenuation of the Lg phase in the Lower Mississippi embayment would be two direct benefits.

The major improvement for MARSN, however, will be the upgrading of the data recording and management facilities at TEIC. Over the next several years we propose to gradually build the capability to digitally record and analyze MARSN data (in conjunction with our Southern Appalachian Net) in an on-line mode. A PDP 11-44 minicomputer was acquired this contract year for this purpose. When such a system is functional it will enable the relatively small TEIC staff to efficiently process and analyze data from up to fifty seismograph stations in the central and southeastern United States.

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APPENDIX I-1

Abstracts Relating to the MARSN Region

THE NEW MADRID RIFT SOUTH OF 35.5° N.: FIRST YEAR RESULTS OF THE MEMPHIS AREA REGIONAL SEISMIC NETWORK

Arch C. Johnston
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Memphis State University
Memphis, Tennessee 38152

Presented at the American Geophysical Union, Midwest Meeting (1980)

A seven-station radio-telemetered network of short-period vertical instruments has been operated by the Tennessee Earthquake Information Center for a year in that portion of the Mississippi embayment between 35.5° N. and 34.5° N. During this period no earthquakes were recorded within the net proper. Several small events occurred further south near Cleveland, Mississippi and Pine Bluff, Arkansas.

A precise minimum magnitude detection threshold has not yet been determined for the network, but, based on the detection of small events occurring in the active New Madrid zone to the north, it is certainly less than $m_b = 1.5$.

Conclusions drawn from only one year of operation are admittedly premature, but these preliminary results do indicate that the seismicity of the lower Mississippi embayment between 34.5° N. and 35.5° N. is extremely low. Why this should be so when activity to the north is high and a clearly-defined rift structure in the magnetic basement is continuous to 34.5° N. is a major question to which, at present, there is no satisfactory answer.

SEISMIC DETECTION OF STRAIN ENERGY RELEASE OCCURRING IN UNCONSOLIDATED SEDIMENTS

Matthew Regis Bob

Presented at the Geological Society of America Annual Meeting (1980)

The recent occurrence of a landslide at Village Creek State Park, Arkansas suggests that the generation of seismic energy in the microearthquake frequency band (∿3-10 Hz) may not be uniquely associated with brittle fracture in competent rock.

The surficial ground slope failure produced a classic up-slope graben, down-slope pressure ridge of overall dimensions 100 x 60 meters. Approximately coincident with the failure, two seismic events were recorded at a short-period, high-gain station of the Memphis Area Regional Seismic Network located 3.7 km away. No other network station recorded the event suggesting it was extremely shallow and nearby. Had the events occurred in bedrock, which is covered by ∿500 meters of alluvium in this region, other network stations would have recorded at least the larger of the two. The possibility of a blast or atmospheric disturbance has been investigated and discounted.

Whether the seismic energy was generated by the slide itself or by failure deeper in the alluvium thereby triggering the slide is as yet unresolved. In either case the production of the high frequency seismic radiation argues for a buildup and abrupt release of strain energy in unconsolidated sediments, a process which heretofore had only been recognized as occurring in well-consolidated materials.

MEMPHIS AREA REGIONAL SEISMIC NETWORK
(as of June 30, 1980)

CODE	STATION	LOCATION	DATE OPENED/CLOSED	SITE GEOLOGY	INSTRUMENTATION
MET	Memphis, TN Engineering Building, MSU	35°07'20.5"N 89°56'4.3"W 93m	13 Nov 73 (Z) - 1 July 75 (3 comp) -	Pleistocene Loess	3 component Sprengnether Long Period T = 15 sec T_g= 1 sec°Broadband photo and visible recording
SFTN +	Shelby Forest, Tennessee	35°21'27.0"N 90°01'07.5"W -23m	02 Aug 79 -	Tertiary snad & gravel	Mark Products L-15 Borehole Seismometer T_o= 0.125 sec
WLA +	Wittsburg Lake, Arkansas	35°11'08.3"N 90°42'56.1"W 115m	02 Aug 79 -	Pleistocene Loess	Kinemetrics Ranger SS-1 T_o=1 sec
LGAR +	La Grange, Arkansas	34°39'05.0"N 90°39'29.3"W 107m 34°39'05.7"N 90°39'23.3"W 100m	7 Aug 79 - 8 Nov 79 15 Nov 79 -	Pleistocene Loess	Kinemetrics Ranger SS-1 T_o=1 sec
PGM +	Pleasant Grove, Mississippi	34°27'50.4"N 90°06'45.1"W 105m	24 Aug 79	Pleistocene Loess	Kinemetrics Ranger SS-1 T_o+1 sec
OLY +	Olyphant, Arkansas	35°30'09.7"N 91°28'12.0"W 236m	06 Nov 79 -	Pennsylvanian Sandstone, Cane Hill Member of Hale Formation	Kinemetrics Ranger SS-1 T_o=1 sec

APPENDIZ I-2 (a) (continued)

MEMPHIS AREA REGIONAL SEISMIC NETWORK
(as of June 30, 1980

CODE	STATION	LOCATION	DATE OPENED/CLOSED	SITE GEOLOGY	INSTRUMENTATION
PWLA +	Pickwick Lake, Alabama	34°58'47.94" 88°03'49.2" 204_m	14 May 1980 -	Residium atop Mississippian Fort Payne	Geotech S-13 $T_o=1$
EBZ +	Ebenezer Cemetery, Tennessee	35°08"28.80 89°21"01.9" 169_m	15 May 1980 -	Pleistocene Loess	Geotech S-13 $T_o=1$

+ Telemetered to TEIC

APPENDIX I-2 (b)

MARSN OPERATIONAL STATUS
FISCAL YEAR 1980

		MARSN TOTAL (telemetered stations)	---Percentage of Operational Station Days---							
			LGAR	OLY	SFTN	PGM	WLA	PWLA	EBZ	MET*
1979	Jul	-	-	-	-	-	-	-	-	100
	Aug	96.4	100	-	[illegible]3.9	91.7	98.1	-	-	96.8
	Sep	95.7	94.7	-	96.5	96.7	95.0	-	-	100
	Oct	96.3	100	-	90.3	98.4	96.5	-	-	96.8
	Nov	64.4	43.3	40	92.8	65.4	76.4	-	-	96.7
	Dec	71.5	89.4	61.2	99.7	99.6	7.3	-	-	100
1980	Jan	63.0	93.5	35.9	97.5	89.8	0.0	-	-	96.8
	Feb	70.3	98.4	55.2	97.7	94.3	6.0	-	-	100
	Mar	61.9	86.6	8.5	96.6	87.8	29.8	-	-	96.8
	Apr	85.7	93.8	56.7	95.0	84.7	98.3	-	-	100
	May	78.8	54.3	57.9	80.6	71.8	95.8	99.5	94.4	100
	Jun	92.5	93.5	97.3	96.5	88.2	87.5	93.5	80.1	100

* MET-Not telemetered

TOTALS	78.8%
TOTAL WITH MET	82.4%
TOTAL DATA HOURS	47,760
USEFUL DATA HOURS	39,371

PRIMARY CAUSES OF STATION OUTAGE

*Radio Noise (interference)	112 days
*Radio Failure	107 days
VCO Canister Failure	44 days
Vandalism at Site	38 days
AC Power Outage	15 days
Lightning damage	10 days
Pens clogged	9 days
Seismometer site moved	8 days
VCO Battery Failure	7 days
Rodent damage	3 days

*Accounts for 95% of down time

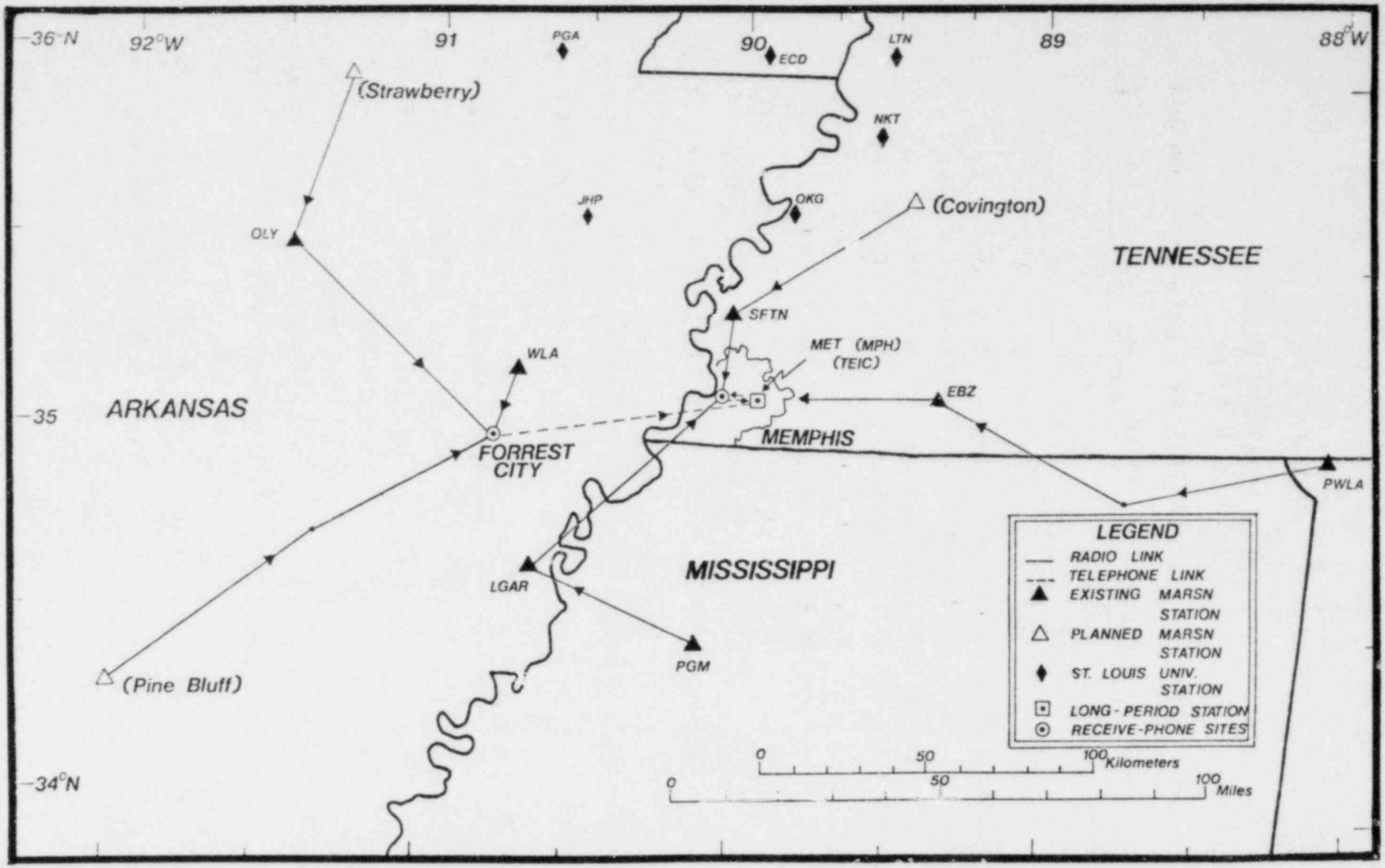

Figure I-1. The MARS Network showing existing and planned stations and telemetry routes.

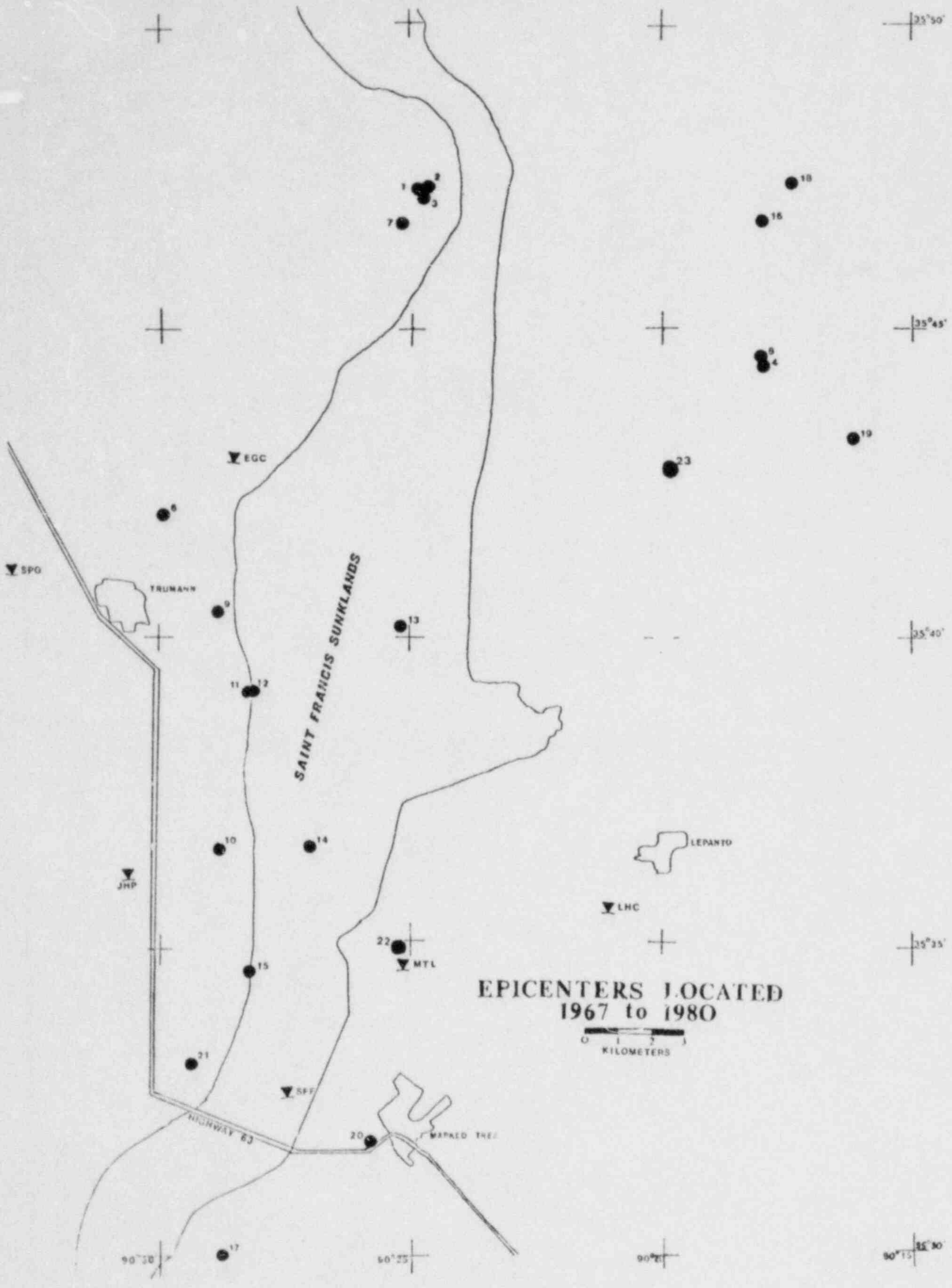

Figure I-2. The Saint Francis sunklands area with located epicenters (circles) and seismic stations (inverted triangles).

