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Abstract

An integrated geophysical/geologic program is being conducted to evaluate the rift complex hypothesis as an explanation for the earthquake activity in the New Madrid Seismic Zone and its extensions, to refine our knowledge of the rift complex, and to investigate the possible northern extensions of the New Madrid Fault Zone, especially its possible connection to the Anna, Ohio seismogenic region. Geologic studies are being used to confirm the existence of rift zones suggested by geophysical signatures with identification of pre-upper Cambrian sedimentary rocks in the subsurface. Drillhole basement lithologies are being investigated to aid in tectonic analysis and geophysical interpretation, particularly in the Anna, Ohio area. Gravity and magnetic modeling combined with limited seismic reflection studies in southwest Indiana are interpreted as confirming speculation that an arm of the New Madrid Rift Complex extends northeasterly into Indiana. Sufficient evidence are unavailable to test the hypothesis that this feature extends into the Anna, Ohio area. The geologic and geophysical evidence confirm that the basement lithology in the Anna, Ohio area is highly variable reflecting a complex geologic history. The data indicate that as many as three major Late Precambrian tectonic features intersect within the basement of the Anna area suggesting that the seismicity may be related to basement zones of weakness.

Technical Summary

Recent geophysical investigations have shown that the seismicity in the New Madrid, Missouri seismogenic region is correlative with an ancient rift complex suggesting that the anomalous seismicity is the result of the localization of the regional compressive stress pattern by basement structures. Preliminary evidence indicates that this inferred basement rift complex extends beyond the immediate realm of the intense New Madrid region microseismicity. An integrated geophysical/geologic research program is being conducted to evaluate the rift complex hypothesis as an explanation for the earthquake activity in the New Madrid area and its extensions, to refine our knowledge of the structure and physical properties of the rift complex, and to investigate the possible northern extensions of the New Madrid Fault Zone and especially the possible north-eastern connection to the Anna, Ohio seismic zone.

Studies of pre-upper Cambrian sedimentary rocks in the midcontinent show that these rocks are limited to the immediate environs of Late Pre-cambrian/Eocambrian rift complexes. Criteria have been determined that are useful in distinguishing these sedimentary rocks from the upper Cambrian Mt. Simon Sandstone. Geochemical analysis of small ultramafic bodies which have intruded the Phanerozoic rocks of the midcontinent have been useful in confirming an upper mantle source and in dating these rocks. Petrologic and geochemical studies of basement rocks continue as an aid in tectonic analysis and geophysical interpretation. Investigations emphasizing the basement rocks in the greater Anna, Ohio seismogenic region suggest a major north-south lithologic boundary extending through western Ohio that is mapped in the Canadian Shield as the Grenville Front.

Gravity and magnetic modeling across the proposed northeast extension of the New Madrid Rift Complex into Indiana suggests a central low density

zone bordered at the margins of the complex by high density/magnetization belts. Seismic reflection studies show that this low density zone beneath the Mt. Simon Sandstone consists of normally-faulted bedded units, presumably either sedimentary and/or volcanic units. Major faulting with cumulative displacements of up to 1.5 km is of pre-Mt. Simon age. Faults of the Wabash River Valley Fault Zone with post-Pennsylvanian and pre-Quarternary movements of up to 120 m may be related to reactivation of the older faults.

Extensive gravity observations have been made in the Anna, Ohio area to fill in gaps in the available coverage and to tie together a number of surveys which cover limited areas. Composite gravity and magnetic anomaly maps of the Anna, Ohio area prepared from existing data indicate a basement of highly variable lithologic composition and complex structural history. Preliminary studies indicate that possibly three tectonic elements intersect in the greater Anna, Ohio region - the Grenville Front, the extension of the northeast arm of the New Madrid Rift Complex, and a northwesterly striking, aborted rift zone of possible Keweenawan age. Earthquake epicenters occur apparently at random in the Anna area with a concentration along the margin of a major geophysical anomaly and at the location of a prominent local gravity and magnetic anomaly northeast of Anna, Ohio.

A total of four technical papers resulting from our research have been accepted for publication and nine papers with abstracts have been presented orally at scientific meetings and conferences.

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Preface

This document is the first annual report of studies in progress by Purdue University, University of Texas at El Paso, and the University of Pittsburgh as part of the second phase of the New Madrid Seismotectonic Study. As a result, the interpretation of data are necessarily limited and preliminary, subject to modification as the research program continues. This project is coordinated by T.C. Buschbach and is funded in part by the U.S. Nuclear Regulatory Commission.

Acknowledgements

This study is the combined effort of students and faculty from Purdue University, University of Texas at El Paso, and the University of Pittsburgh. The authors of this report acknowledge the major contributions to this project of the following individuals: Purdue University - Cheryl Avery, Michael Campbell, Philip Hodgson, Paul Jones, Leo Kucek, James McPhee, Abdulhadi Musrati, Keith Peregrine, Dhananjay Ravat, Paula Roberts, Mokhtar Shakshuki, David Taylor and Fredrick Verner; University of Texas at El Paso - Carlos Chaidas and James S. Schmidt; University of Pittsburgh - M. Mikerman, M. Halpern and J.J. Kersting. Special thanks go to James McPhee who helped supervise the geophysics program during the summer of 1982.

We also acknowledge the cooperation of Thomas C. Buschbach and John L. Sexton. The assistance of P.L. Jackson of the University of Michigan and C.F. Kahle of Bowling Green (Ohio) State University is appreciated.

INTRODUCTION

Over the past several years, considerable new information has been obtained related to the distribution of earthquake activity. The pattern of historical seismicity in the midcontinent is centered near New Madrid, Missouri, the site of three major earthquakes which occurred in 1811 and 1812, and has been shown to be associated with an extensive rift complex. One viable explanation for the anomalous seismicity of the New Madrid area is the localization of the regional compressive stress pattern by basement structures associated with the rift complex. If this model is valid, then assessment of the earthquake hazards in the midcontinent will be facilitated and the prediction of the locations and expected maximum magnitudes of future earthquakes will be feasible by mapping the extent and character of the rift complex.

Since the mid-1970's, a number of university, state, and federal investigators have been engaged in a variety of geophysical, seismic, and geologic investigations of the midcontinent with particular emphasis on the New Madrid Fault Zone and its possible extensions. Gravity and magnetic survey data, basement geological studies, crustal seismic investigations and synthesis of these data with seismicity, earthquake focal mechanisms and stress measurements, have led to identification of a multi-segment rift complex near the head of the Mississippi Embayment (Hildenbrand et al., 1977; Braile et al., 1982a and 1982b). The New Madrid Seismic Zone is related to the segment of this complex which is located near the axis of the Embayment.

The objective of this investigation is to utilize geological, geophysical and seismological studies to investigate the possible northern extensions of the New Madrid Fault Zone (Fig. 1). Specifically, this research has the following goals:

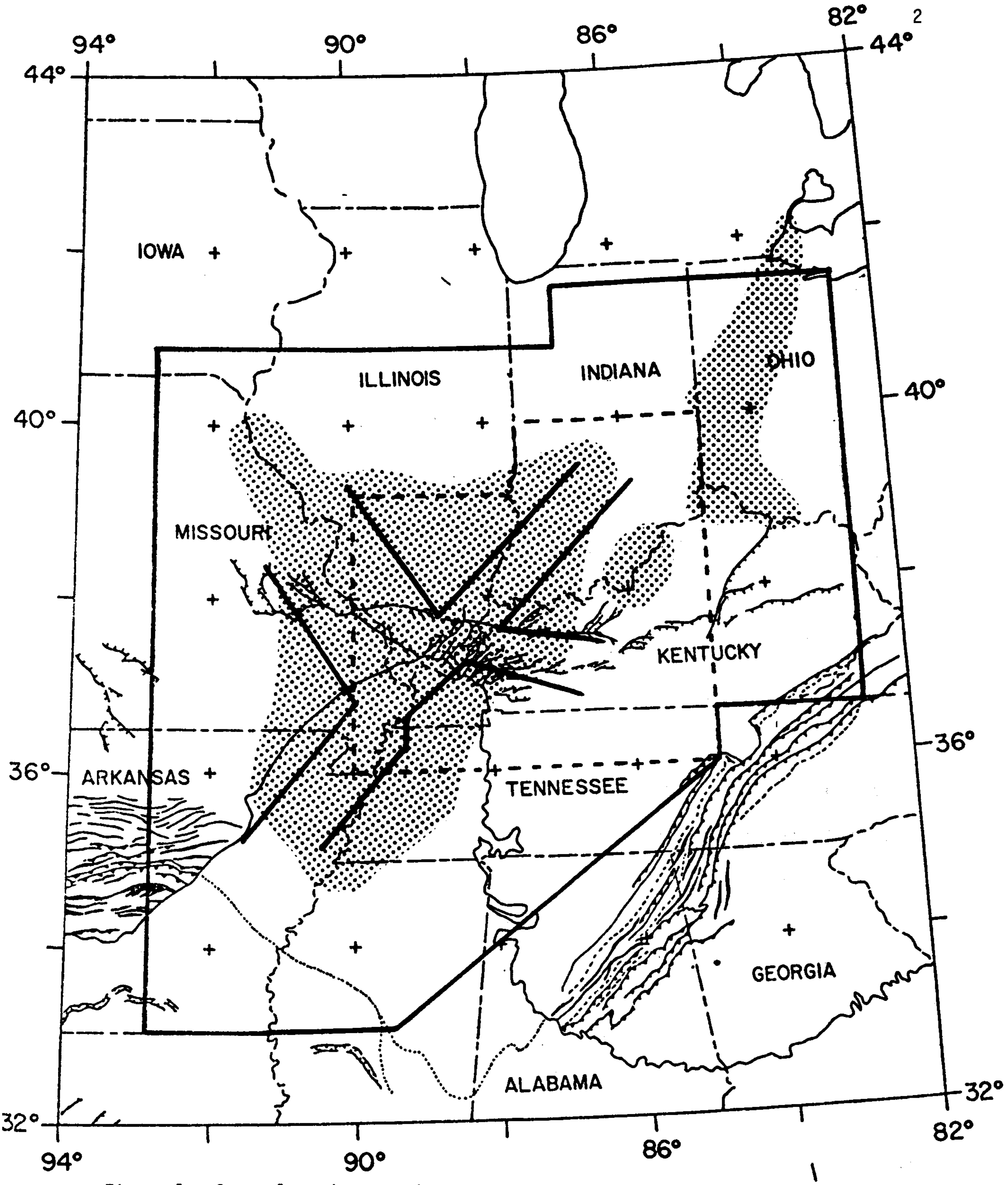


Figure 1. General study area showing northeast extension study area (dashed line), inferred rift complex (heavy lines) and earthquake epicenter density of greater than 4 per 10^4 km^2 area (dotted pattern) as shown by Hadley and Devine (1974).