LAKE AUSTELL SLIDE (JUNE 1980)

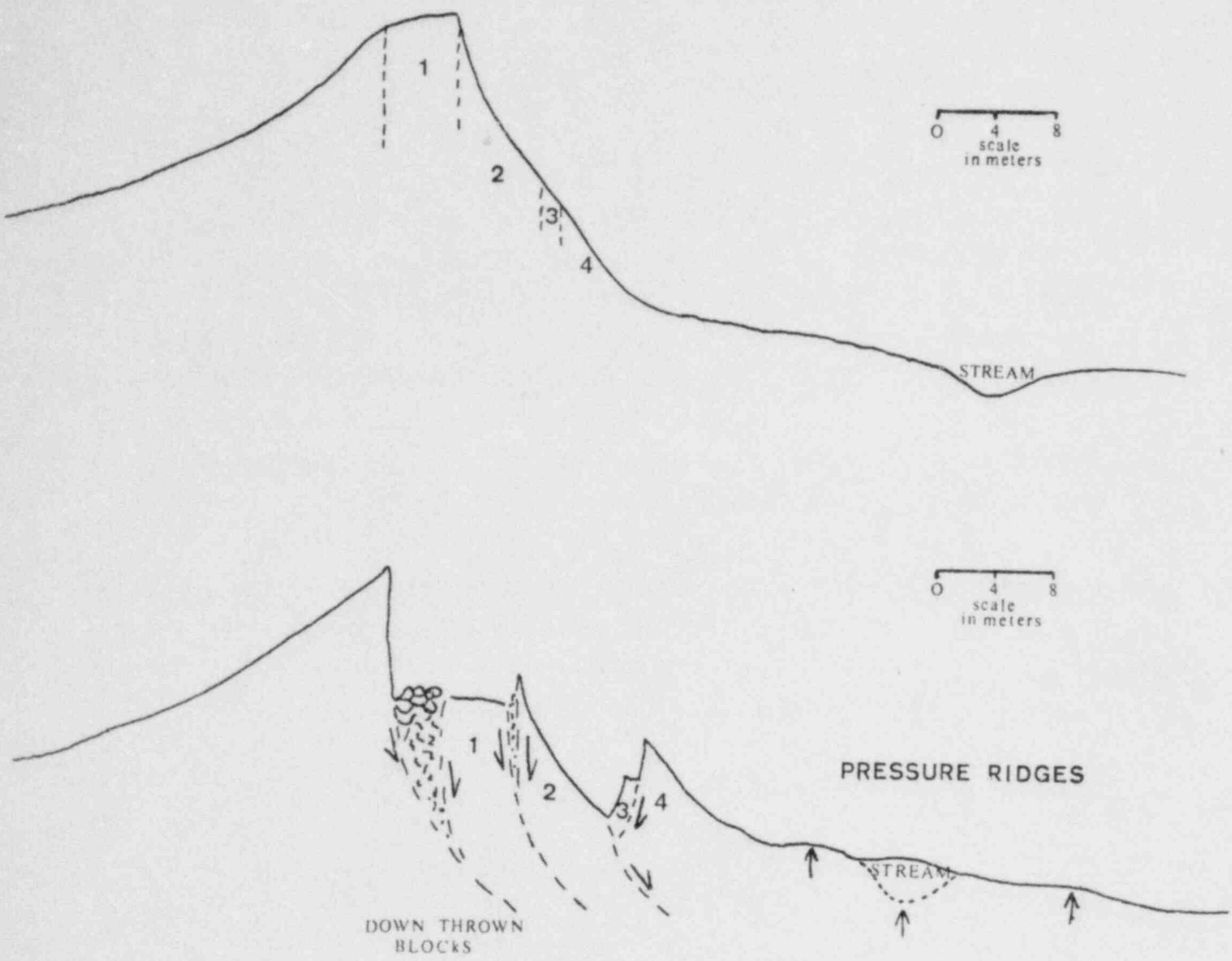

Figure I-3. Interpretive cross-section of the Lake Austell slide, Village Creek State Park, Arkansas (after McFarland: 1980).

A SEISMOLOGICAL STUDY OF THE NORTHERN EXTENT OF THE NEW MADRID SEISMIC ZONE

Annual Progress Report - Fiscal Year 1980

Contract No. NRC-04-76-282

Robert B. Herrmann
Saint Louis University

INTRODUCTION

The objective of this project is to develop a seismological data base in order to answer precise questions on the nature of the New Madrid earthquakes. This work is being performed in conjunction with USGS supported research. In the mind of the principal investigator, the problem of New Madrid earthquakes cannot be separated from other eastern U.S. earthquakes. Hence, the research area is considerably broader than the project title implies. The breadth of the studies performed is indicated somewhat by the publications.

This report contains a summary of earthquake activity during 1979 (Appendix J-1) as well as an initial study on the three-dimensional distribution of earthquakes in the central Mississippi Valley (Appendix J-2). Work has just begun to obtain a surface-wave focal mechanism for the July 27, 1980 northern Kentucky earthquake.

APPENDIX J-1

CENTRAL MISSISSIPPI VALLEY EARTHQUAKES - 1979

W. Stauder, R. Herrmann, S. Singh, C. Nicholson, D. Reidy, R. Perry, S. Morrissey and E. Haug

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During 1979, 238 earthquakes were located and 485 other nonlocatable earthquakes were detected by a twenty-four station regional microearthquake network operated by Saint Louis University under contract for the USGS and NRC. Figure JA1-1 shows the 238 earthquakes located within a $4^o \times 4^o$ region centered on 37.0^o N. and 89.5^o W. Seismograph stations are denoted by the triangles together with the station code. The magnitudes are indicated by the size of the open symbols. Figure JA1-2 shows the locations and magnitudes of 197 earthquakes located within a $1.5^o \times 1.5^o$ region centered at 36.25^o N. and 89.75^o W. Figures JA1-3 and JA1-4 are similar maps to Figures JA1-1 and JA1-2 but with the epicenters scaled according to depth.

Magnitude formulas for the central United States were recently revised to account for observed time-domain scaling properties. The significance of the revised formulas is that consistency is now achieved in assigning body-wave magnitudes to both large and small earthquakes, using the attenuation of the Lg wave. The new formulas are given in the Appendix and were applied to magnitude calculations starting January 1, 1979. Large events previously detected in the central Mississippi Valley would not be affected; whereas the magnitudes of small earthquakes would be revised upwards proportionately. An earthquake previously assigned a magnitude of 0.0 would now have an m_b = 0.7, a 1.0 would become a 1.5, and a 1.8 would become an m_b = 2.0.

There were two sequences of earthquake swarm activity during the first quarter of 1979. The Ridgely area of western Tennessee, near the station GRT, experienced an earthquake swarm of unusual duration from 2 February to 4 February. 135 earthquakes were recorded in 57 hours. At least 8 of the earthquakes were felt in the immediate vicinity of the swarm epicenters. The 4 largest earthquakes generated MM intensities of II-III in Ridgely. Focal depths for most of the events were less than 5 km. The Tennessee Earthquake Information Center was able to field portable instruments for part of the swarm's duration. The majority of the earthquakes occurred close to Lat. 36.26^{o} N. and Lon. 89.47^{o} N.

The second swarm occurred near the station POW from 27 February to 28 February. 42 earthquakes were detected in 22 hours. The main event of 27 February at 2254 UTC was felt strongly in Powhatan, Arkansas (MM intensity of V), m_b3Hz = 3.5 (FVM). The second event 18 seconds later was also felt in Powhatan, M_b3Hz = 3.2 (FVM). Pr[illegible] activity indicated a migration in seismicity from the north to th[illegible] area near Strawberry, Arkansas. TEIC was able to field instruments during part of this swarm sequence.

Other than the above two swarm sequences, the significant earthquakes during 1979 include the following:

1. 05 February, 0531 UTC, 35.84^{o} N., 90.08^{o} W., felt in the Blytheville, AR area; MM intensity IV at Blytheville A.F.B., m_b3Hz = 3.0 (FVM).
2. 27 February, 0826 UTC, felt in Pine Bluff, AR; m_bLg = 2.9 (FVM).
3. Event of 07 March, 0640 UTC, 35.98^{o} N., 91.42^{o} W., unusually deep focus of 29 km; m_b3Hz = 2.2 (FVM).
4. Event of 03 June, 0550 UTC, 38.61^{o} N., 90.52^{o} W., felt in S.W. Ladue and Jennings, MO area. Audible and felt reports from second story buildings were reported. m_b3Hz = 1.93 (FVM).
5. Event of 11 June, 0412 UTC, 36.17^{o} N., 80.65^{o} W., felt widely in the Caruthersville, MO region and felt as far as Dyersburg, TN. m_b3Hz = 3.9 (FVM).
6. Event of 25 June, 1711 UTC, 35.53^{o} N., 90.43^{o} W., felt in Marked Tree, AR region. m_b3Hz = 3.2 (FVM).
7. Event of 08 July, 1235 UTC, 36.89^{o} N., 89.29^{o} W., felt in Charleston, MO area. m_b3Hz = 3.1 (FVM).
8. Event of 13 July, 0729 UTC, 36.08^{o} N., 89.77^{o} W., felt in Caruthersville, MO region. m_b3Hz = 2.8 (FVM).
9. A very shallow event of 12 September, 1059 UTC, 37.74^{o} N., 89.95^{o} W., felt S.W. of Perryville, MO. A house was reported being shaken. m_b3Hz = 2.54 (FVM).

10. Event of 05 November, 1635 UTC, 36.44° N., 91.01° W., felt in Dalton, AR. MM intensity IV at Dalton, AR. $m_bLg = 3.2$ (FVM).

APPENDIX JA-1

I. For magnitudes determined by records from the network telemetered stations, the formulae used apply to signals in the period range 0.08 sec. $\leq T \leq$ 0.12 sec. and for Embayment events only.

$m_b10Hz = 0.95 \log \Delta(km) + \log A\ (m\mu) - 1.05$ $10\ km \leq \Delta \leq 40\ km$

$m_b10Hz = 1.25 \log \Delta(km) + \log A\ (m\mu) - 1.50$ $40\ km \leq \Delta \leq 100\ km$

$m_b10Hz = 1.55 \log \Delta(km) + \log A\ (m\mu) - 2.10$ $100\ km \leq \Delta \leq 200\ km$

$m_b10Hz = 2.5 \log \Delta(km) + \log A\ (m\mu) - 4.30$ $200\ km \leq \Delta \leq 300\ km$

II. For magnitudes determined by records from near regional stations, (e.g. FVM, etc.), and for periods 0.2 sec. $\leq T \leq$ 0.50 sec.:

$m_b3Hz = 0.88 \log A\ (km) + \log A\ (m\mu) - 1.00$ $10\ km \leq \Delta \leq 100\ km$

$m_b3Hz = 1.06 \log A\ (km)\quad \log A\ (m\mu) - 1.36$ $100\ km \leq \Delta \leq 200\ km$

$m_b3Hz = 1.29 \log A\ \Delta(km) + \log A\ (m\mu) - 1.89$ $200\ km \leq \Delta \leq 400\ km$

III. For all other stations, and for periods 1 ± 0.4 sec.:

$m_bLg = 3.75 + 0.90 \log \Delta(^{\circ}) + \log A\ (\mu)$ $0.5^{\circ} \leq \Delta \leq 4.0^{\circ}$

$m_bLg = 3.30 + 1.66 \log \Delta(^{\circ}) + \log A\ (\mu)$ $4.0^{\circ} \leq \Delta \leq 30^{\circ}$

For further information on magnitudes in the central United States, see Nuttli (1973).

IV. FMAG - duration magnitude for the station (GRT). The equations are:

$$m_D = 2.7 \log (T) - 2.7 \qquad T \geq 40 \text{ sec.}$$

$$m_D = 0.9 \log (T) + 0.2 \qquad T \leq 40 \text{ sec.}$$

Where T is the coda duration in seconds from the onset of the P-wave to the time the peak-to-peak trace amplitude drops below 10 mm as measured off the Develocorder film on the 3-M viewer.

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APPENDIX J-2

PRELIMINARY RESULTS OF MICROEARTHQUAKE STUDIES IN THE CENTRAL MISSISSIPPI VALLEY

by

Robert B. Herrmann

INTRODUCTION

The earthquake problem in eastern North America is interesting as well as frustrating. Large earthquakes have occurred in the past, such as the 1811-1812 New Madrid and the 1929 Grand Banks earthquakes, but a working model for their occurrence has yet to be discovered. There seem to be patterns of earthquake occurrence, but at the same time damaging earthquakes also occur away from these patterns.

A statement of the problem is expressed as a series of questions:

a) Why do earthquakes occur in eastern North America, especially in the middle of a tectonic plate?

b) Given the occurrence of these earthquakes, how large could the earthquake be?

c) What are the source zones, if any, and where cannot a large earthquake occur?

Similar questions can be asked about any specific earthquake zone, even the central Mississippi given recently acquired microearthquake data.

It is the object of this report to present a summary of the present knowledge of earthquakes in the central Mississippi Valley as well as to address additional research that is required.

HISTORICAL DATA

Nuttli (1979) compiled a catalog of over 1100 historical earthquakes in the central United States prior to 1975. Figure JA2-1 shows the 116 earthquakes in the nineteenth century that occurred in the central Mississippi Valley. The earthquakes in southeast Missouri predominate. Significant earthquakes also occurred in south central Illinois. Figure JA2-2 shows the location of 265 earthquakes which occurred in the first half of the twentieth century while Figure JA2-3 presents data from 164 earthquak for the third quarter of this century. A very interesting observation is the migration of activity southward from Cairo, Illinois during the twentieth century. Southeastern Illinois seems somewhat spatially stable. Finally, Figure JA2-4 shows the 1190 earthquake located by a regional microearthquake array for the six year period between July 1, 1974 and June 30, 1980. Very definite seismicity patterns are obvious near New Madrid. In addition an interesting north-south pattern west of the Missouri bootheel, a north-south pattern in southeastern Illinois and a southeast trending pattern near Cape Girardeau, Missouri are evident.

MAGNITUDE PATTERNS

One must be careful about the specification of patterns, though, because they may be due to varying magnitude detection thresholds of the seismic array. For example, Figure JA2-4 apparently indicates a very dense cluster of seismicity near New Madrid, MO and Ridgely, TN with a "thinning out" southward into Arkansas.

Figures JA2-5, -6, -7 and -8 are plots of all earthquakes located in a 6 year period with $m_b \geq 3.0$, $m_b \geq 2.5$, $m_b \geq 2.0$ and $m_b \geq 1.5$, respectively in a $4^o \times 4^o$ search area. Figures JA2-9, -10, -11 and -12 are plots of all earthquakes located in the 6 year period in a $1.5^o \times 1.5^o$ search area for $m_b \geq 3.0$, 2.5, 2.0 and 1.5, respectively. No patterns are obvious in the $m_b \geq 3.0$ plots. However, the high seismicity trend from New Madrid into Arkansas is well defined by the $m_b \geq 2.5$ data. Besides this, the pattern seems quite uniform in space. This spatial uniformity is also apparent in the $m_b \geq 2.0$ data. However, the $m_b \geq 1.5$ plots indicate considerable clustering. Because of the spatial uniformity at higher magnitude cutoffs, a magnitude dependent detection capability is indicated. This indicates that the seismic activity near New Madrid, MO and Ridgely, TN is not necessarily that much different from other areas within the zone. The north-south trend in Arkansas and southern Missouri at 91^o W. also suffers from detection capability but may be a legitimate pattern, or zone of seismicity. A north-south zone in southeastern Illinois at 88.5^o W. may also represent a definite source zone.

VERTICAL DEPTH PROFILES

Given the distinctly linear patterns of seismicity near New Madrid, a projection of the seismicity onto vertical plane could serve to define the fault plane orientation. As a first attempt, the six year micro-earthquake data base was searched for all free depth hypocenter solutions between January 1, 1976 through December 31, 1979. The epicenters are plotted in Figure JA2-13 as well as a rectangular search area for a study of the 100 km long seismicity trend in northeastern Arkansas. The orientations of two planes of projection, WX and YZ, are indicated. Figure JA2-14 shows the vertical projections. The majority of well located solutions occur at depths between 5 and 15 km. Profile YZ indicates that the seismicity pattern is very narrow and extends down to at least 15 km and that the fault zone is almost vertical.

Two other zones of interest are examined in Figures JA2-15 and JA2-16. The Ridgely, TN search area and the corresponding projections, OP and OR, indicate a northwest striking seismicity zone, which is not that evident from the epicenter plots. The New Madrid, MO cluster does not show much other than the fact that the seismicity has an east-west trend.

The previous plots were contaminated somewhat by the fact that the earthquake data was extracted from the data base without qualifications. In an attempt to refine the depth profiles, a search was made of all earthquakes which occurred between April 1, 1977 and June 30, 1979 which were located by 4 or more stations and which had data in a distance range adequate to constrain focal depth. This selected data set was then relocated using joint hypocenter techniques. Amazingly, there was little difference in the hypocenter locations before or after the JHD relocation (Figures JA2-17 and JA2-18).

Figure JA2-19 shows the relocated epicenters as well as the search areas near New Madrid, MO and Ridgely, TN. Profile OP now shows a very narrow pattern for the Ridgely trend, and indicates a steeply dipping pattern of seismicity to the southwest. It also shows that many of the earthquakes used really were not well constrained in depth as evidenced by the migration of focal depths to the minimum depth of 1 km permitted in the inversion. With respect to the vertical profiles near New Madrid, a very tight pattern was obtained by allowing the plane of projection to strike N. 20^{o} E. Thus a southerly dipping fault plane striking N. 110^{o} E. is inferred (Figure JA2-20).

REVIEW OF FOCAL MECHANISMS

Canas and Herrmann (1978) presented focal mechanisms for earthquakes in the Central Mississippi Valley obtained by composite focal mechanism techniques as well as surface wave studies of larger earthquakes. Unambiguous composite focal mechanisms were obtainable for only a few of the linear patterns of seismicity evident in Figure JA2-12. Along the Arkansas trend, Figure JA2-17, the P-wave first motion data could be fit by focal mechanisms with significant components of right lateral strike-slip motion with a strike in the direction of the seismicity trend. The Ridgely, TN area, Figure JA2-19, indicated a northwest striking reverse fault with one nodal plane dipping steeply to the northeast and the other dipping at an angle of about 30° to the southwest.

Surface wave solutions were available for three points along the Arkansas trend, indicating significant components of right lateral strike slip motion along a northeast trending nodal plane, and in two of the solutions, reverse faulting with the nodal plane dipping about 60° to the northwest. Two surface wave focal mechanisms near the New Madrid trend of Figure JA2-19 indicated predominantly left lateral strike-slip motion on an east-west trending nodal plane.

There is some discrepancy between the focal mechanism inferred fault plane orientation and the fault plane geometry inferred from the hypocenter distribution. In particular, the Arkansas trend indicates a very steeply dipping plane to the southeast while the surface wave data infers a fault plane dipping about 60° to the northwest. This is also a problem on the Ridgely trend. The focal mechanism and hypocenter dips along the New Madrid trend are in agreement, but the inferred strikes differ by 30°.

DISCUSSION

We know much more today about central Mississippi Valley earthquakes than we knew 6 years ago. Major questions remain to be answered. As before, we are hampered in seismological studies by relatively low occurrence rates as well as high levels of cultural noise, especially in the active agricultural areas of southern Illinois and the Mississippi Embayment. The major problems that require more data are:

a) What are the northern and southern extents of a possible 1811-1812 earthquake sequence?

b) What are the strong ground motions that can be generated by such earthquakes?

c) How can we be specific about the northern and southern extent of possible major earthquakes if we do not know why the earthquakes are occurring at all? The central Mississippi Valley may be a reactivated ancient zone of weakness, but what are the precise characteristics of this zone. These are difficult questions to be answered, but the data base is slowly being improved upon which judgment can be based.

Some research areas and tasks are suggested, though.

a) Continue monitoring of microearthquake activity with an enhanced seismic network. The new seismicity patterns in Arkansas and southeastern Missouri require monitoring.

b) Carefully reanalyze the existing 6 year data base using joint hypocenter relocation techniques to pin down the geometrical patterns of the seismicity. Given this, reconstruct composite focal mechanisms.

c) Obtain detailed Q, P and S velocity models for the central Mississippi Valley. The installation of a dense accelerography network in the area by the USGS will yield important strong motion data, but an accurate earth model is required for interpretation of that data base.

The earthquakes in the central Mississippi Valley are contributing a great deal of new data which must continue to be analyzed with the view of applying these results to the broader problem of earthquake hazard in eastern North America.

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PUBLICATIONS

During this period, the following publications were prepared:

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Herrmann, R.B., J.W. Dewey and S.K. Park (1980). The Dulce, New Mexico Earthquake of January 23, 1966, Bull. Seism. Soc. Am. (in press).

Stauder, W., R. Herrmann, C. Nicholson, S. Singh, M. Woods, C. Kim, R. Perry, S. Morrissey and E. Haug (1980). Central Mississippi Valley Earthquakes - 1978, Earthquake Notes 51, 22-24.

Stauder, W., R. Herrmann, S. Singh, C. Nicholson, D. Reidy, R. Perry, S. Morrissey and E. Haug (1981). Central Mississippi Valley Earthquakes - 1979, Earthquake Notes (in press).

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Central Mississippi Valley Earthquake Bulletin, Quaterly Report No. 23, First Quarter 1980, 1 January - 21 March 1980.

Central Mississippi Valley Earthquake Bulletin, Quarterly Report No. 24, Second Quarter 1980, 1 April - 30 June 1980.