(1) Evaluation of the rift complex hypothesis as an explanation for the origin of earthquake activity in the greater New Madrid area.

(2) Investigation of the northern extension of the New Madrid Fault Zone and the possible connection to the Anna, Ohio earthquake area.

(3) Refinement of the structure and physical properties of the rift complex and its extensions and correlation of geologic structure with the pattern of earthquake activity.

During the initial year of project activity, progress has been made on a broad number of research fronts leading to the achievement of these goals. Primarily, these studies have focused upon the greater Anna, Ohio area and the northeast arm of the rift complex. The northeastern arm is the site of the Wabash River Valley Fault Zone which occurs on the extension of the New Madrid Seismic Zone and the Anna, Ohio seismic zone occurs in northwestern Ohio on the extrapolation of the northeastern arm of the rift complex. The origin of the Anna seismic zone, which is one of the major centers of seismic activity in the eastern U.S., remains an enigma despite many years of investigations (Hadley and Devine, 1974; Pawlowicz, 1975; Jackson et al., 1982). Geologic studies during this period have concentrated on the acquisition and petrographic and geochemical examination of pre-upper Cambrian rocks from the greater New Madrid and Anna areas. Limited gravity data have been acquired in the Wabash River Valley area, but extensive segments of the greater Anna area have been surveyed. These data plus previously available data from these areas as well as eastern Missouri are in various stages of reduction, processing, modeling, and interpretation. Major emphasis in the magnetic program has focused upon compositing the available aeromagnetic anomaly data from the greater Anna area. The seismological program is directed towards preparation for focal plane solutions in the Anna area and compilation of seismicity and stress measurements for this area.

GEOLOGIC PROGRAM

Geologic studies in the current program are concerned with petrologic and geochemical descriptions and the physical properties of basement samples obtained from deep drill holes, geologic investigations of the igneous intrusives into the Phanerozoic sedimentary rock section, studies of pre-upper Cambrian sedimentary rocks and integration of geologic interpretation of geophysical data. All of these studies remain an active part of the on-going research program, thus results to date are of a preliminary nature.

The study of the pre-upper Cambrian sedimentary rocks is aimed at identifying these rocks in the subsurface, mapping the distribution of them and testing the validity of the hypothesis that these rocks are preserved in late Precambrian or Eocambrian grabens associated with rift complexes in the midcontinent (Lidiak and Hinze, 1980). The presence of the older sedimentary rocks within the grabens beneath the widespread upper Cambrian Mt. Simon Sandstone offers the promise of mapping the rift complexes by seismic reflection studies and corroborating their existence and location with direct geologic information obtained from drilling.

The Mt. Simon Sandstone of Illinois, western Kentucky and western Tennessee is a quartzose to feldspathic, submature to mature sandstone deposited during an upper Cambrian advance of an epeiric sea. It is predominantly a very fine to very coarse grained conglomeratic white to white and pink sandstone with sporadic intervals of finer grained, better sorted material. The base of the Mt. Simon Sandstone is a lithic arkose which lies, in most areas, unconformably on Precambrian igneous basement. The greatest thickness of the sandstone occurs in northeastern Illinois where it is up to 2600 feet thick, and gradually thins to the south in southern Illinois and western Kentucky and Tennessee to less than 500 feet.

Within the areas of the crustal rifts, the pre-Mt. Simon Sandstone lies immediately beneath the Mt. Simon, where it is defined mainly by anomalous thickness of sandstone. The lithology of the pre-Mt. Simon Sandstone varies considerably (Kersting, 1982; Schwalb, 1982), but certain characteristics allow a tenuous lithologic separation to be made from the Mt. Simon Sandstone. The pre-Mt. Simon Sandstone is generally finer grained, more argillaceous, and contains intervals of red shales and red silty shales which are much rarer in the Mt. Simon. Mineralogically, the pre-Mt. Simon is less mature, containing more feldspar. The presence of authigenic epidote in some areas and the lack of tourmaline in the pre-Mt. Simon also distinquish this sandstone from the Mt. Simon. The description and characterization of the pre-Mt. Simon Sandstone is important in that knowledge of its extent provides evidence of the latest Pre-cambrian-Cambrian tectonic activity of the central midcontinent, in particular, the formation of a complex series of rifts. An example of the correlation of these older sedimentary units with the New Madrid Rift Complex is illustrated in Figure 2. Another interesting correlation is depicted in Figure 3. Schwalb (1982) has mapped the thickness of the Mt. Simon Sandstone from the sparse drill hole data. His map shows a correlative thickening of this formation with the northeast arm of the New Madrid Rift Complex. This relationship suggests that the postulated rift had an effect upon the deposition of these sedimentary rocks and that the deformation along this element of the complex extended into early Paleozoic time.

A significant factor in studying the tectonic history of the greater New Madrid region is the occurrence of small ultramafic igneous intrusives which have penetrated the Paleozoic sedimentary rocks. A petrologic

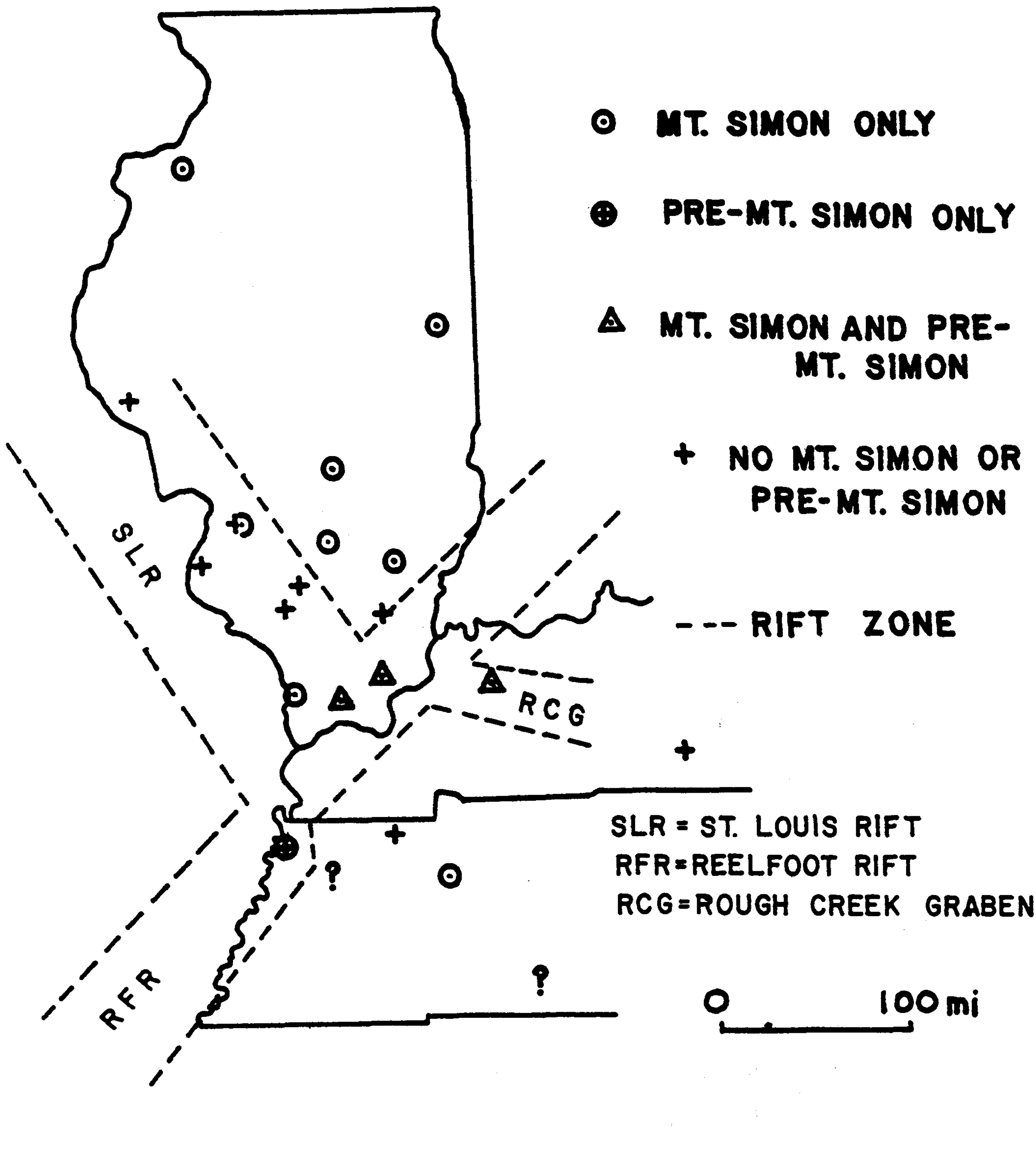


Figure 2. Distribution of Mt. Simon and pre-Mt. Simon Sandstones in relation to the New Madrid Rift Complex.

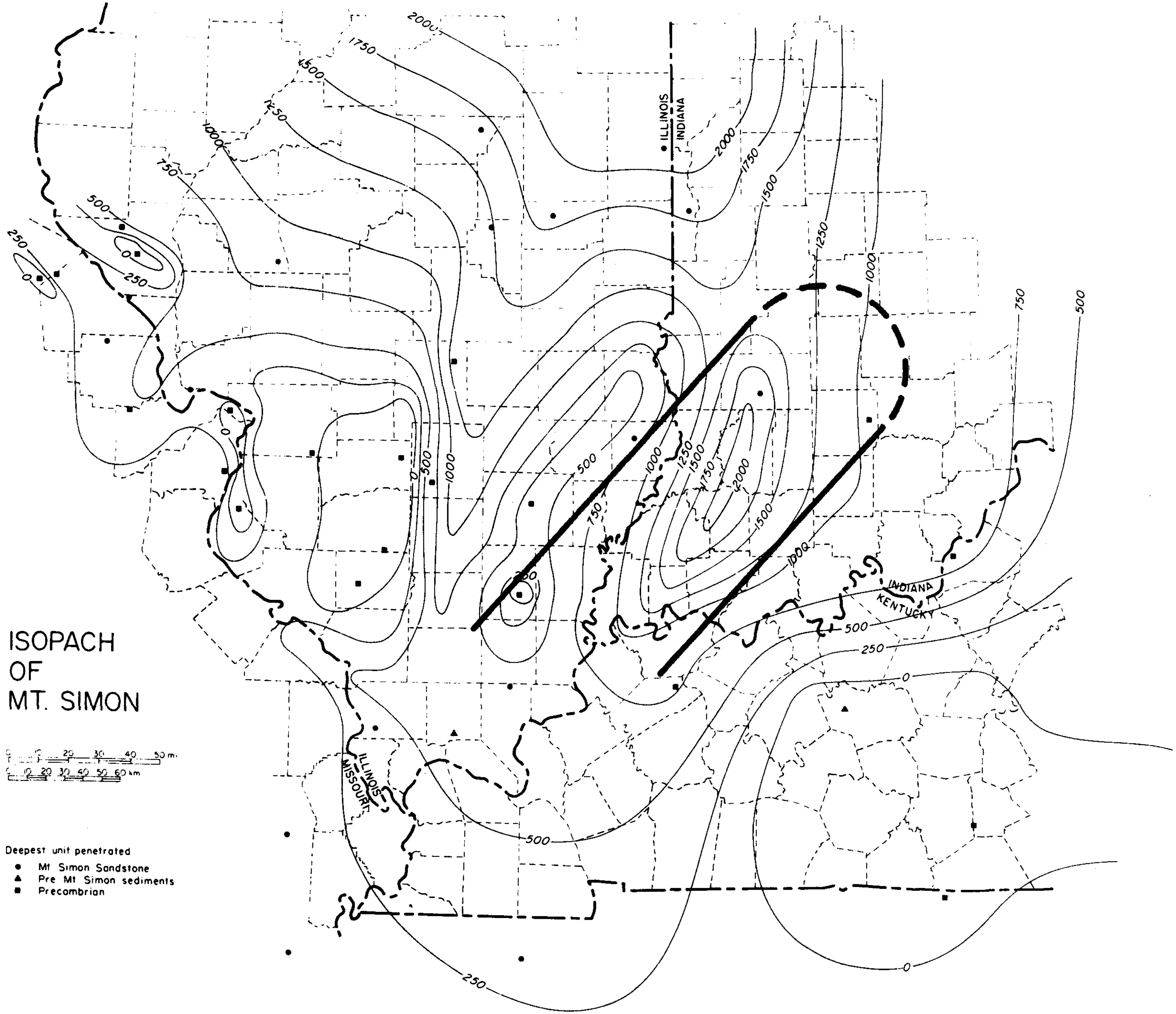


Figure 3. Isopach map of the Mt. Simon Sandstone (after Schwalb, 1982) and approximate location of the margins of the northeast arm of the New Madrid Rift Complex. Contour interval is 250 feet.

and geochemical study of these igenous rocks employing the electron microprobe confirms a mantle origin for them. Isotopic age dating (K-Ar and Rb-Sr) of one of these intrusives, the Omaha Oil Field Intrusion of Gallatin County, Illinois, provides an age of 290 ± 6 m.y.

Recent geophysical studies have illustrated the importance of intraplate rifts on the tectonism and earthquake history of the midcontinent. Hinze et al. (1977, 1980) and Braile et al. (1982a) have emphasized the significance of ancient rifts in controlling recent tectonics of the midcontinent, particularly in the New Madrid area. These studies have been summarized and updated in a paper in press in Tectonophysics entitled "The Role of Rifting in the Tectonic Development of the Midcontinent, USA" by G.R. Keller, E.G. Lidiak, W.J. Hinze and L.W. Braile. This paper, which is presented in Appendix I, develops the theme that rifts are likely candidates for tectonic reactivation and occur widely throughout much of mid-America. A related paper, "Evidence for a Major Late Precambrian Tectonic Event (Rifting?) in the Eastern Midcontinent U.S." by G.R. Keller, A.E. Bland, and J.K. Greenburg, has been published in Tectonics. This paper discusses possible geological sources of intense gravity and magnetic anomalies in central Kentucky and Tennessee and their relationship to neotectonism. The geological and geophysical evidence favors an origin related to late Precambrian rifting. The text of this paper is given in Appendix II.

An expanded abstract of a paper 'Geologic Significance of Regional Gravity and Magnetic Anomalies in the East-Central Midcontinent' presented by W.J. Hinze, E.G. Lidiak, J.E. Reed, G.R. Keller, L.W. Braile, and R.W. Johnson at the 1982 International Meeting of the Society of Exploration Geophysicists (SEG) is given in Appendix III. This paper illustrates how regional gravity and magnetic anomaly maps and a variety of derived filtered maps are useful in isolating and identifying particular attributes

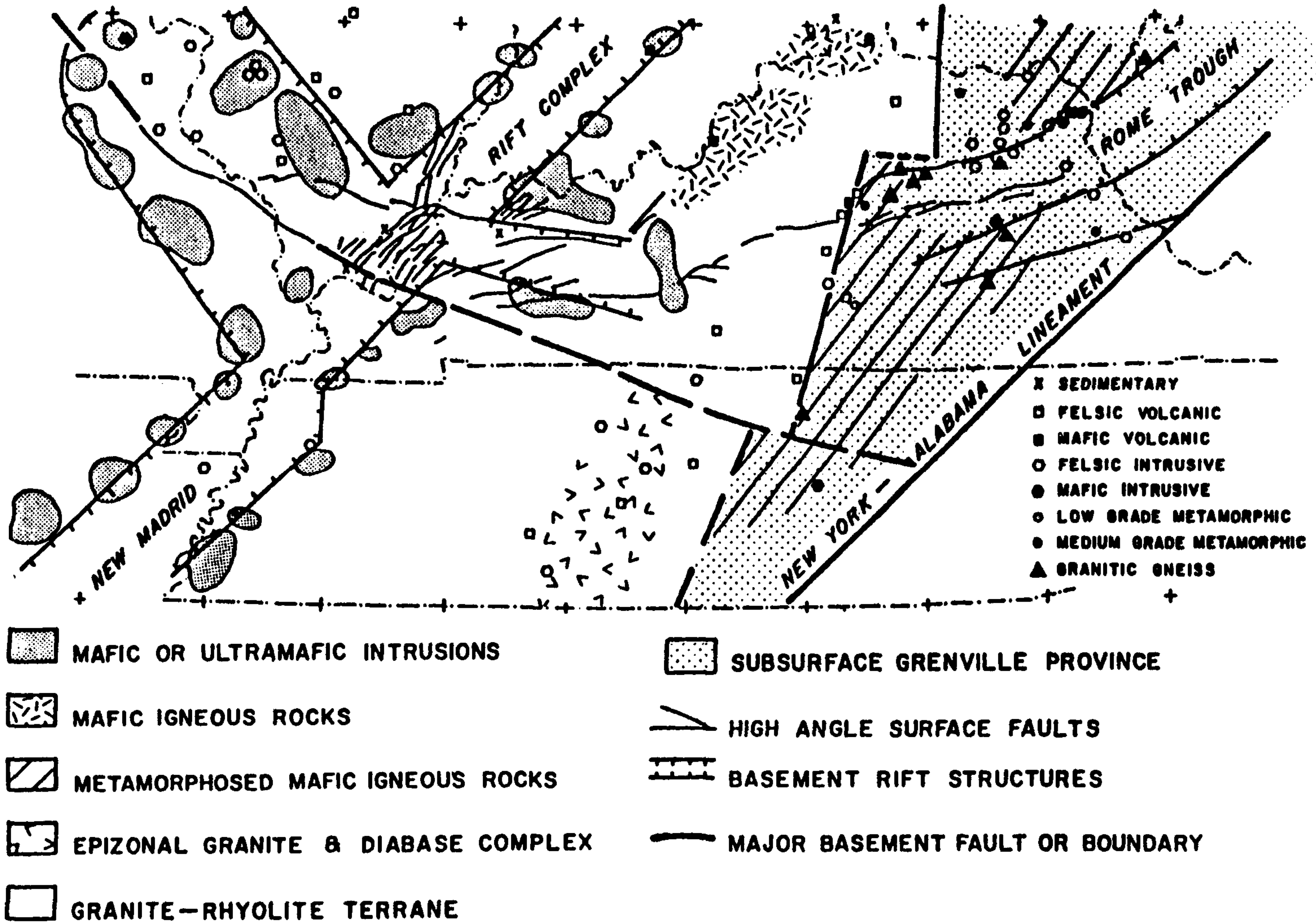


Figure 4. Basement rock map of east-central midcontinent, U.S.

of anomalies associated with basement rocks. These maps are used to define the principal basement zones and continental rifts. The basement rock map of the east-central midcontinent shown in the expanded abstract is presented in Figure 4. A related paper also presented at the 1982 SEG meeting by E.G. Lidiak and W.J. Hinze entitled 'Relation Between Drill-Hole Basement Lithology and Magnetic and Gravity Anomalies in the East-Central Midcontinent' is presented in expanded abstract form in Appendix IV. This paper explores the relation between the lithology and physical parameters of buried basement rock samples and the magnitude and amplitude of magnetic and gravity anomalies that occur in the immediate vicinity of the basement drill holes. Correlations are often poor for a variety of reasons which are discussed in the abstract. The evidence shows many possible pitfalls in using buried basement drillhole lithologies and characteristics in interpreting geophysical anomalies.