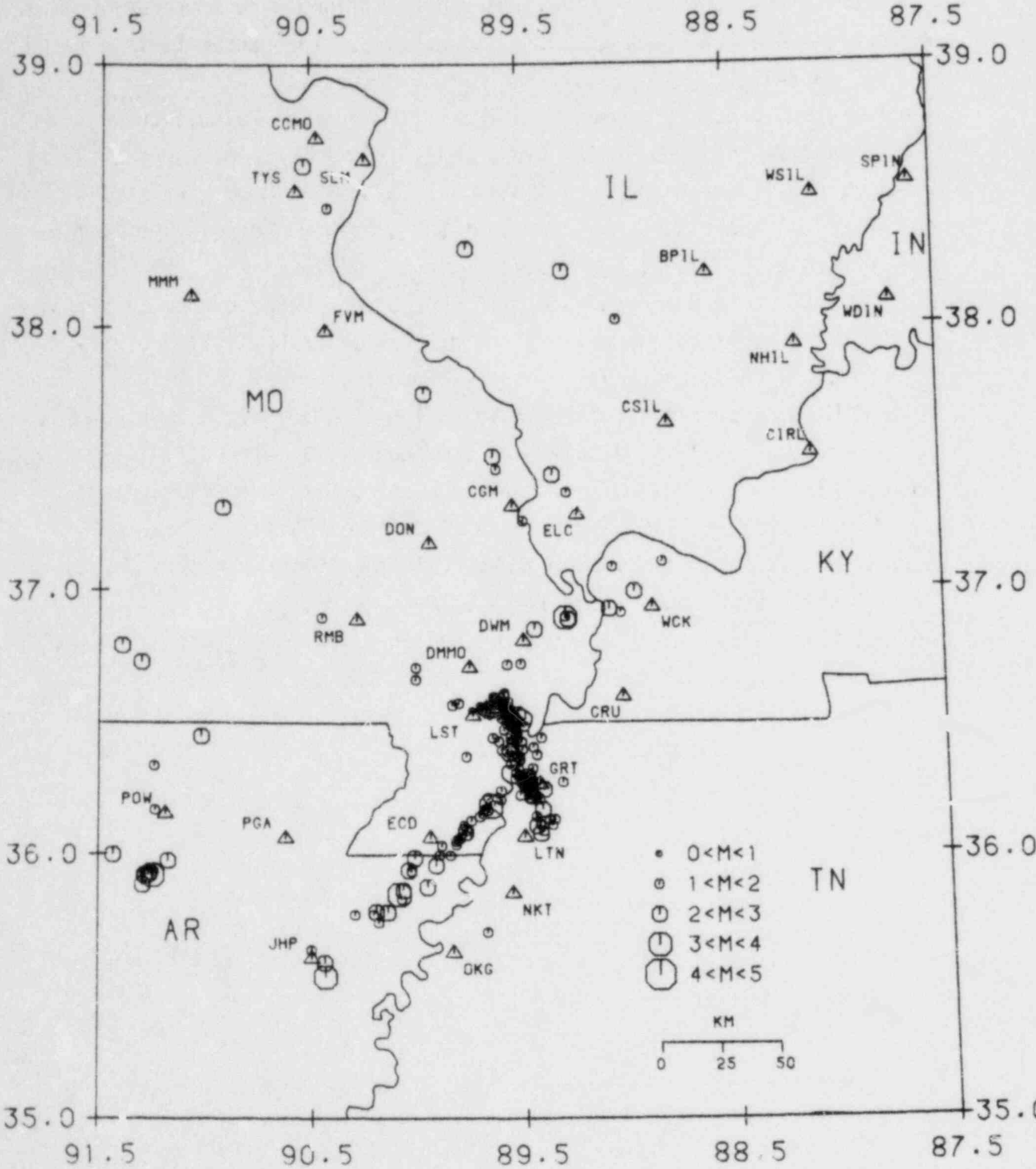


FIGURE JA1-1

CUMULATIVE EVENTS 01 JAN 1979 TO 31 DEC 1979
LEGEND . △ STATION ⊙ EPICENTER

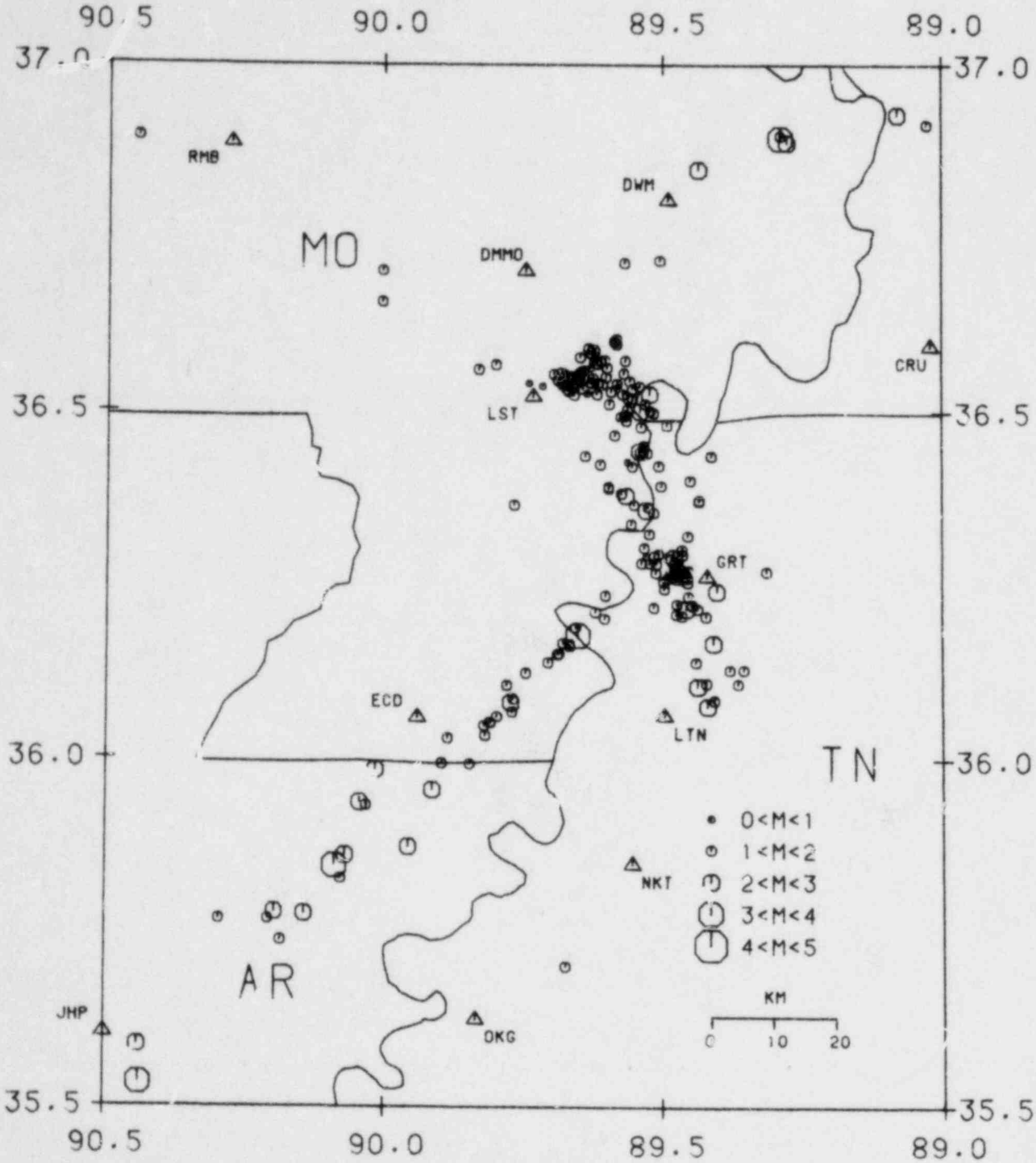


FIGURE JA1-2

CUMULATIVE EVENTS 01 JAN 1979 TO 30 DEC 1979
LEGEND . ▲ STATION ⊙ EPICENTER

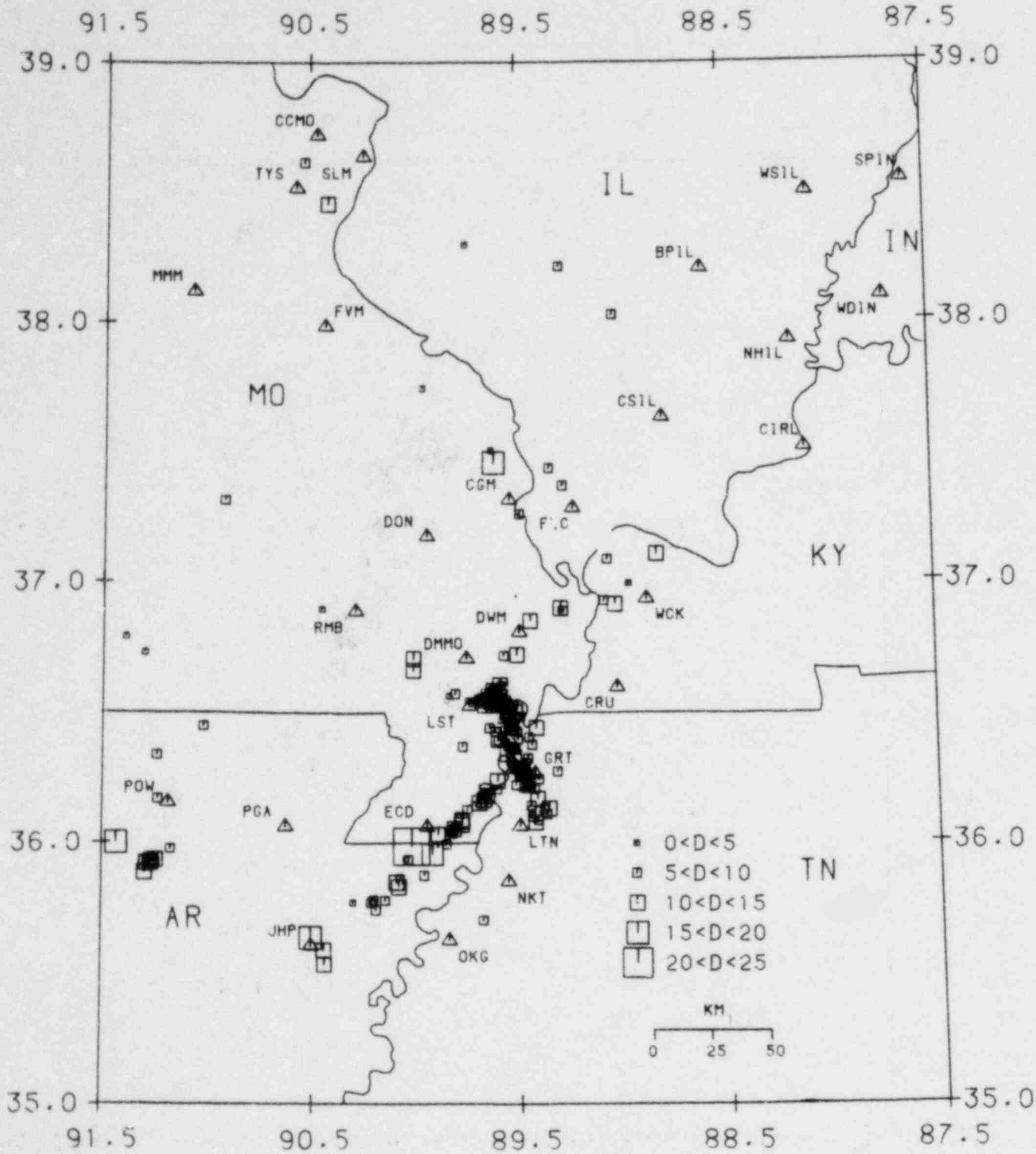


FIGURE JA1-3

CUMULATIVE EVENTS 01 JAN 1979 TO 31 DEC 1979
LEGEND . △ STATION ⊡ EPICENTER

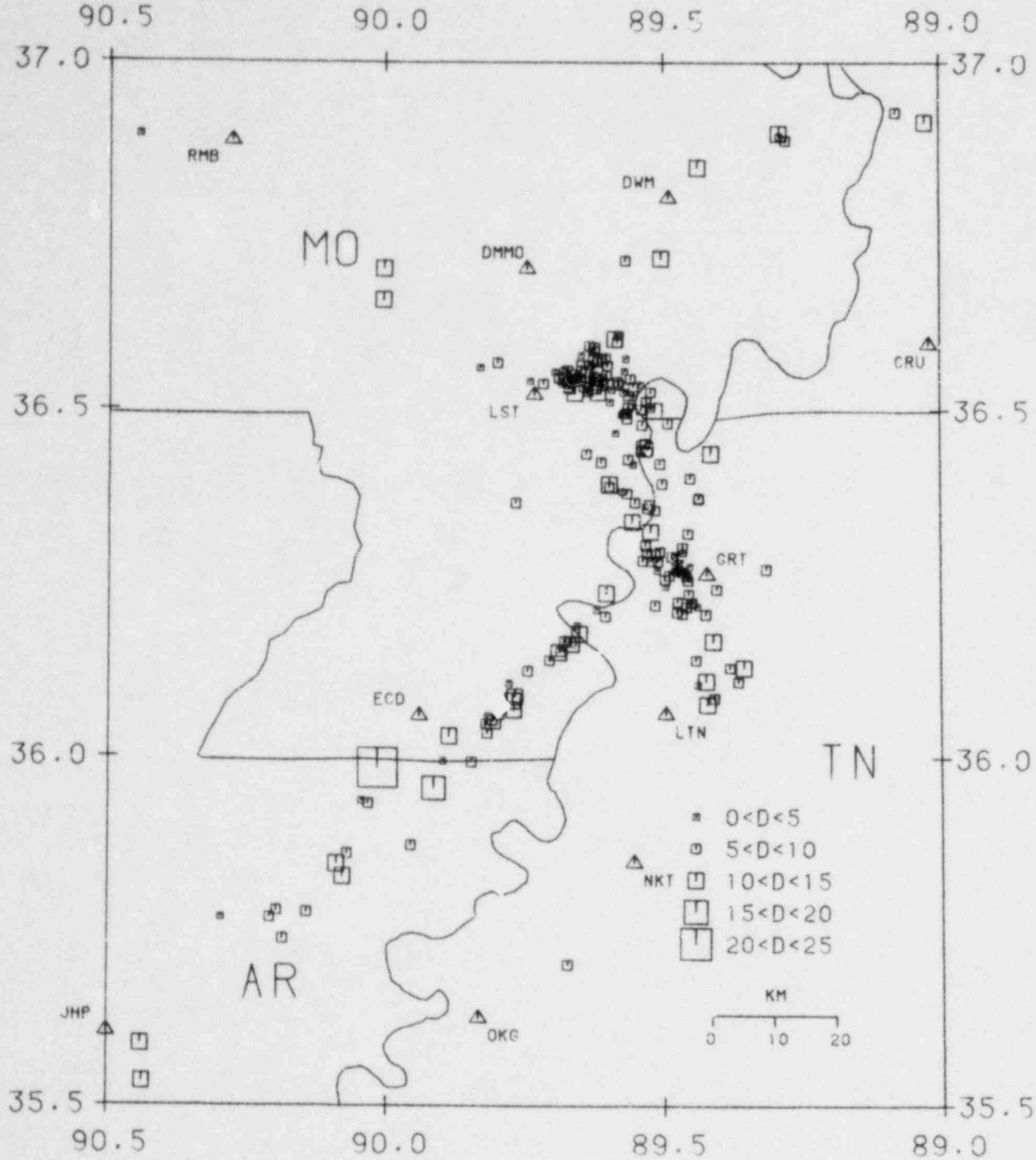


FIGURE JA1-4

CUMULATIVE EVENTS 01 JAN 1979 TO 30 DEC 1979
LEGEND . △ STATION ▫ EPICENTER

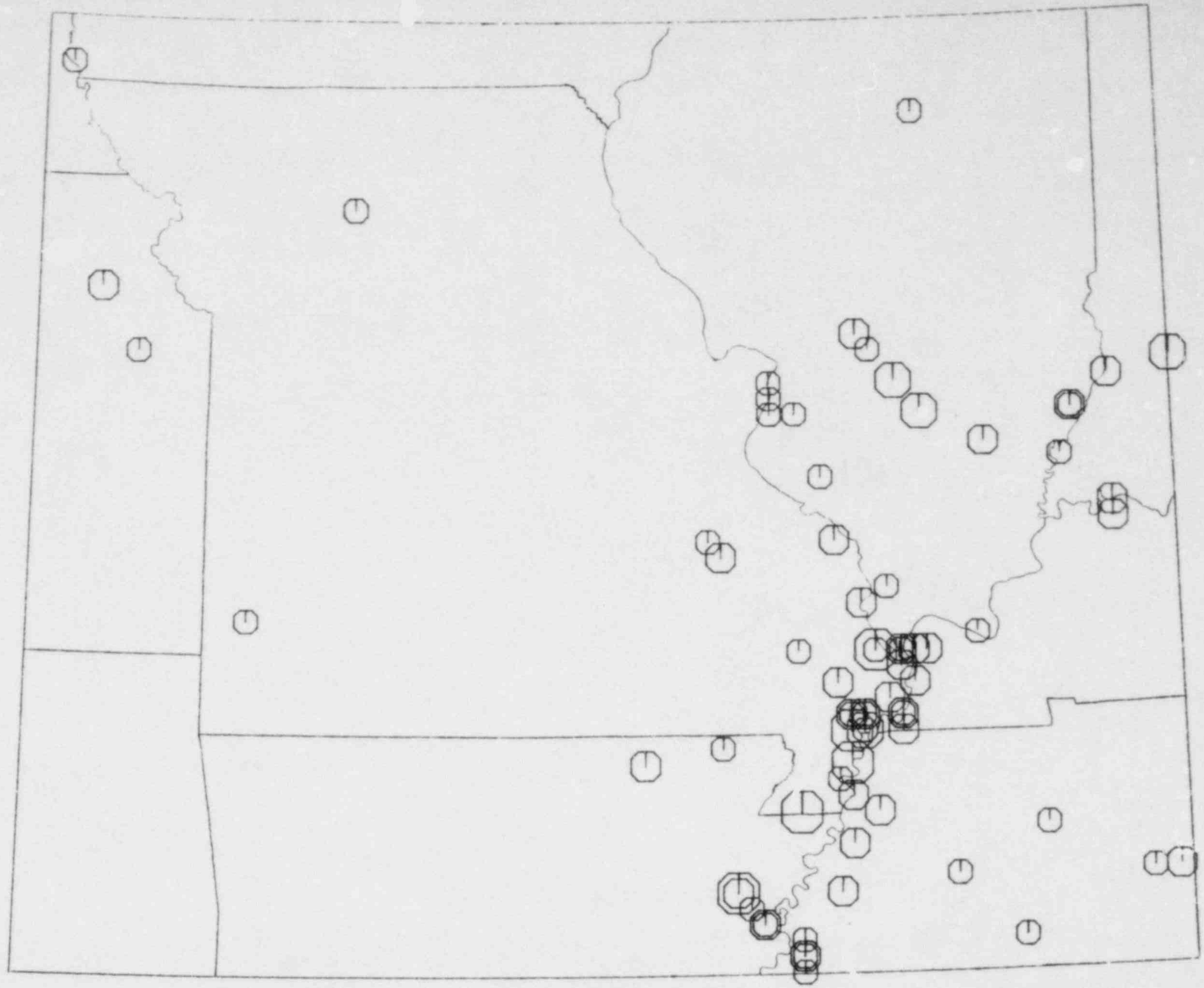


Figure JA2-1. Epicenters from the Nuttli (1979) earthquake catalog for the years 1800-1899. Symbol size is proportional to magnitude.

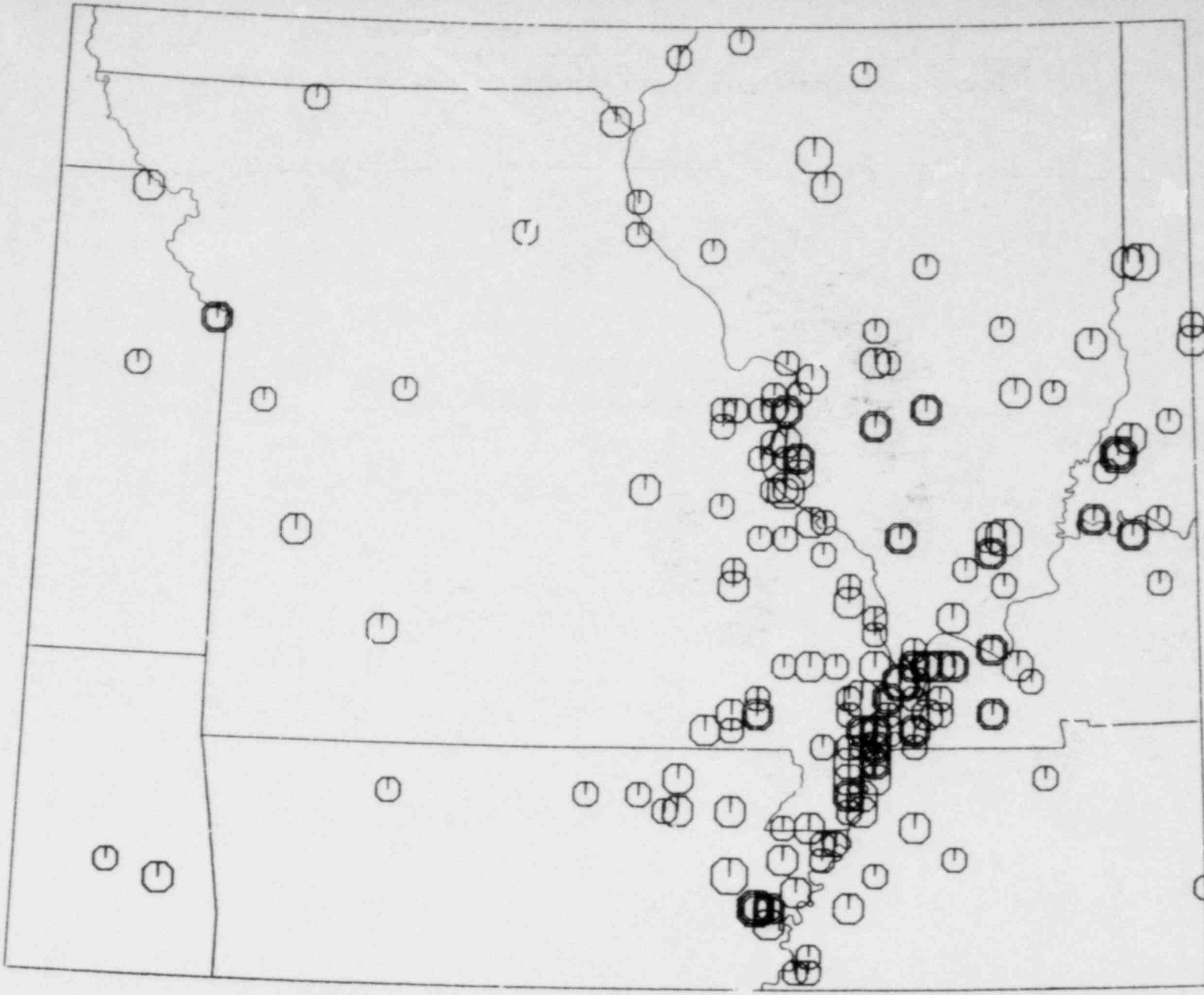


Figure JA2-2. Epicenters from the Nuttli (1979) earthquake catalog for the years 1900-1949. Symbol size is proportional to magnitude.

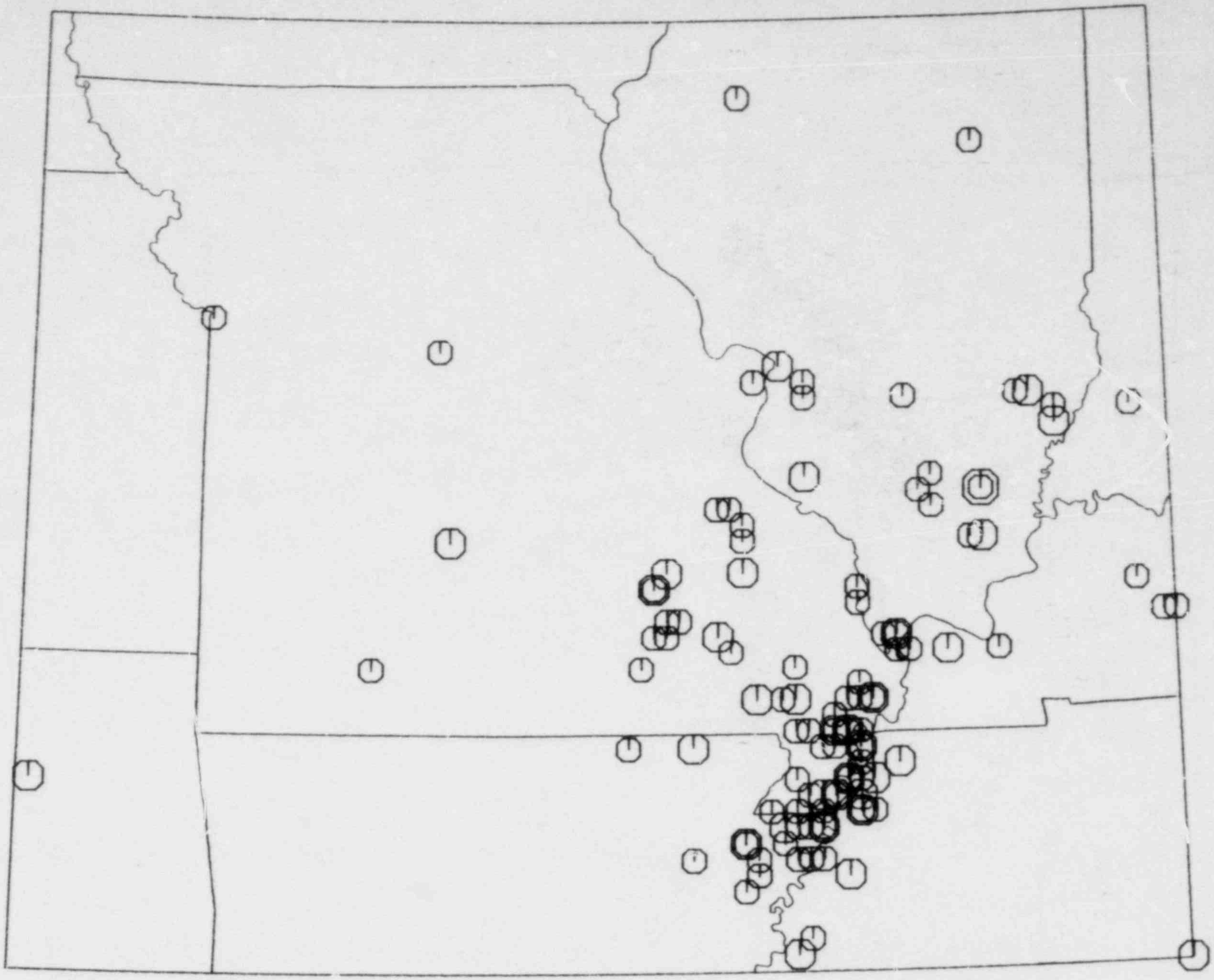


Figure JA2-3. Epicenters from the Nuttli (1979) earthquake catalog for the years 1950-1974. Symbol size is proportional to magnitude.