Much of the effort in the geologic program was directed toward preparing regional geologic maps useful in the study of the Anna, Ohio seismic zone. An extensive map area from 36°N to 52°N latitude and from 76°W to 88°W longitude was selected to show a variety of regional attributes related to the Anna seismic region. The area was extended south and west to include the northeastern arm of the New Madrid Rift Complex and north and east to show the location of the Grenville Front where it outcrops in the Canadian Shield. The Grenville Front marks the boundary between older basement rocks to the west and Grenvillean (≅ 1 b.y. old) rocks to the east.

Figure 5 shows a simplified map of the major structural features of the regional area. The Anna, Ohio seismic zone occurs near the axis of the Cincinnati Arch on the Indiana-Ohio Platform. The basement rocks dip to the west into the Illinois Basin, the north into the Michigan Basin, and the east into the Appalachian Basin. The location of the

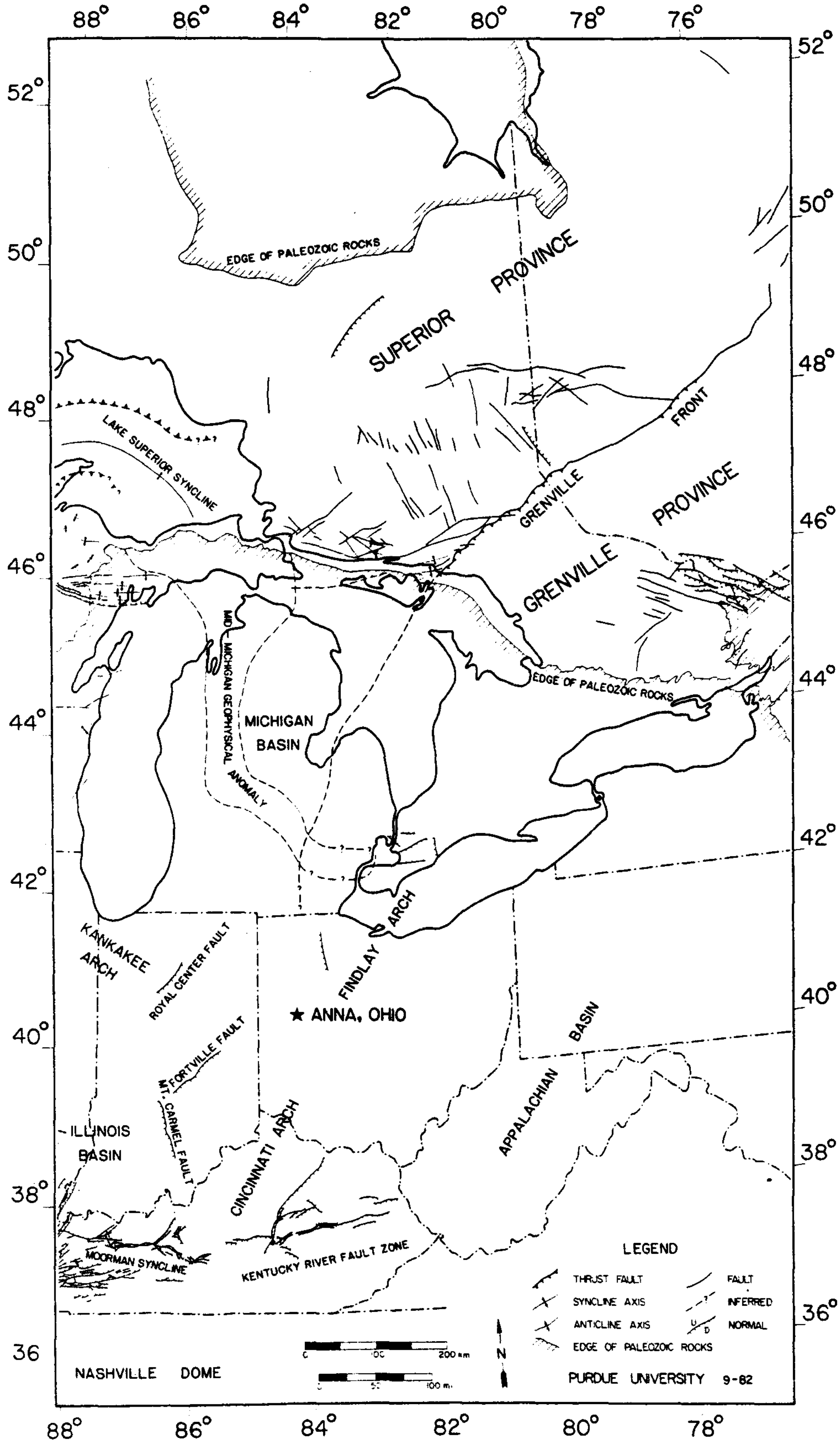


Figure 5. Simplified map of the major structural features of the greater Anna, Ohio region.

Grenville Front which marks the northwestern boundary of the Grenville basement province is shown in Canada on the basis of direct observations and southerly across Lake Huron and the Southern Peninsula of Michigan from the interpretation of geophysical anomalies and data from isolated basement drill holes (Hinze et al., 1975; O'Hara and Hinze, 1980). The Grenville Front is a major tectonic feature of North America and is variously a fault, shear, and metamorphic transition zone several tens of kilometers wide. It separates the high-grade metamorphic rocks of the Grenville Province from the low-grade metamorphic rocks of the Superior Province to the northwest and the Southern Province to the southwest. These geological variations are illustrated in Figure 6 which shows the mapped basement geology in the Canadian Shield and the basement drillhole lithologies in the area to the south of the Shield which is covered by Phanerozoic sedimentary rocks. The basement drillhole lithologies in the states adjacent to the Anna area are focused upon in Figure 7. The basement rocks in Indiana are shown to be either granites or extrusive rocks. These same lithologies continue into western Ohio for approximately 75 km. East of a line extending south from the interpreted location of the Grenville Front in Michigan (Fig. 5), the lithologies are predominantly high-grade metamorphic rocks of the Grenville Province. Isotopic age dates on these rocks also indicate an abrupt increase in the age from east to west along this line.

SEISMOLOGICAL PROGRAM

An earthquake epicenter data file for greater Anna, Ohio area has been assembled from the historical seismicity record available in a data file prepared by Barstow et al. (1981) and the earthquakes recorded by the Western Ohio-Indiana seismological array (Jackson et al., 1982) operated by the Department of Geological Sciences, the University of Michigan

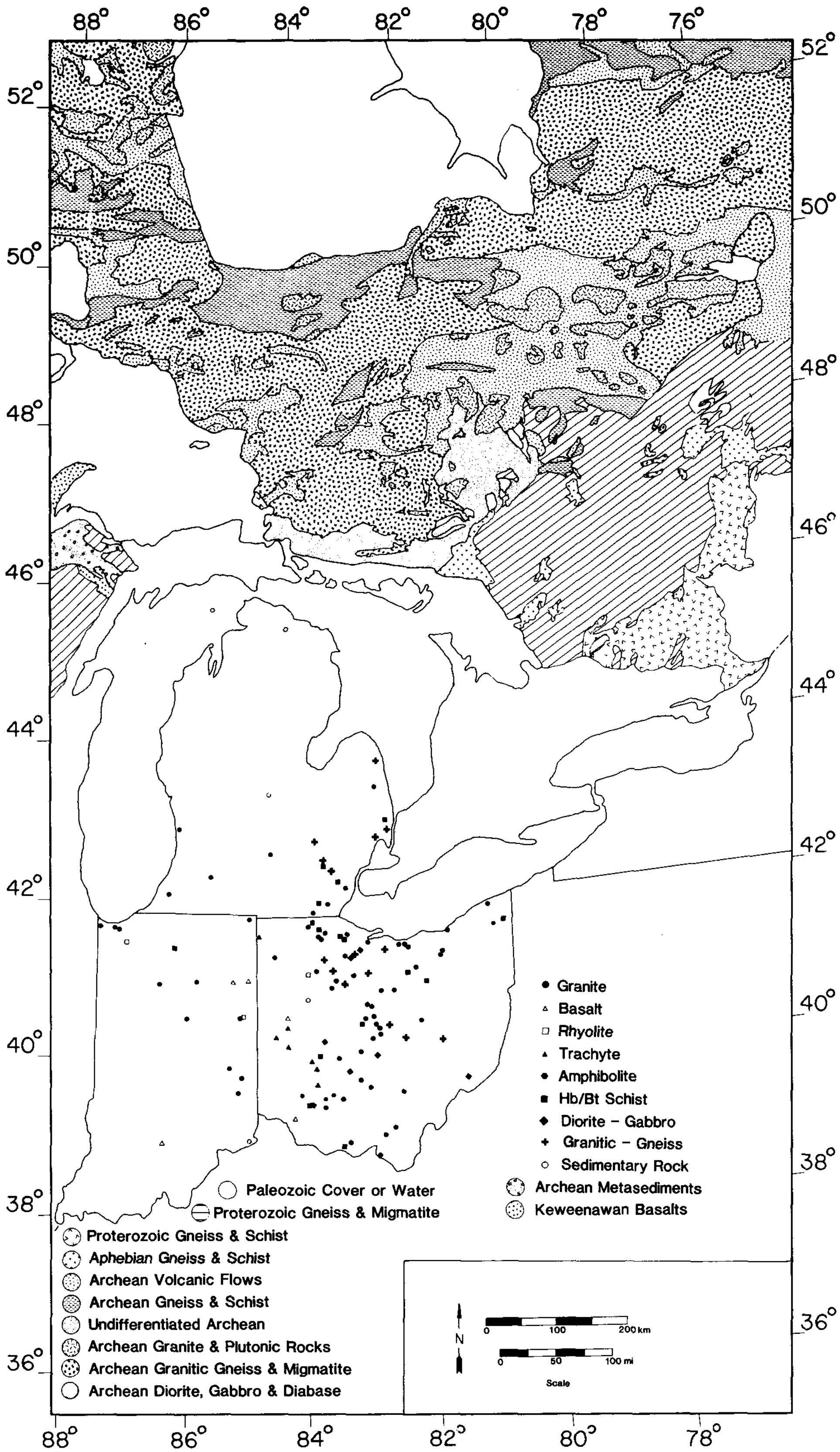


Figure 6. Simplified basement geology map of the greater Anna, Ohio region.

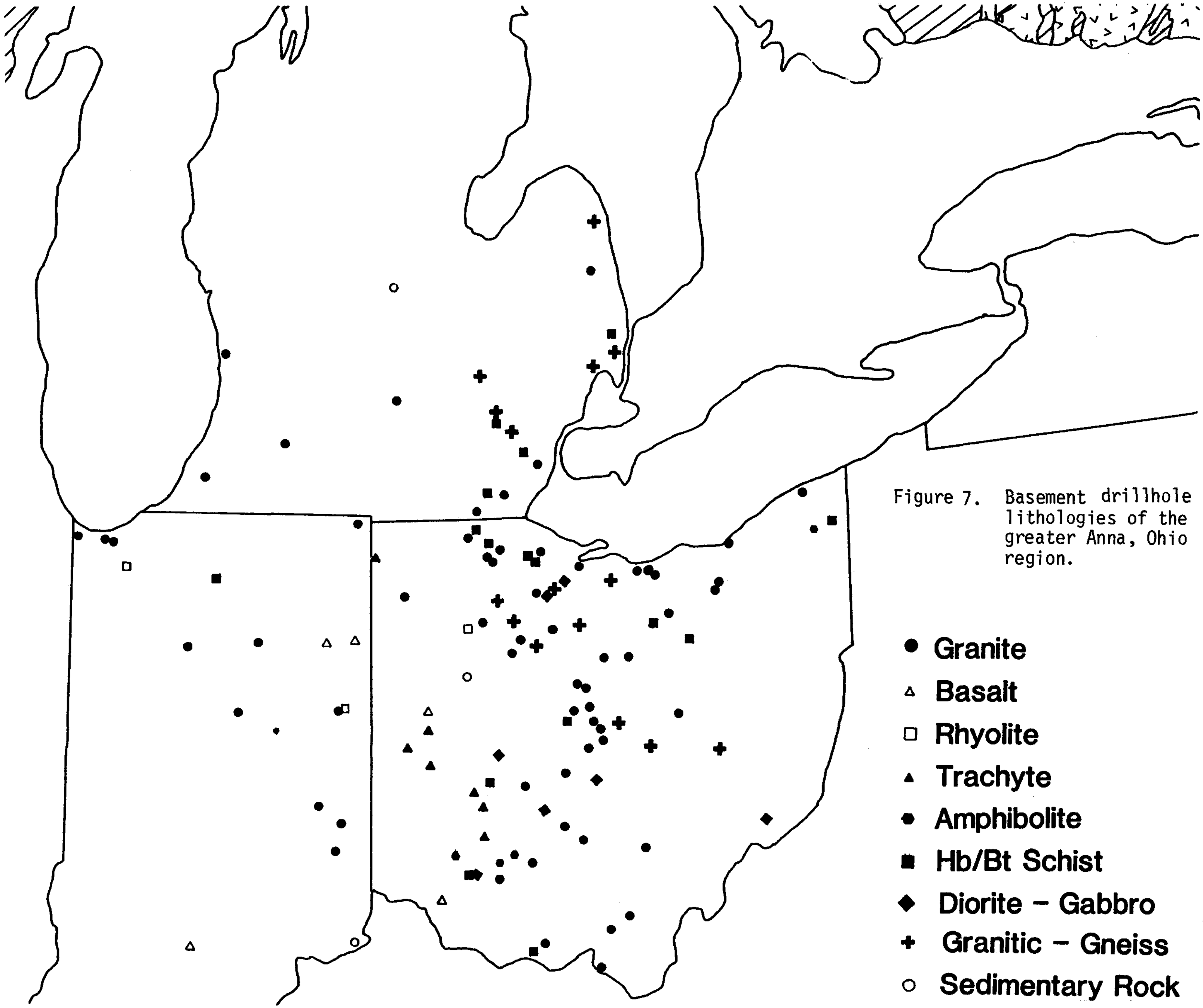


Figure 7. Basement drillhole lithologies of the greater Anna, Ohio region.

for the U.S. Nuclear Regulatory Commission. A total of 48 earthquakes have been felt in the Anna region since 1848; the largest having an intensity of VI-VII occurred in 1937. Nine stations, which have been operational since mid-1978, are located within a 40 km radius near Anna (Fig. 8). These were supplemented by four stations in Indiana early in 1981. The distribution of earthquake epicenters and the seismic stations in western Ohio and eastern Indiana are shown in Figure 8. There is no obvious pattern to the seismicity, but there is a cluster of epicenters near Anna (≅ 84.2°W, 40.3°N).

Focal mechanisms of earthquakes provide very important information for tectonic analysis. Unfortunately, limited information is available from the Anna, Ohio seismic region. Dames and Moore (1976) conducted a fault plane solution on the March 8, 1937 (maximum intensity VII-VIII) Anna, Ohio earthquake. The solution suggests a "thrust-type" mechanism with the maximum compressive axis oriented nearly horizontal along an east-west to northeast-southwest direction. Three of the fault planes which satisfy the data strike approximately north-south and one fault plane would strike approximately northwest-southeast. Preparations are now being made to do additional focal mechanism studies using the S to P amplitude ratio technique (Kisslinger, 1980; Kisslinger _et al_., 1981).

Processing and interpretation of the Wabash River Valley seismic reflection data is continuing and will be reported on in detail elsewhere. A preliminary discussion of the results are included in a recent paper by Braile _et al_. (1982b) which is presented in Appendix V. The reflection data indicate that the Phanerozoic sedimentary rocks are relatively flat-lying and undisturbed with the exception of small-offset faults (total displacements of up to 120 m) associated with the Wabash River Valley faults. However, within the Precambrian beneath the Wabash River Valley area, prominent normal faults (cumulative displacements of up to 1.5 km)

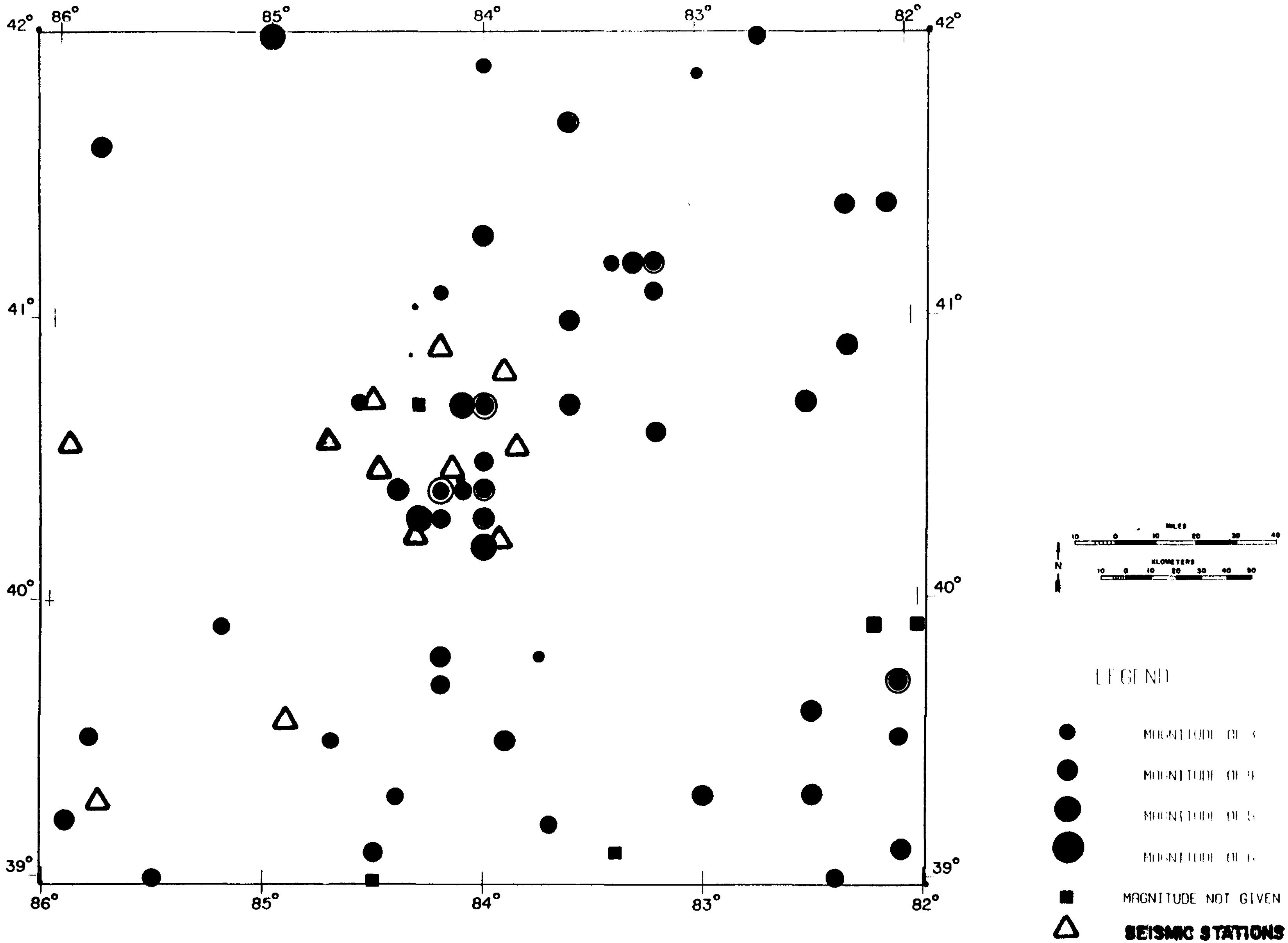


Figure 8. Earthquake epicenters in the Anna, Ohio region.

cut the layered volcanic and/or sedimentary units. The Phanerozoic faults are localized over Precambrian faults which have much greater displacements suggesting a reactivation of ancient structures. The seismic reflection data indicate the existence of a major Precambrian fault zone previously interpreted on the basis of gravity and magnetic anomaly data (Braile et al., 1982b).