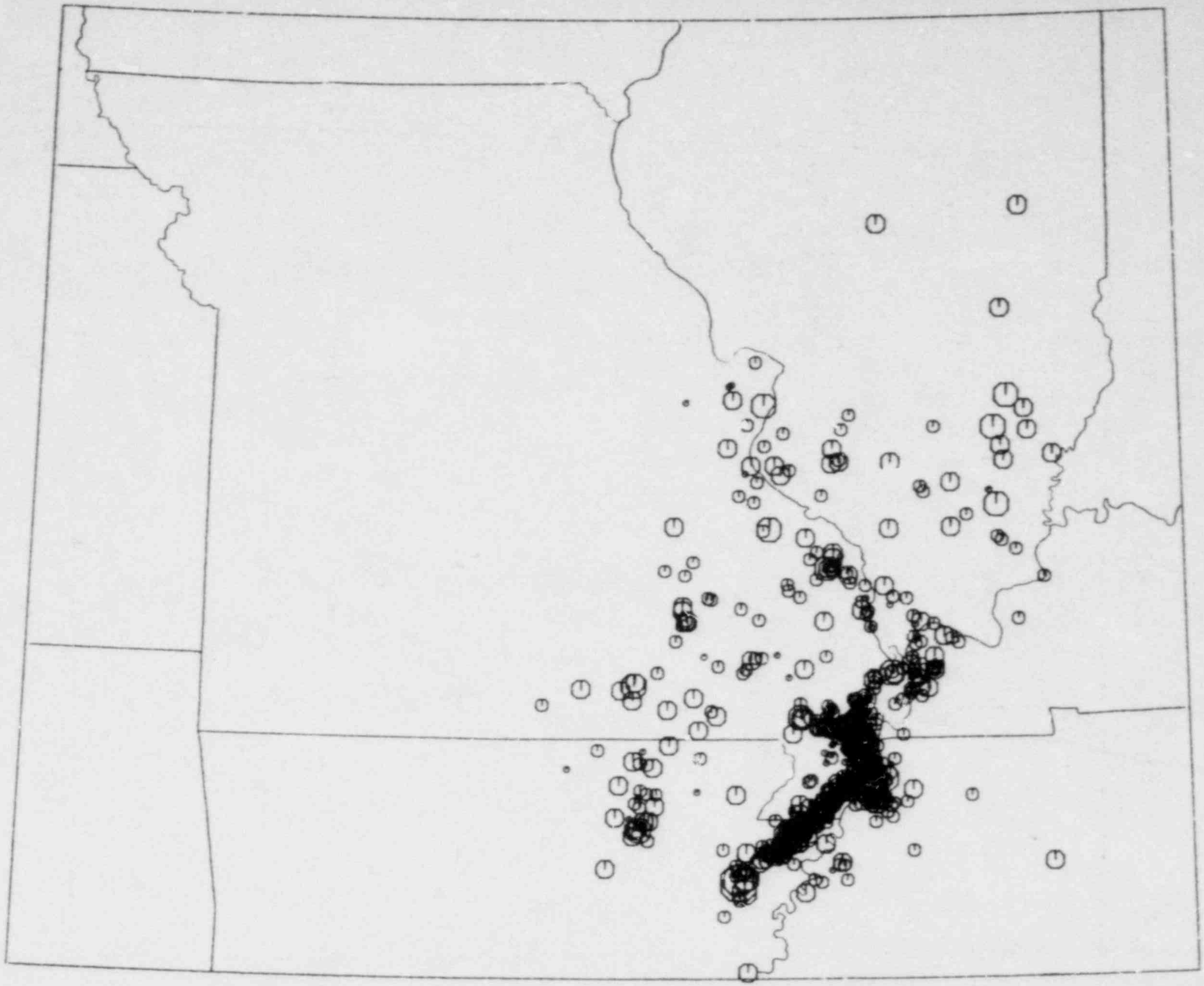
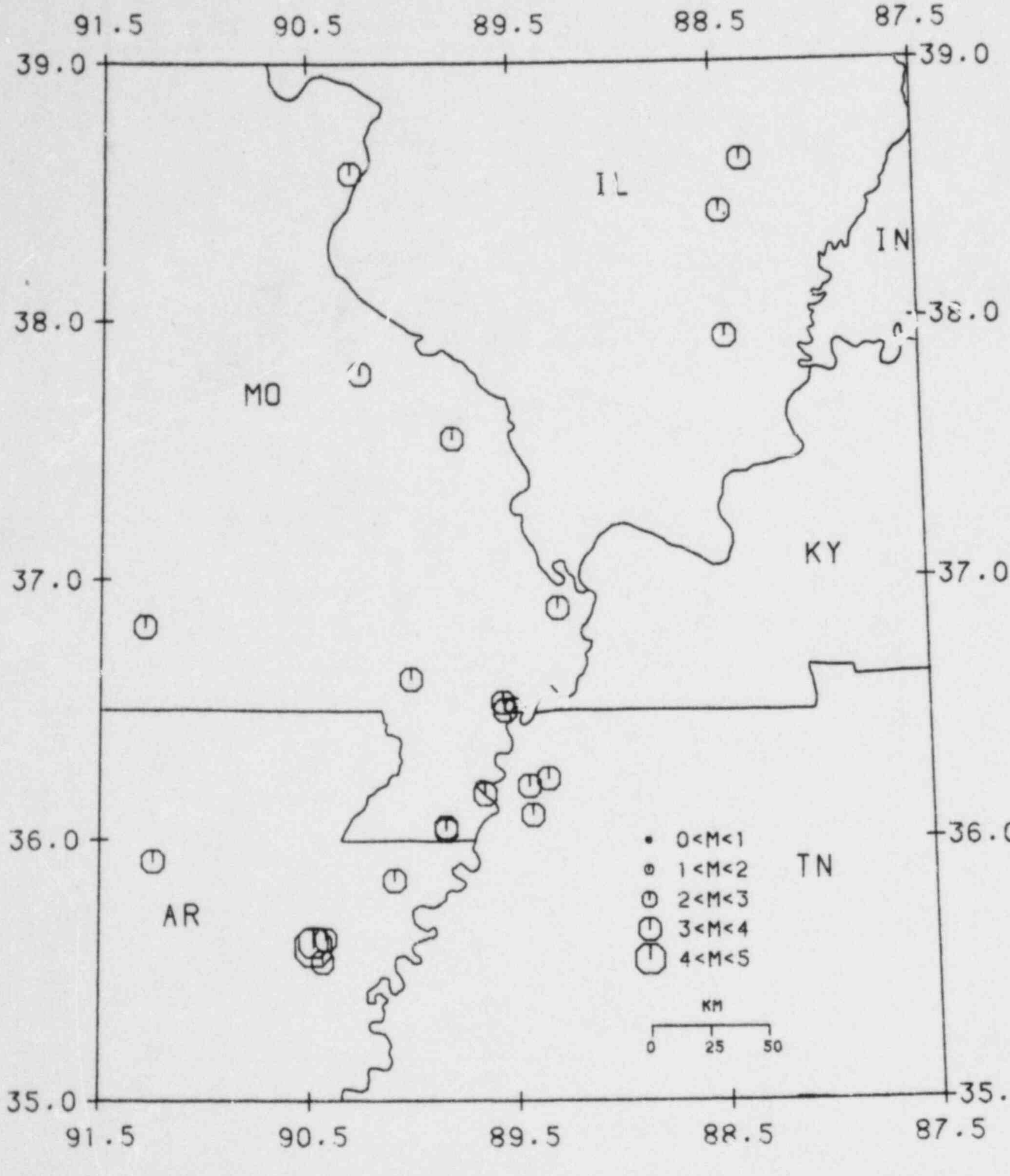


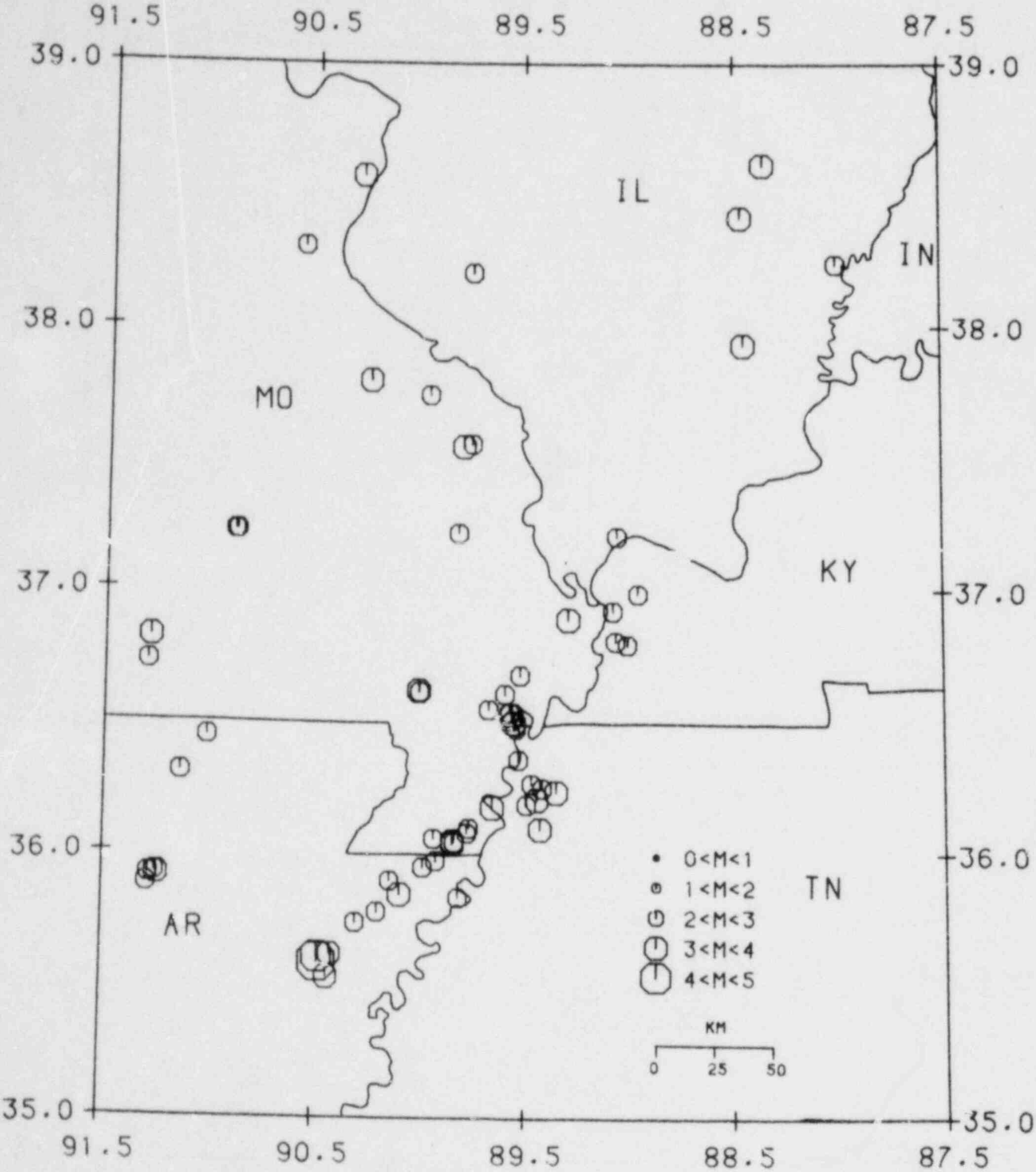
Figure JA2-4. Epicenters located between July 1, 1974 - June 30, 1980 by the Saint Louis University regional seismic array. Symbol size is proportional to magnitude.

Figure JA2-5. Plot of all earthquakes located in 6 years with $m_b \geq 3.0$.



REPORTING PERIOD 01 JUL 1974 TO 30 JUN 1980
LEGEND . ▲ STATION ⊕ EPICENTER

Figure JA2-6. Plot of all earthquakes located in 6 years with $m_b \geq 2.5$.



REPORTING PERIOD 01 JUL 1974 TO 30 JUN 1980
LEGEND .' ▲ STATION ⊙ EPICENTER

Figure JA2-7. Plot of all earthquakes located in 6 years with $m_b \geq 2.0$.

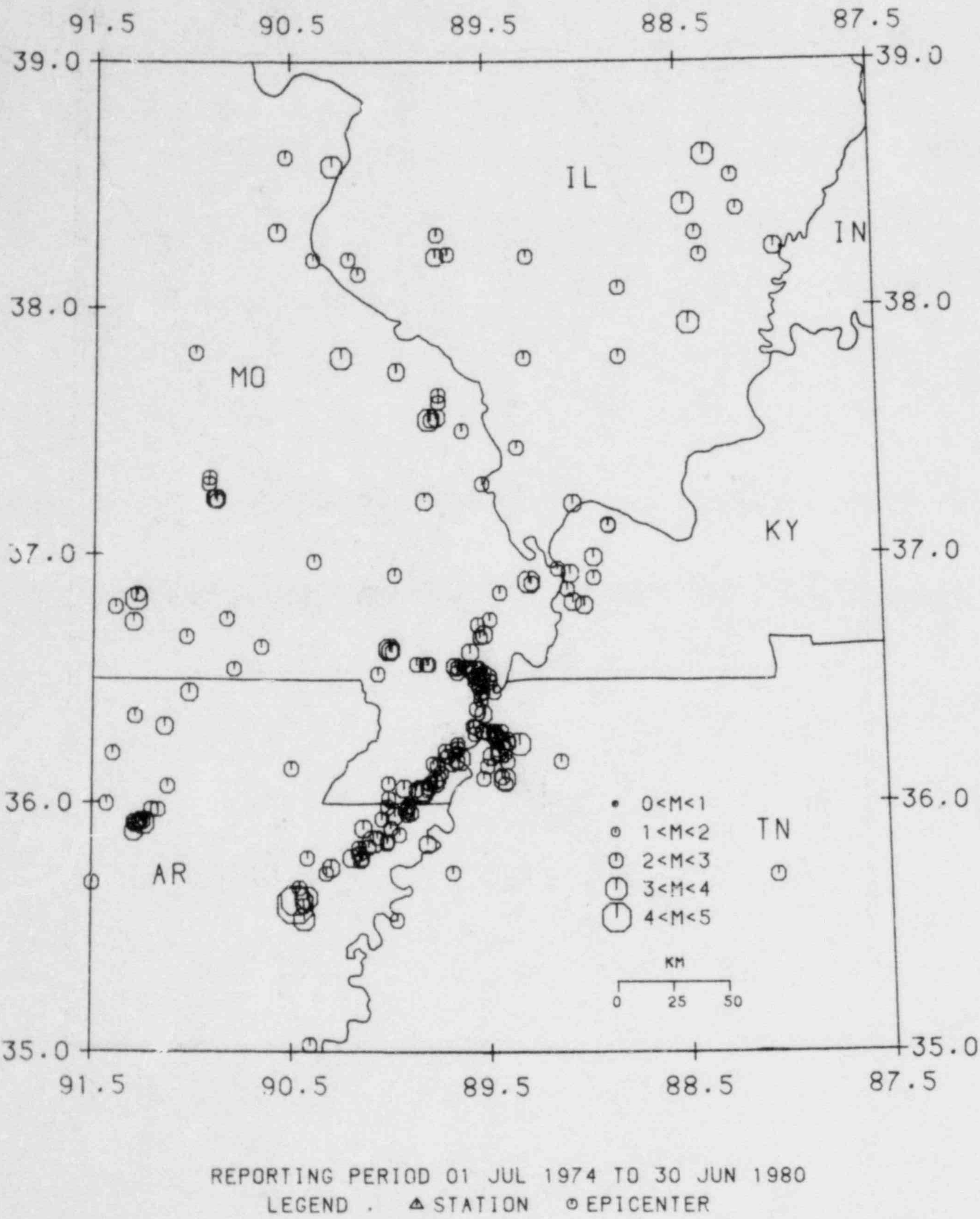
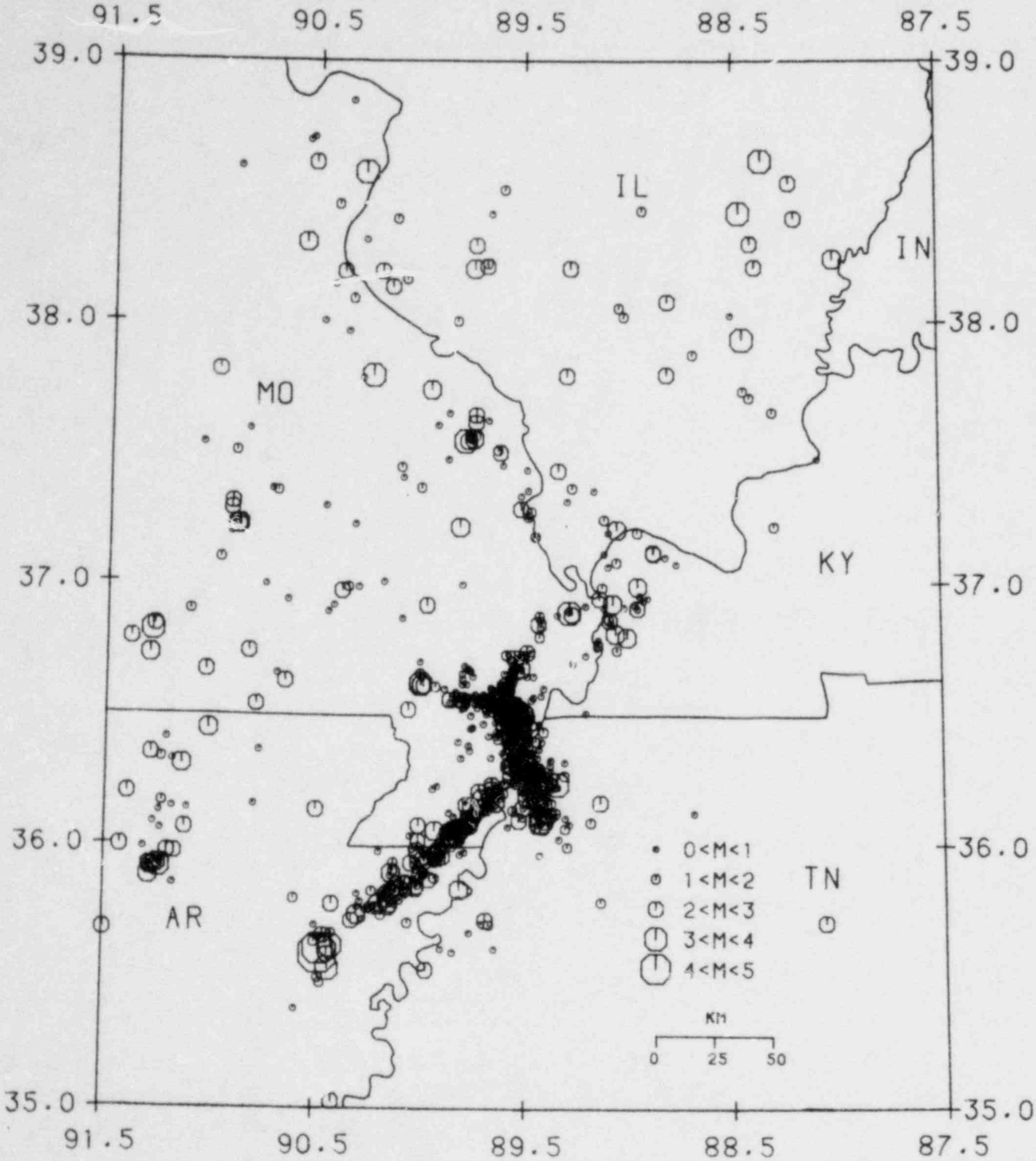