GRAVITY AND MAGNETIC PROGRAM

Gravity and magnetic anomaly data are widely used in mapping intracrustal petrologic variations in the midcontinent and have been particularly successful in defining the location and characteristics of ancient structures in the New Madrid area that by reactivation have localized the seismicity of the region. Thus, acquiring and compiling regional gravity and magnetic anomaly data is an important element at this early stage in the seismotectonic investigation of the extensions of the rift complex. Emphasis is placed upon the regional nature of the data. Compelling evidence indicates that the regional perspective, which can only be obtained from data covering extensive regions adjacent to the specific study area, are very necessary in tectonic investigations. The combination of limited data acquisition funds and the need for extensive data sets require that maximum use be made of currently available data. Thus, in these early stages of studying the Anna, Ohio region, every effort is being made to tie together and composite existing data.

A regional, simple Bouguer gravity anomaly map of the greater Anna, Ohio is presented in Figure 9. The map has been compiled from a large number of individual gravity surveys in the U.S. and Canada and is primarily derived from the regional compilation maps prepared by Keller et al. (1980) and O'Hara (1981). The data shown on the map has been reduced utilizing the 1930 International Gravity Formula and a rock density of

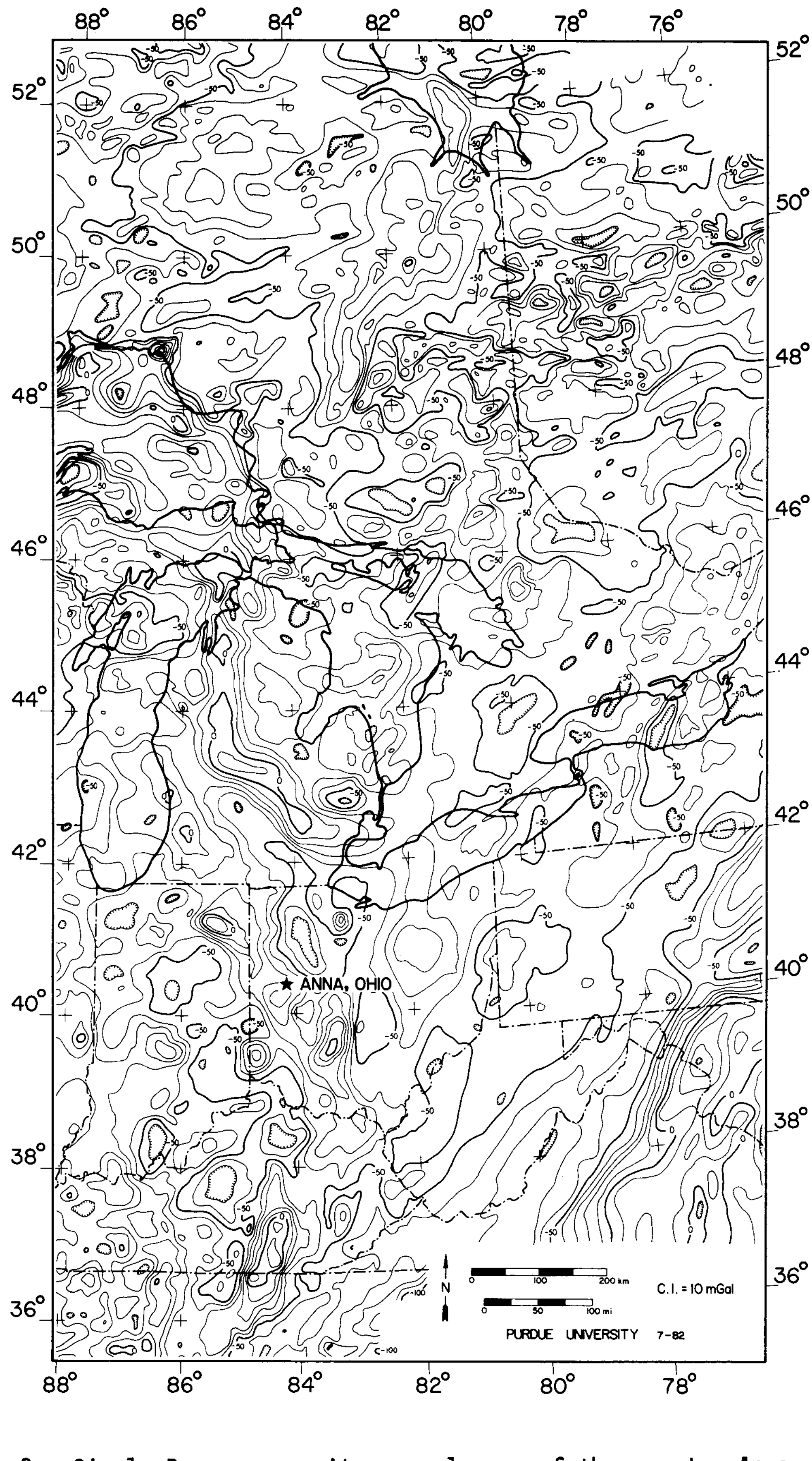


Figure 9. Simple Bouguer gravity anomaly map of the greater Anna, Ohio region.

2.67 gm/cc. The composite aeromagnetic anomaly map of the greater Anna, Ohio region is shown in Figure 10. This map is also based on a number of aeromagnetic surveys which have independently been corrected with an appropriate core-derived magnetic field model, but is primarily based upon previously prepared compilation maps by Johnson et al. (1980) and O'Hara (1981).

For comprehensive analysis of the basement geology in the Anna, Ohio region, more detailed gravity and magnetic anomaly maps are required. Data from previous gravity surveys of limited areas in the region are available from Bowling Green State University, the University of Michigan and Purdue University. Approximately 1000 useable gravity station observations are available. A gravity survey has tied these data together and an additional 2000 gravity stations have been observed in the area to fill in gaps in the coverage. These data have been reduced and compiled. A hand-drawn contour map of these, roughly, 3000 reduced observations is presented in Figure 11. For the purposes of preliminary analysis, these data are being gridded at a 2 km interval over the entire area of the map, 39°30'-41°30'N latitude and 82°-86°W longitude, using presently available regional data coverage in the area outside of the more closely spaced observations.

The available aeromagnetic data covering the Anna, Ohio area consists of four independent surveys. The sources of these data and the critical survey parameters are given in Figure 12. The Indiana portion of the map is based on a late 1940's aeromagnetic survey of the State which was subsequently re-reduced by Richardson (1978). The coverage in Ohio is from U.S. Geological Survey programs which cover a time span of approximately 17 years. The surveys have been flown along east-west tracks at 1 to 1.5 mile spacing and an elevation of from roughly 1200 to 2000 feet above mean sea level. The maps from these surveys have been adjusted

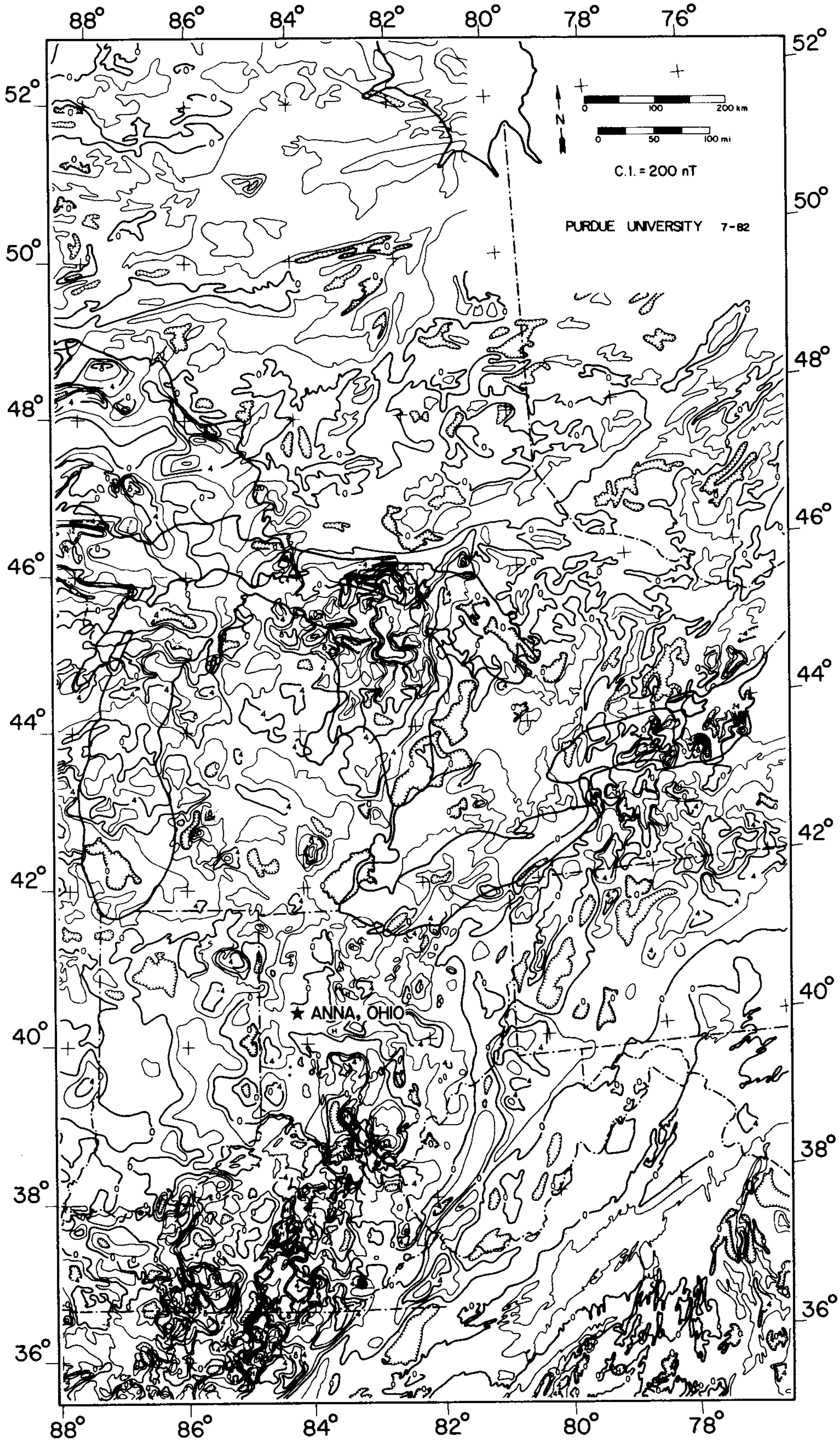


Figure 10. Aeromagnetic anomaly map of the greater Anna, Ohio region.

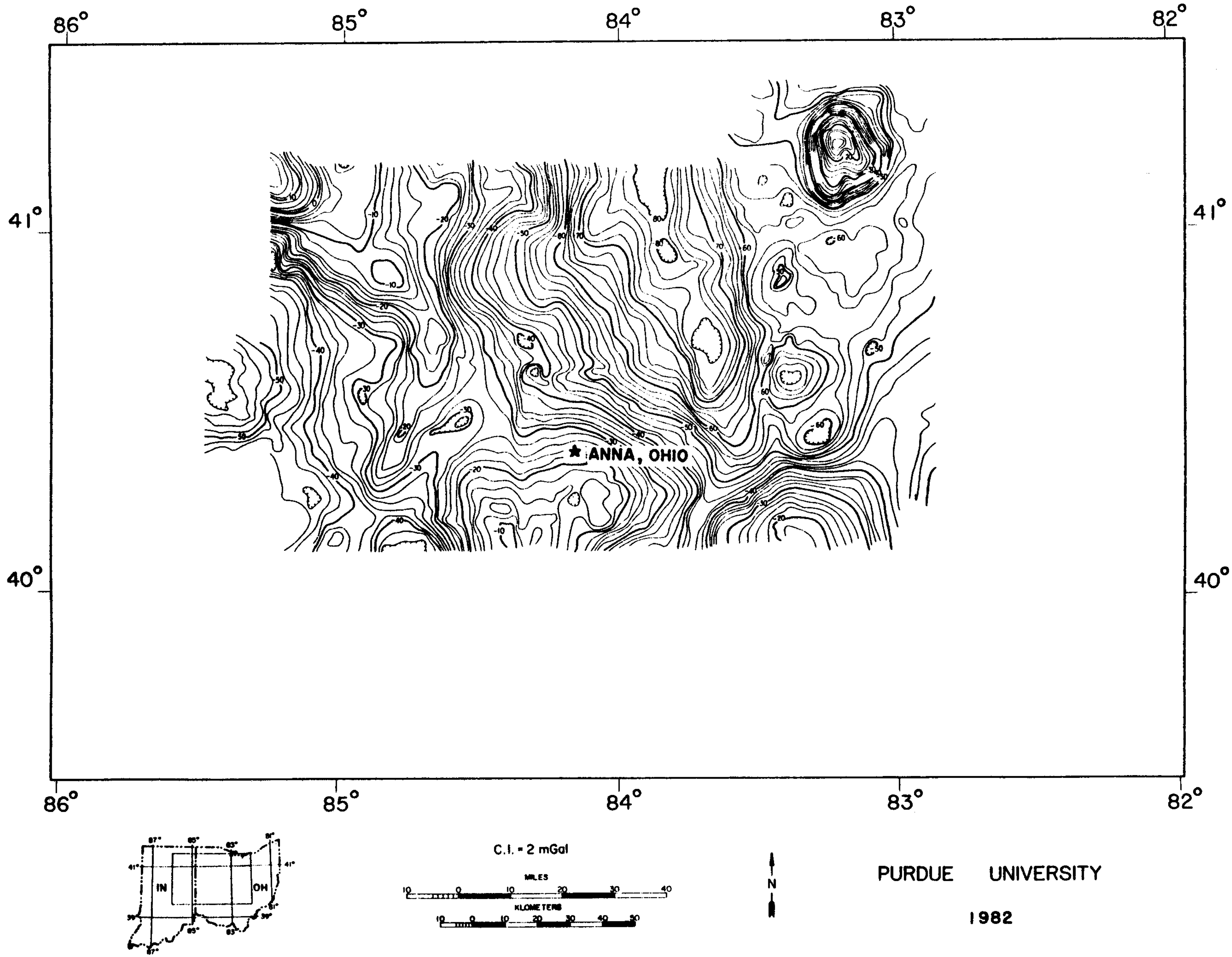
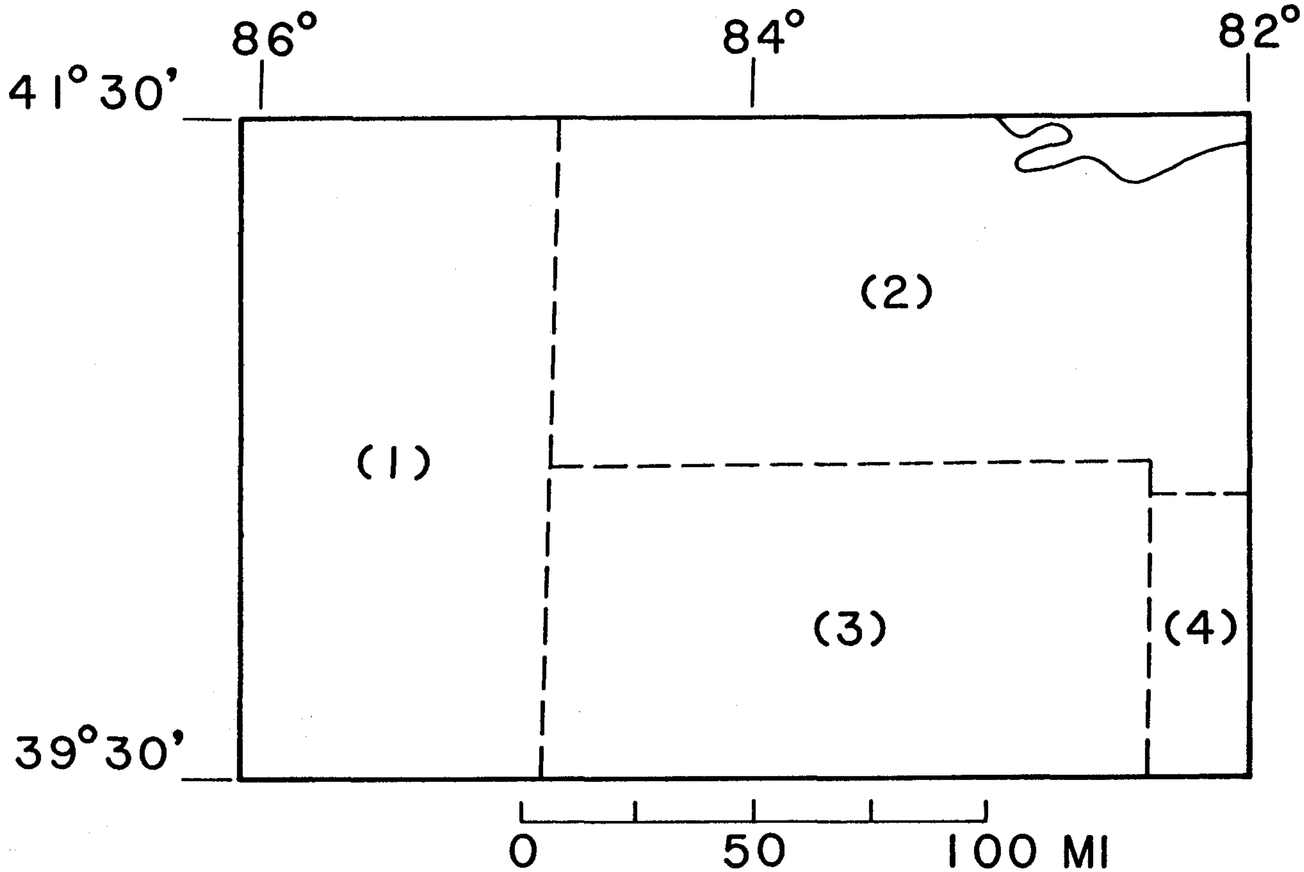


Figure 11. Simple Bouguer gravity anomaly map of the Anna, Ohio region.