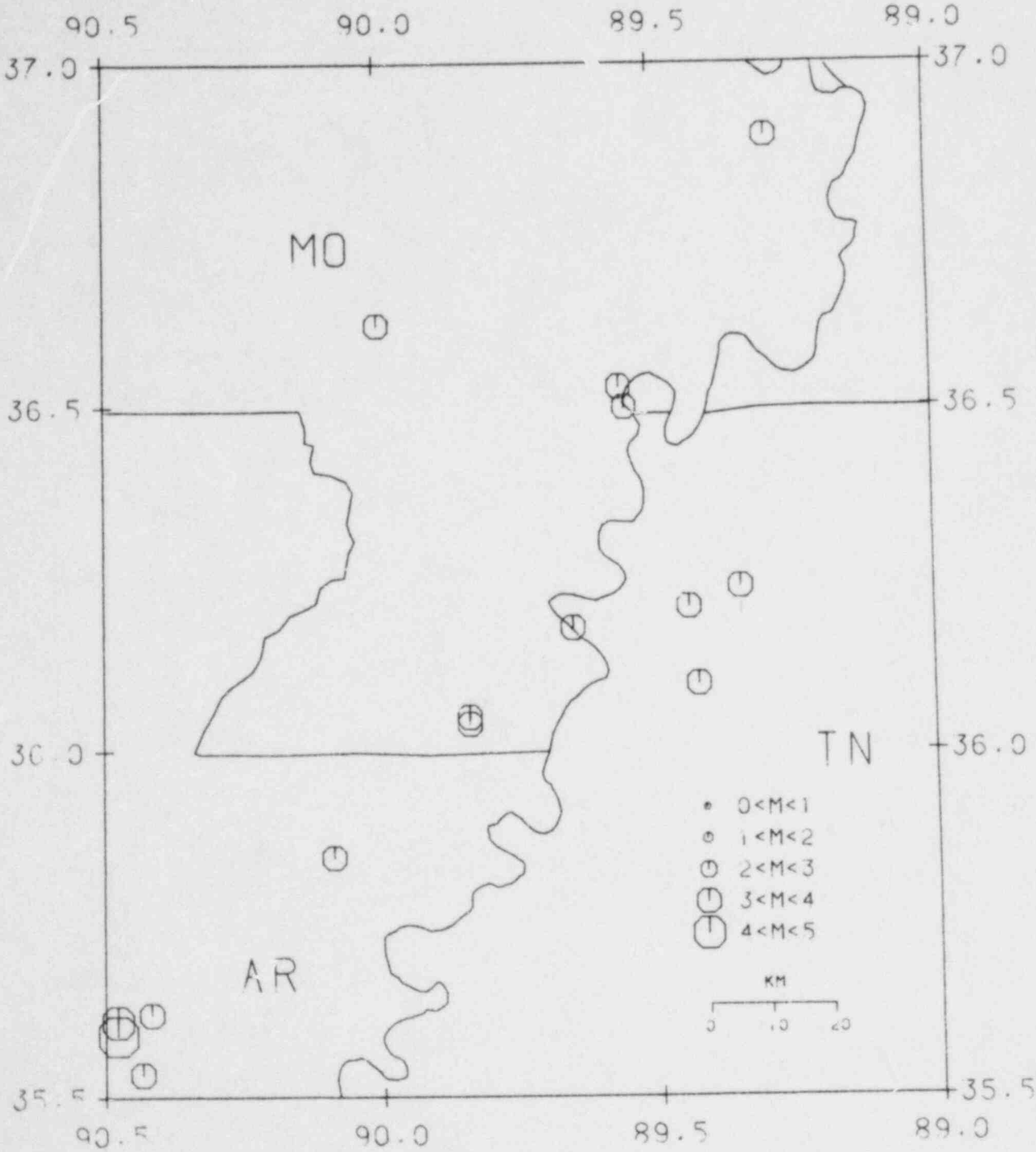
Figure JA2-8. Plot of all earthquakes located in 6 years with $m_b \geq 1.5$.



REPORTING PERIOD 01 JUL 1974 TO 30 JUN 1980

LEGEND . ▲ STATION ⊙ EPICENTER

Figure JA2-9. Plot of all earthquakes located in 6 years with $m_b \geq$ 3.0.



REPORTING PERIOD 01 JUL 1974 TO 30 JUN 1980
LEGEND . △ STATION ⊙ EPICENTER

Figure JA2-10. Plot of all earthquakes located in 6 years with $m_b \geq 2.5$.

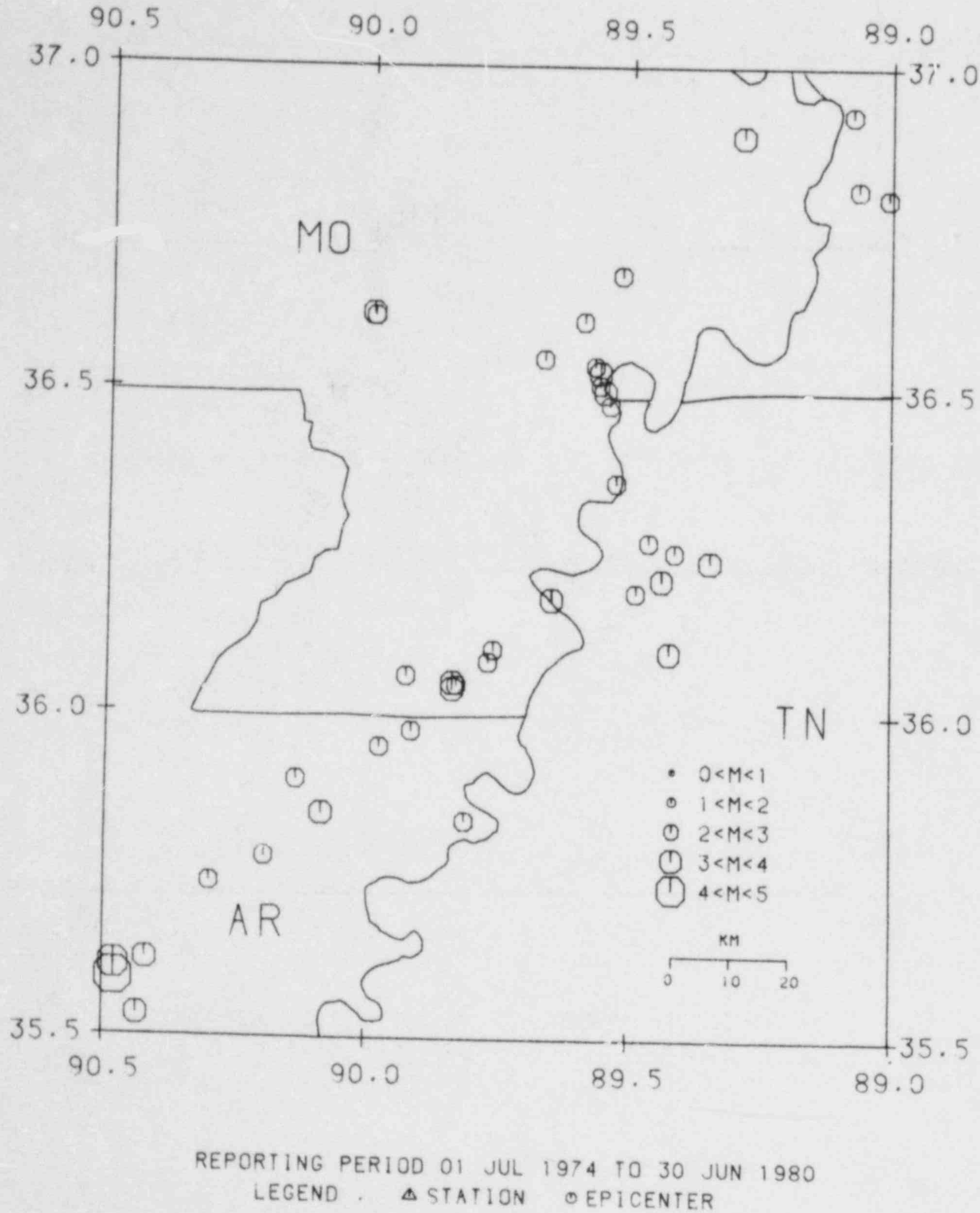
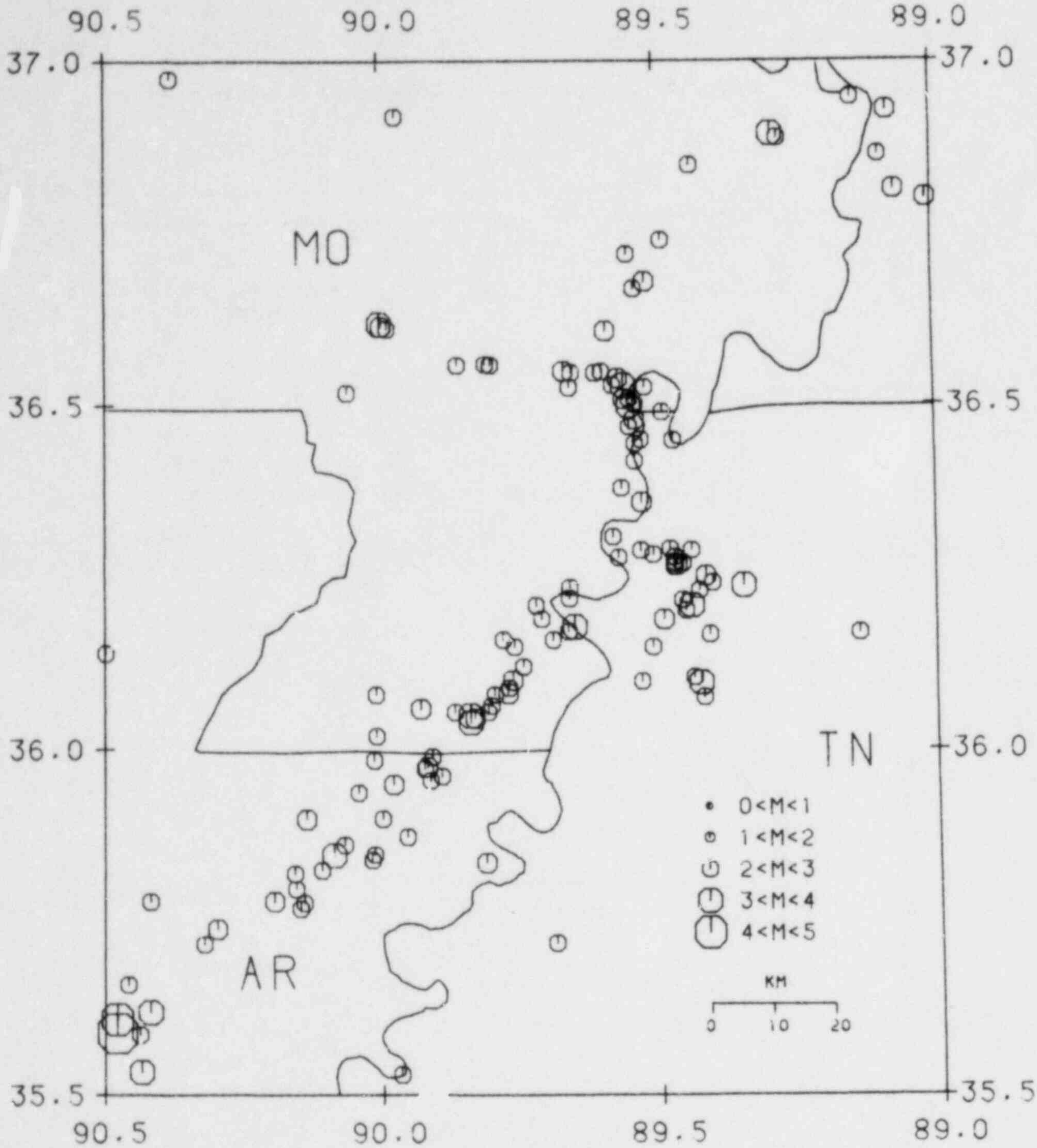


Figure JA2-11. Plot of all earthquakes located in 6 years with $m_b \geq 2.0$.



REPORTING PERIOD 01 JUL 1974 TO 30 JUN 1980
LEGEND . ▲ STATION ⊙ EPICENTER

Figure JA2-12. Plot of all earthquakes located in 6 years with $m_b \geq 1.5$.

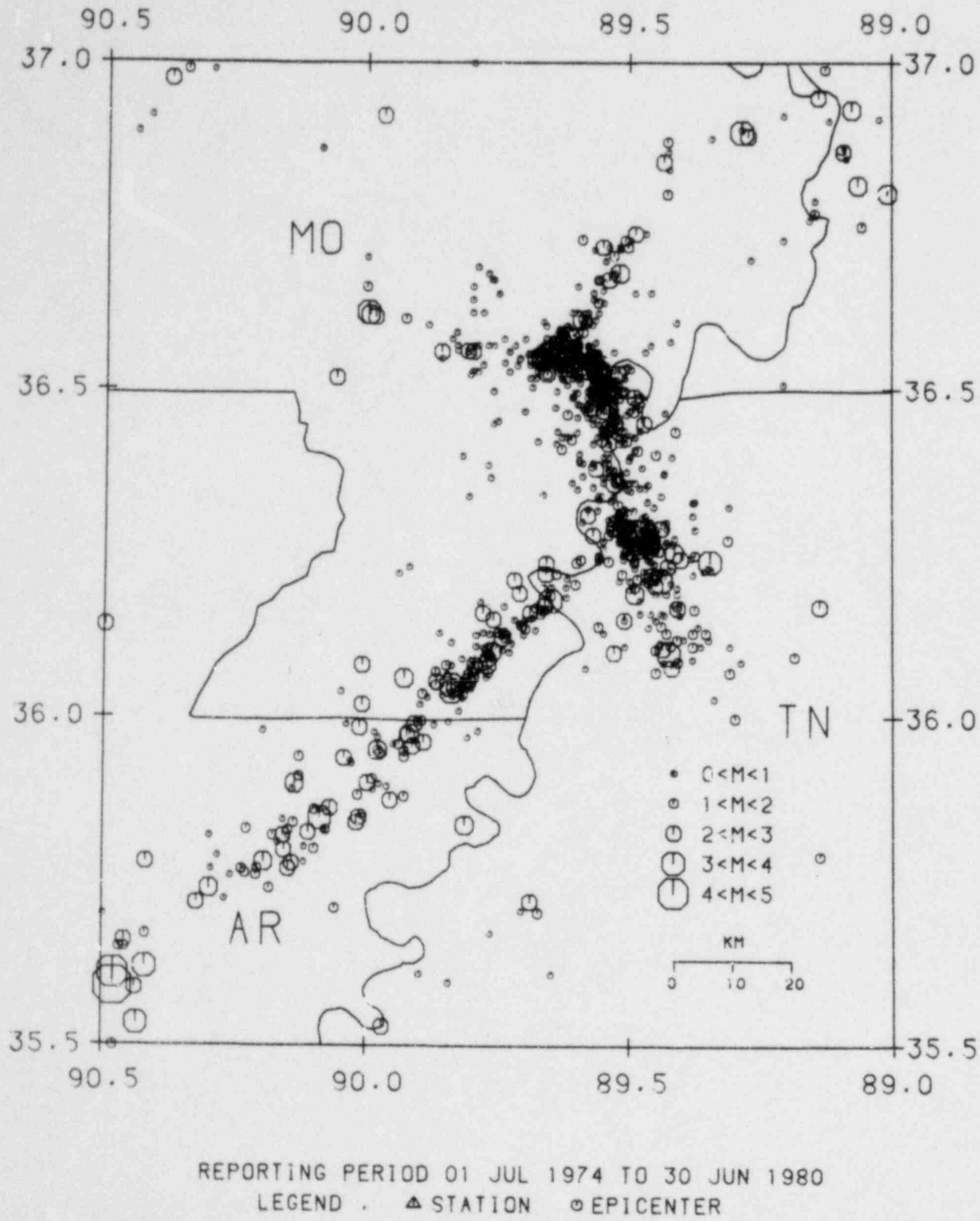


Figure JA2-13. Epicenters located between January 1, 1976 through December 31, 1979. The search area for a study of the Arkansas trend is indicated as well as the orientation of planes of projection.

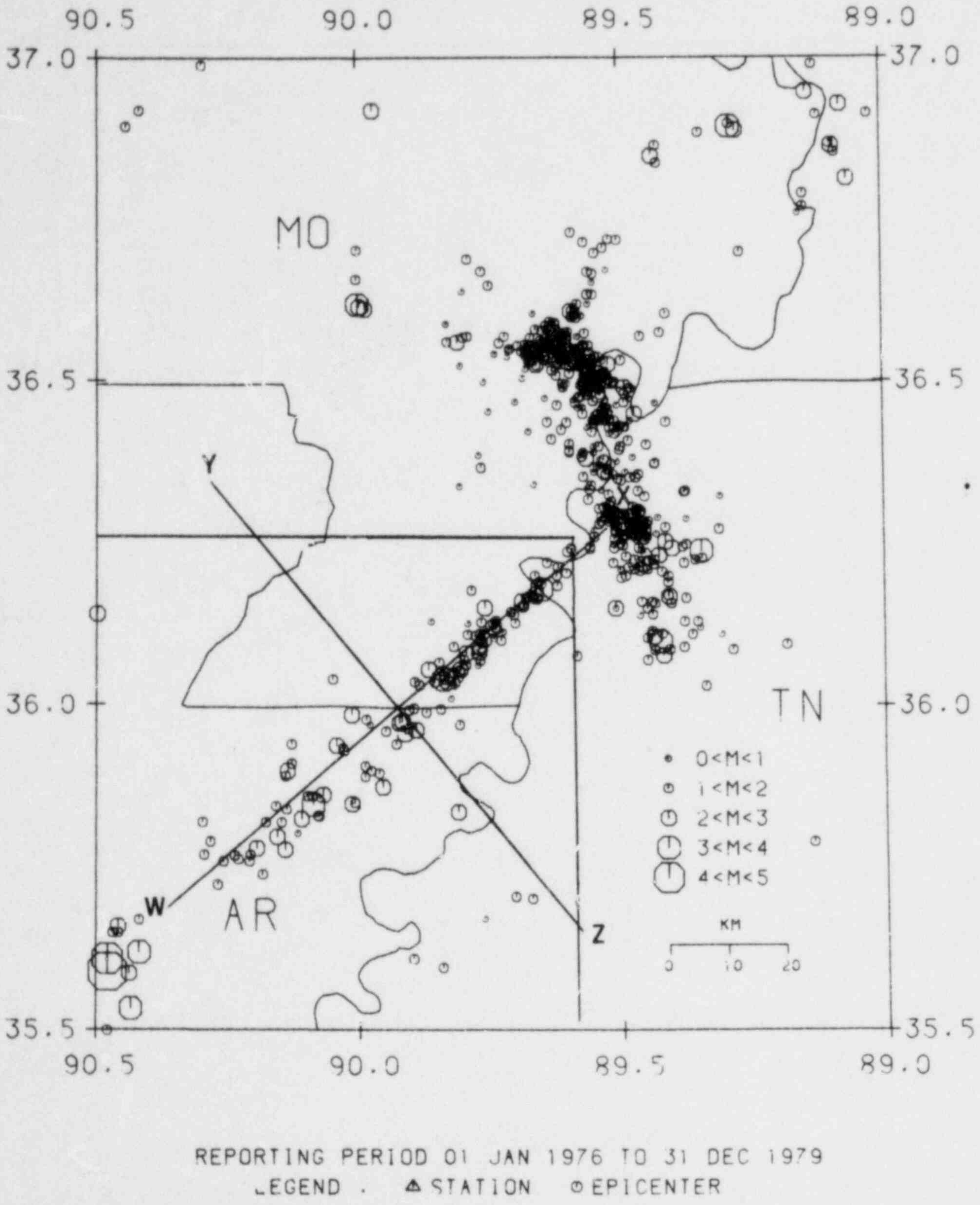
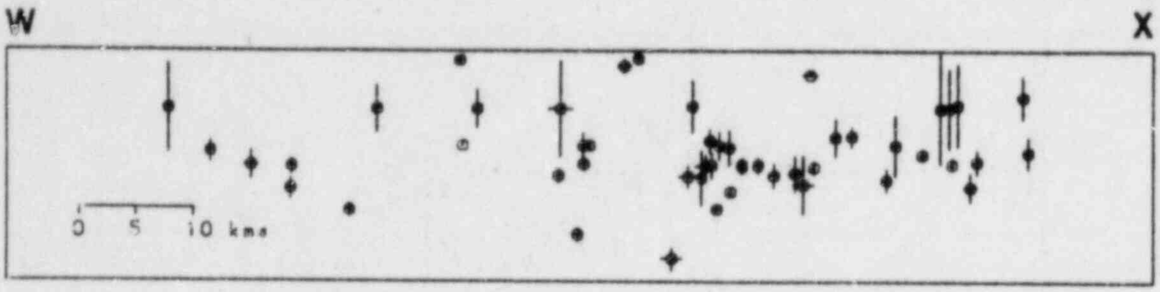
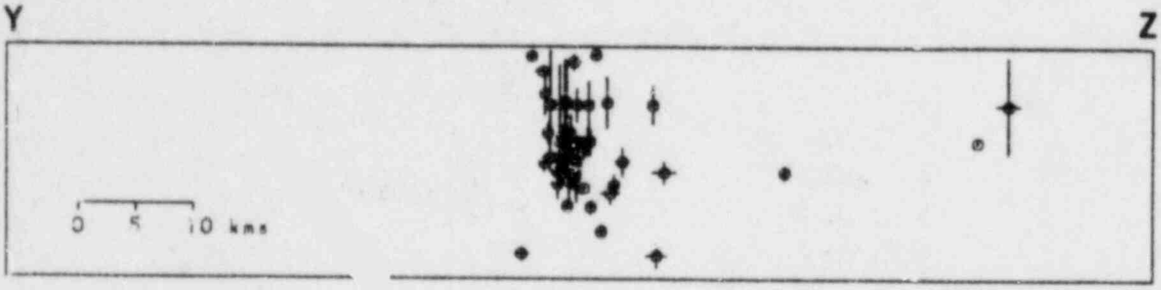


Figure JA2-14. Vertical projections of hypocenters for the Arkansas trend. Error bars are the 95% confidence limits of the HYPO71 solutions. There is no vertical exaggeration in the plots.



vertical profile centered at 35.970° n, 89.929° w
with strike 50°



vertical profile ntered at 35.970° n, 89.929° w
with strike 140°

Figure JA2-15. Epicenters located between January 1, 1976 and December 31, 1979. Search areas and profiles are indicated near New Madrid, MO, EF and GH, and Ridgely, TN, OP and QR.

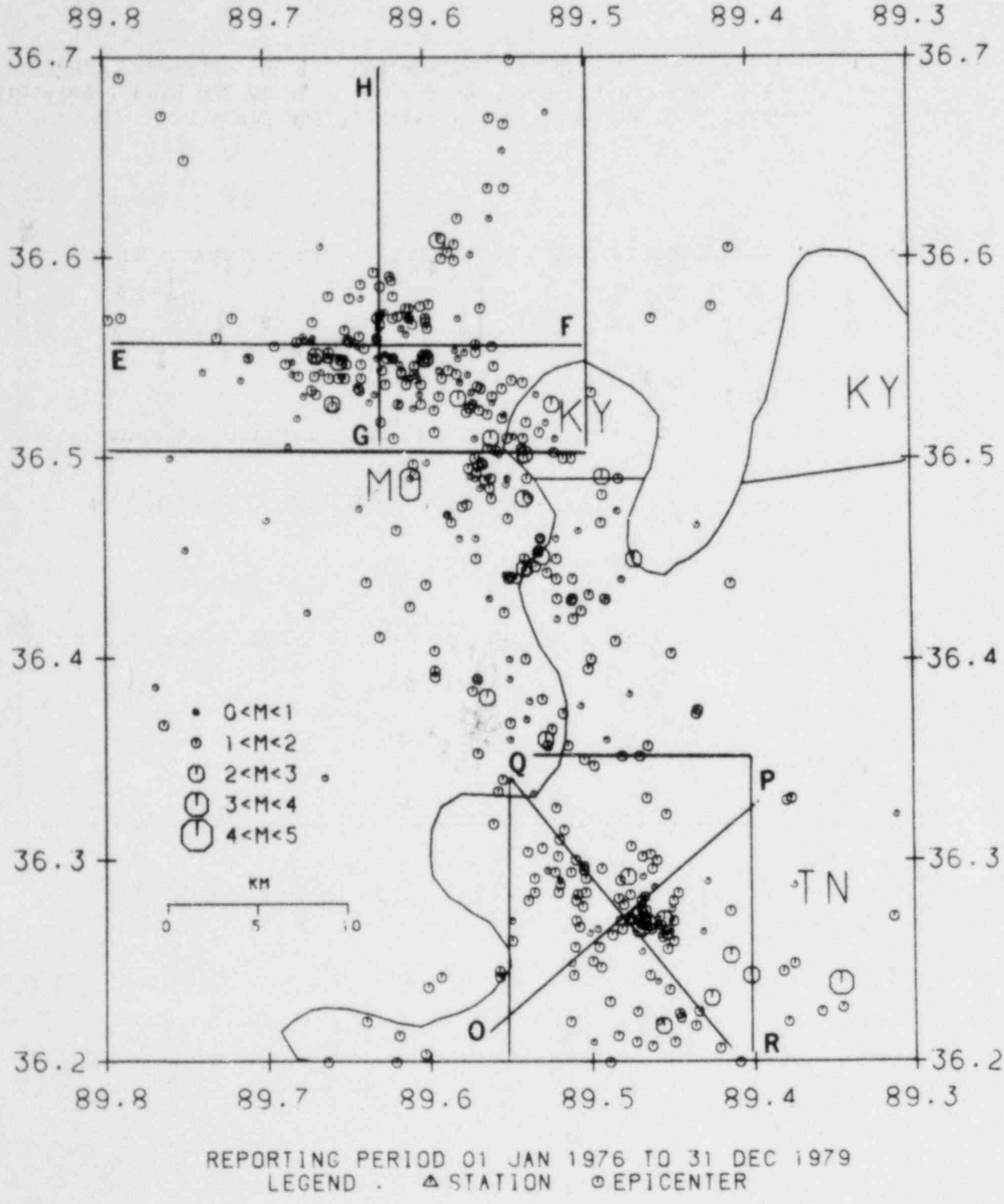
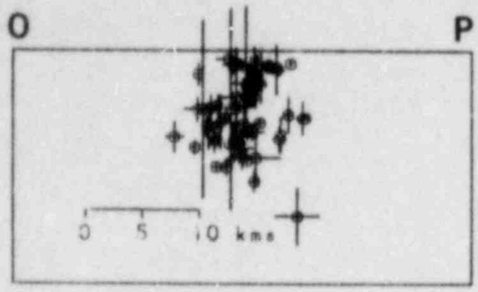
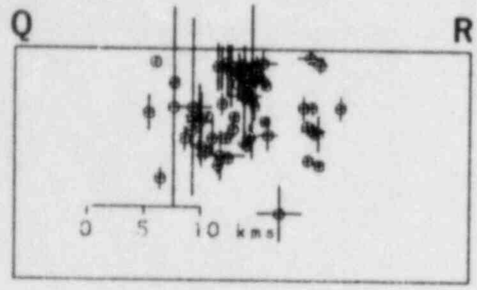


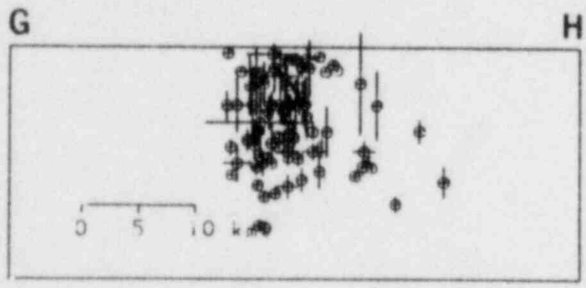
Figure JA2-16. Vertical hypocenter profiles corresponding to the profiles indicated in Figure JA2-15.



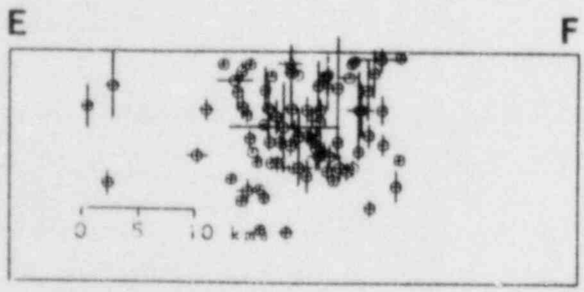
vertical profile centered at 36.270° n, 89.480° w
with strike 50°



vertical profile centered at 36.270° n, 89.480° w
with strike 140°



vertical profile centered at 36.555° n, 89.626° w
with strike 0°



vertical profile centered at 36.555° n, 89.626° w
with strike 90°

Figure JA2-17. Plot of 177 relocated earthquakes for the time period April 1, 1977 through June 30, 1979. The search zone for the Arkansas trend is indicated.

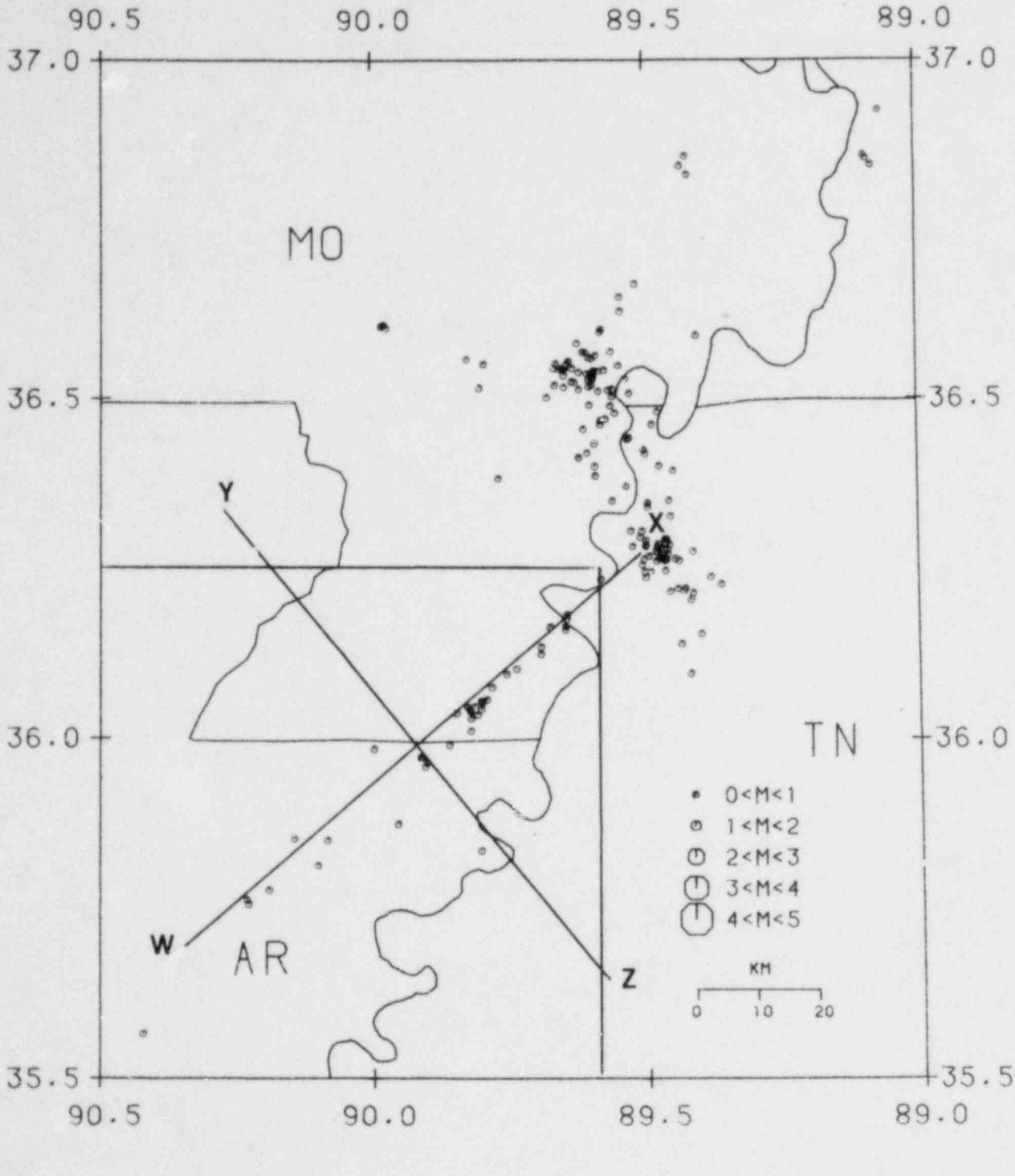
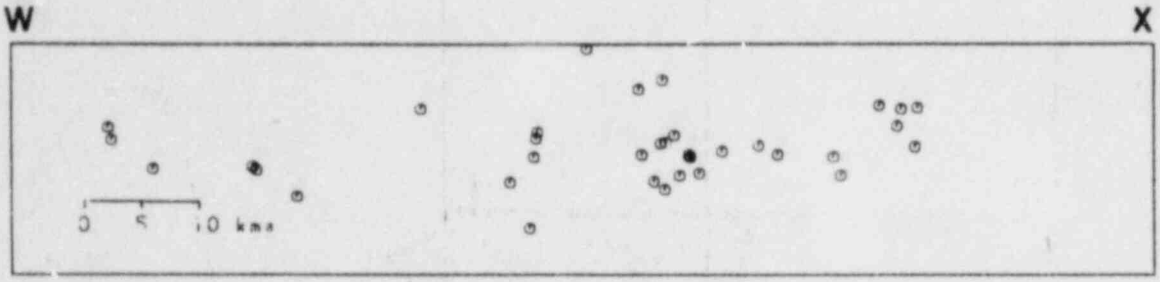
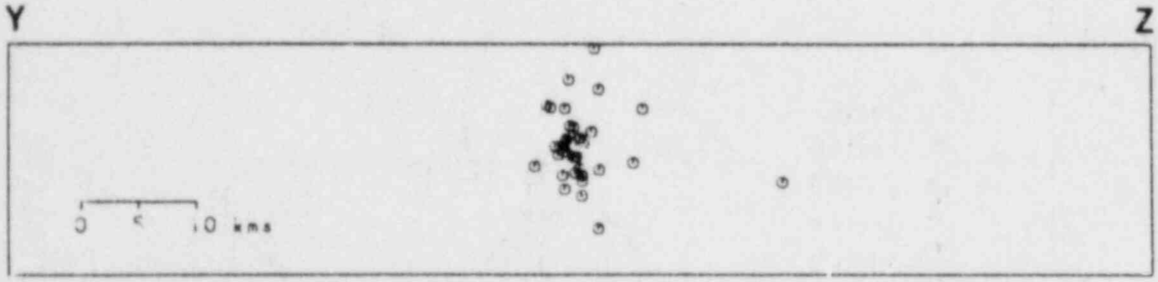


Figure JA2-18. Vertical depth profiles of relocated hypocenters.



vertical profile centered at 35.996° n, 89.877° w
with strike 50°



vertical profile centered at 35.996° n, 89.877° w
with strike 140°

Figure JA2-19. Relocated epicenters and search areas near New Madrid, MO and Ridgely, TN.

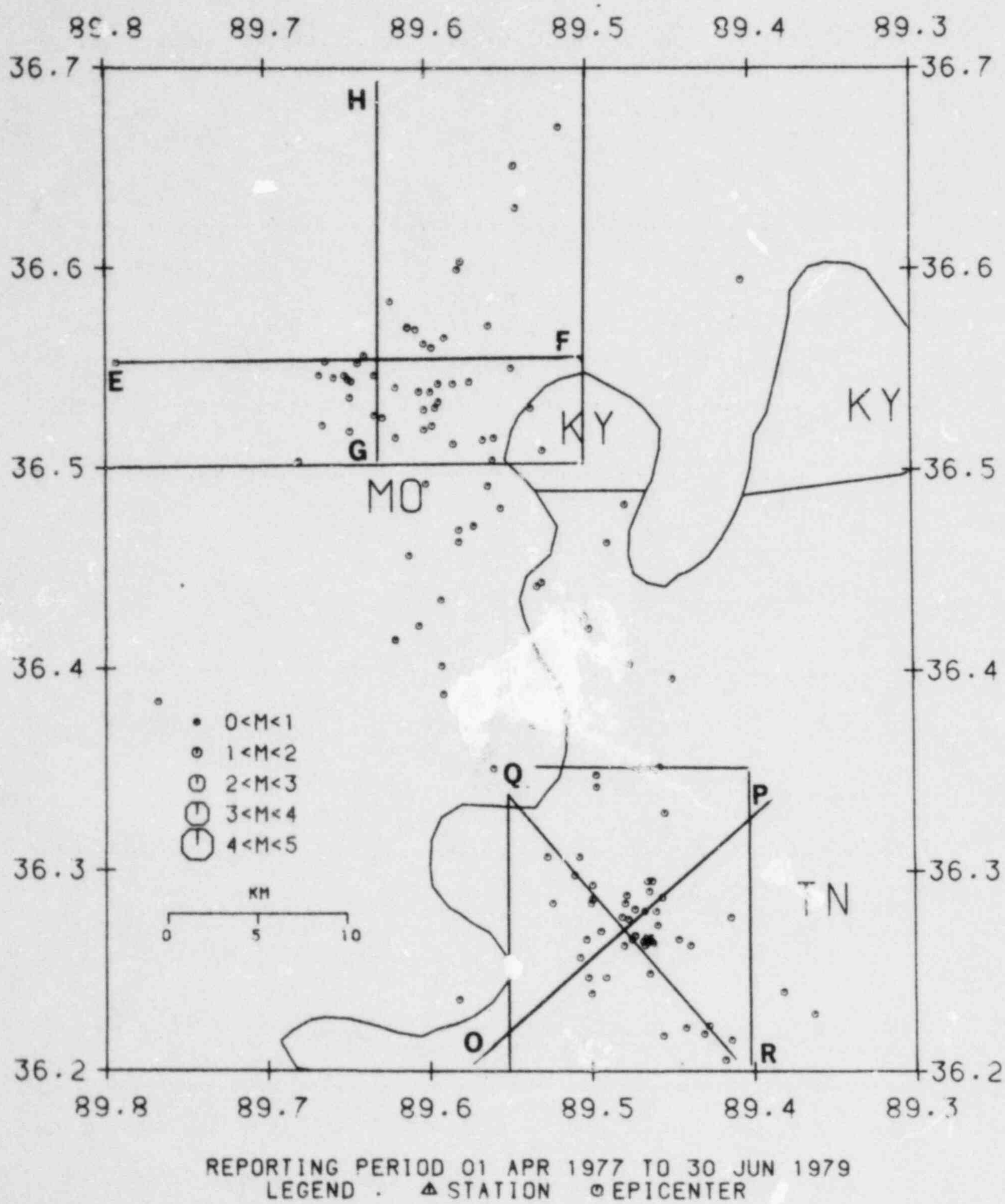
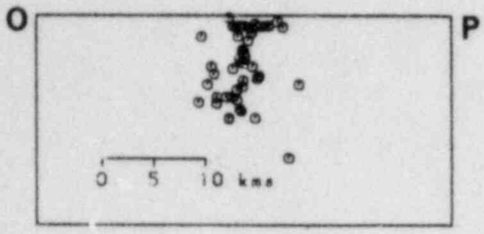
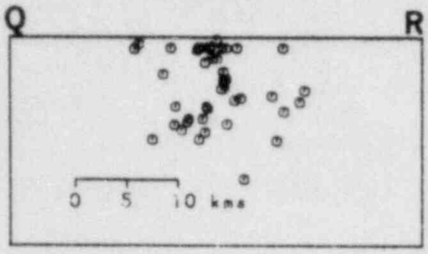


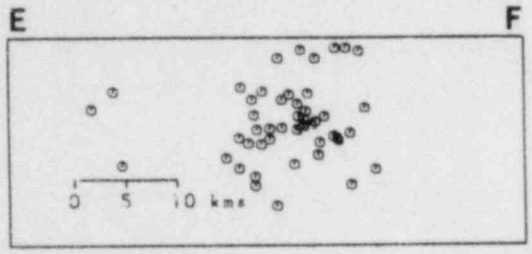
Figure JA2-20. Vertical profiles of hypocenters within the search zones of Figure JA2-19. The profile G'H' strikes N20°E.



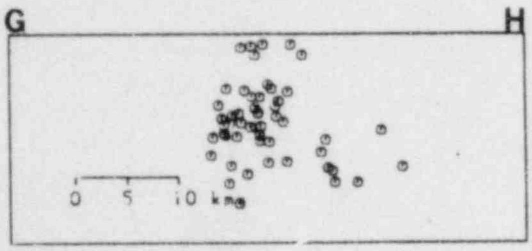
vertical profile centered at 36.272° n. 89.474° w
with strike 50°



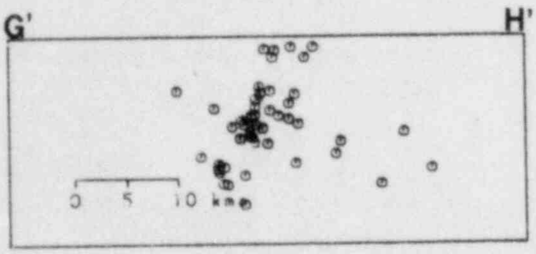
vertical profile centered at 36.272° n. 89.474° w
with strike 140°



vertical profile centered at 36.553° n. 89.637° w
with strike 90°



vertical profile centered at 36.553° n. 89.637° w
with strike 0°



vertical profile centered at 36.553° n. 89.637° w
with strike 20°

RESEARCH PROGRAMS IN THE NEW MADRID AREA SPONSORED BY OTHER AGENCIES

During the fiscal year 1980 staff members of the U.S. Geological Survey published the results of their deep-penetrating seismic reflection studies in the Mississippi Embayment. The reflection profiles revealed major faults in northeastern Arkansas that coincided with the main earthquake trends in the area. Deep seismic refraction studies are currently being performed by U.S.G.S. personnel in the New Madrid region. The purpose of these surveys is to study the structure of the middle and lower crust in the area of New Madrid seismicity. Profiles to be established include one along the axis of the Reelfoot Rift, one parallel to the rift to the southeast, and two perpendicular to the rift. Preliminary reports of the findings from this study should be available in Spring of 1981, after the data are processed.

Several of the participants in the N.R.C. - New Madrid study group have prepared papers to be included in a U.S.G.S. Professional Paper on the New Madrid area. The report is in final stages of editing and should be published in 1981.

Some of the current U.S.G.S. Earthquake Hazards Reduction programs that are of significance to the coordinated studies of seismotectonics in the New Madrid area are shown on table 2.

The U.S. Army Corps of Engineers, St. Louis District, continued its geological and seismological review of the midwestern United States. They have prepared a seismic zoning map for the region that is currently undergoing in-house review. The Corps published a paper in their series entitled "State-of-the-Art for Assessing Earthquake Hazards in the United States" - Miscellaneous Paper S-73-1. It is Report 16, "The relations of sustained maximum ground acceleration and velocity to earthquake intensity and magnitude," by Otto W. Nuttli, 1979.

The coordinator and other members of our study group have cooperated with the Tennessee Valley Authority, National Oceanic and Atmospheric Administration, Oak Ridge National Laboratories, National Science Foundation, researchers working on Department of Energy programs, and the Federal Emergency Management Agency. Cooperation and communication have been excellent among all of the organizations participating in the New Madrid Seismotectonic Study.

Table 2

U.S. Geological Survey
Earthquake Hazards Reduction Programs
New Madrid Area - FY 1980

TECTONIC HISTORY OF EASTERN OZARK UPLIFT, E.E. Glick, U.S. Geological Survey, Branch of Central Environmental Geology, Denver Federal Center, Denver, Colorado 80225, (303) 234-3353.

TECTONIC ORIGIN OF EASTERN UNITED STATES SEISMICITY, R.M. Hamilton, U.S. Geological Survey, Branch of Earthquake Tectonics and Risk, 12201 Sunrise Valley Drive, Reston, Virginia 22092, (703) 860-7684.

GEOPHYSICS OF THE NEW MADRID SEISMIC ZONE, T.G. Hildenbrand, U.S. Geological Survey, Branch of Regional Geophysics, Denver Federal Center, Denver, Colorado 80225, (303) 234-5464.

MISSISSIPPI VALLEY SEISMOTECTONICS, D.P. Russ, U.S. Geological Survey, Branch of Earthquake Tectonics and Risk, Denver Federal Center, Denver, Colorado 80225, (303) 234-5065.

TILTMETER RESEARCH PROGRAM IN THE NEW MADRID SEISMIC ZONE, Sean T. Morrissey, Saint Louis University, Department of Earth and Atmospheric Sciences, St. Louis, Missouri 63103, (314) 658-3129.

EARTHQUAKE HAZARD STUDIES IN SOUTHEAST MISSOURI, W.V. Stauder, Saint Louis University, Department of Earth and Atmospheric Sciences, St. Louis, Missouri 63103, (314) 658-3131.

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T.C. Buschbach

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St. Louis, MO 63156

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Division of Health, Siting and Waste Management
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555

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Parallel linear geophysical trends, similar to those associated with the New Madrid seismic zone, were found to extend from New Madrid northeastward into Indiana and northwestward to St. Louis, Missouri. The origin of the basement structures may be a Precambrian triple junction associated with rifting during a period of continental break-up. Aeromagnetic and gravity data from much of the study area have been integrated, gridded, and contoured. Fault studies in the area this year found no faults that displaced Quaternary deposits. There were 238 earthquakes detected and located by the St. Louis regional microearthquake array in the New Madrid area during annual year 1979. A map has been prepared to show the epicenters of 1190 earthquakes detected and located by that array for the six-year period between July 1, 1974 and June 30, 1980.

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