(1) TOTAL MAGNETIC INTENSITY ANOMALY MAP OF INDIANA (1978)
FLIGHT ALTITUDE 1000 FEET AMT
FLIGHT INTERVAL 1.5 MILES
FLIGHT DIRECTION EAST-WEST

(2) USGS OPEN FILE REPORT 82-191 (1982)
FLIGHT ALTITUDE 1800 FEET MSL
FLIGHT INTERVAL 1.5 MILES
FLIGHT DIRECTION EAST-WEST

(3) USGS MAP GP-491 (1965)
FLIGHT ALTITUDE 500 FEET AMT
FLIGHT INTERVAL 1.0 MILE
FLIGHT DIRECTION EAST-WEST

(4) USGS OPEN FILE REPORT 79-615 (1979)
FLIGHT ALTITUDE 2000 FEET MSL
FLIGHT INTERVAL 1.5 MILES
FLIGHT DIRECTION NORTH-SOUTH

Figure 12. Source of data used in compiling the aeromagnetic anomaly map of the Anna, Ohio area.

to a common datum and composited. The resulting map is shown in Figure 13.

In addition to the gravity and magnetic anomaly studies in the Anna area, gravity data previously observed in eastern Missouri is being processed and gravity and magnetic data observed along the seismic reflection lines in the Wabash River Valley have been reduced and are being processed for interpretation together with the seismic data.

To investigate the character of the northeast arm of the New Madrid Rift Complex, four coincident gravity and magnetic profiles in southwest Indiana were selected for analysis. These profiles (Fig. 14) are perpendicular to and centered over the northeast arm. Subsurface density and geologic information obtained from nearby drill holes were used to constrain the two-dimensional modeling of the profiles particularly within the Phanerozoic sedimentary rocks (Peregrine, 1982).

Three tectonic models were assumed in the gravity and magnetic modeling based upon the tectonic mechanisms reviewed by Hinze et al. (1980). These models - graben, thick sedimentary, and intrabasement intrusive - are illustrated schematically in Figure 15. They are designed to account for the central gravity minimum with flanking positive anomalies and directly correlatable magnetic anomalies. The two-dimensional gravity and magnetic graben models for Profiles A, B, C, and D are presented in Figures 16, 17, 18 and 19, the thick sedimentary rocks models are shown in Figures 20, 21, 22, and 23, and the intrabasement intrusive models are illustrated in Figures 24, 25, 26, and 27. Several similarities are apparent in the three tectonic models: 1) Two parallel zones of high density/high magnetization basement material occur on all profiles. 2) Correlation of gravity and magnetic causative bodies decrease from Profile A to Profile D. 3) A continuous zone of low density material is likely to exist between the two parallel zones of positive anomalies,

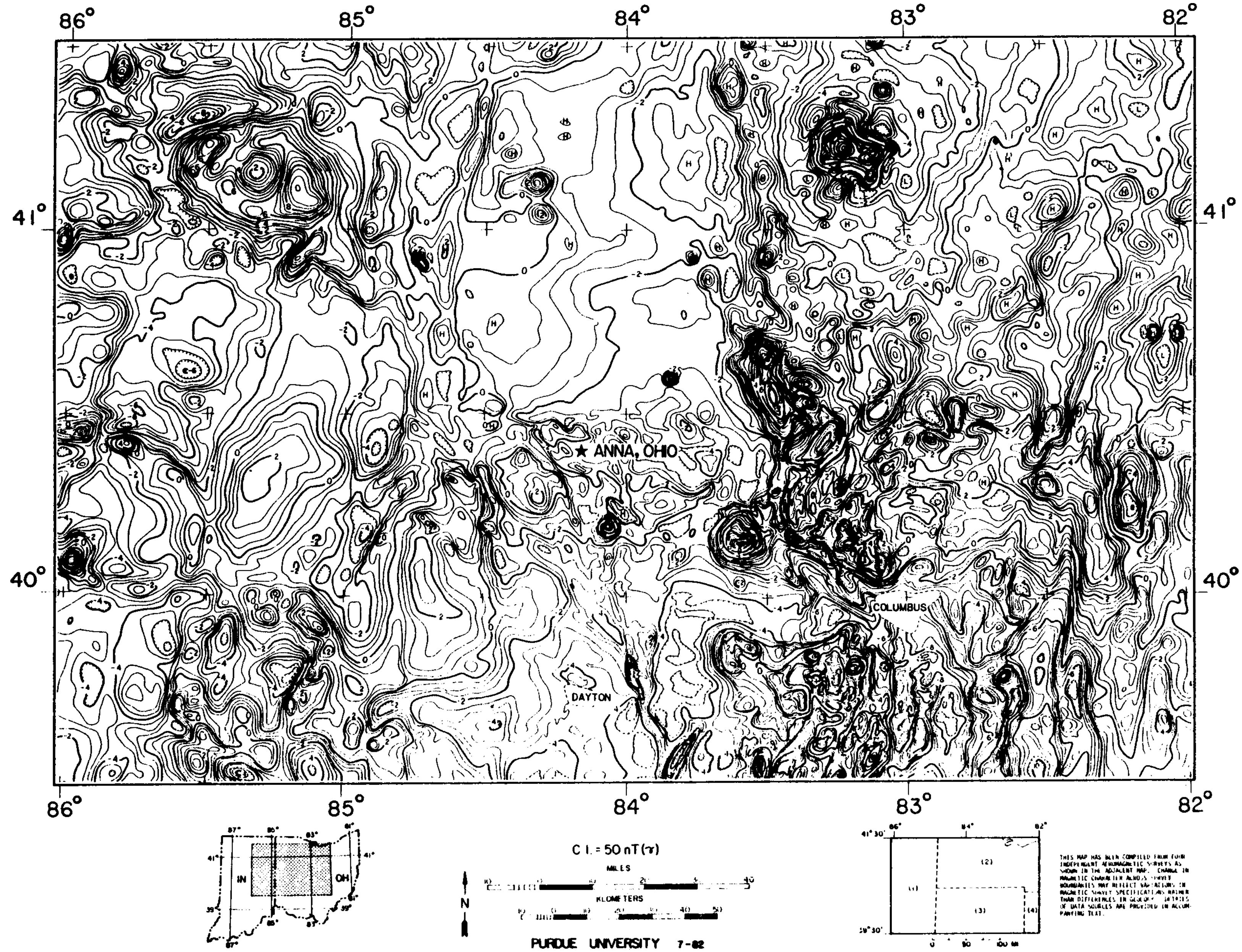


Figure 13. Composite aeromagnetic anomaly map of the Anna, Ohio area.

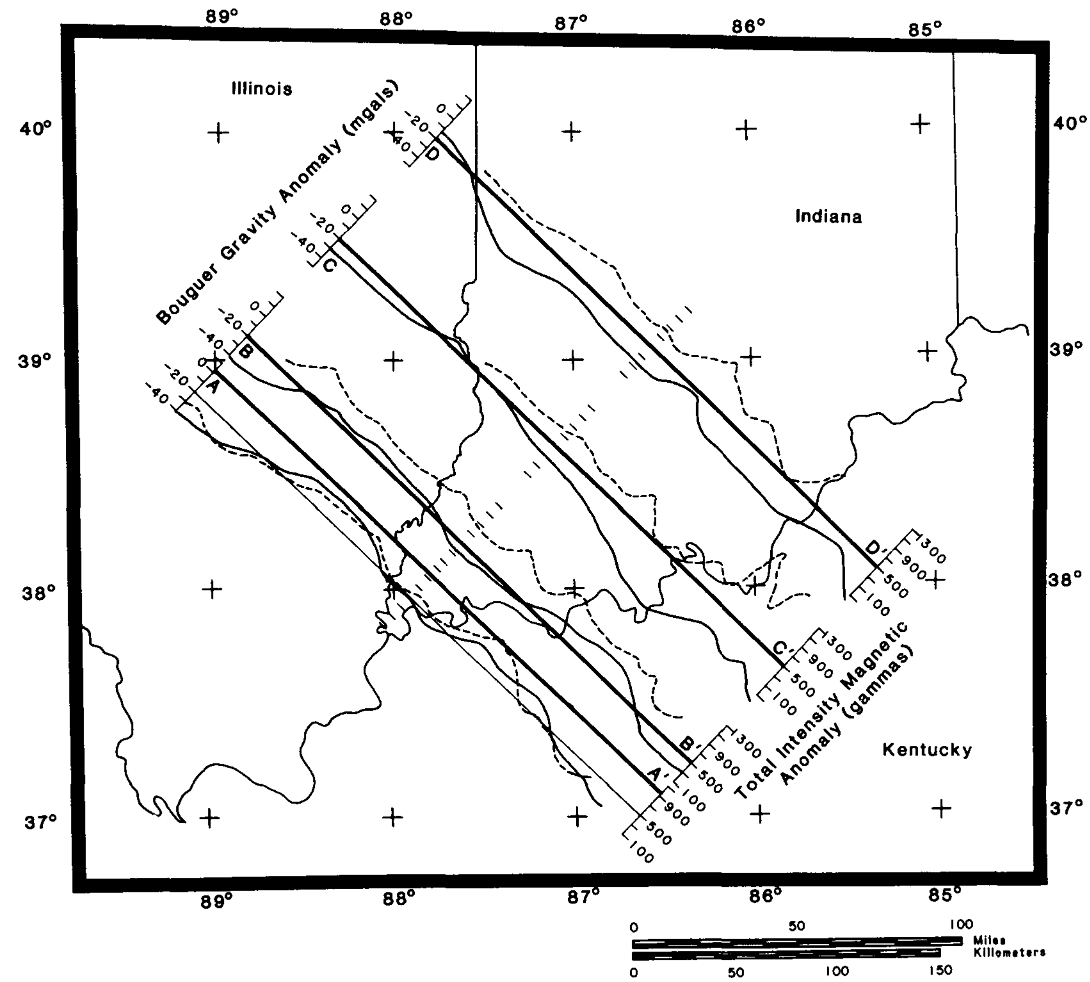


Figure 14. Gravity (solid lines) and magnetic (dashed lines) data along Profiles A to D. Note that the Profile A data have been shifted southwest from the actual Profile A location.

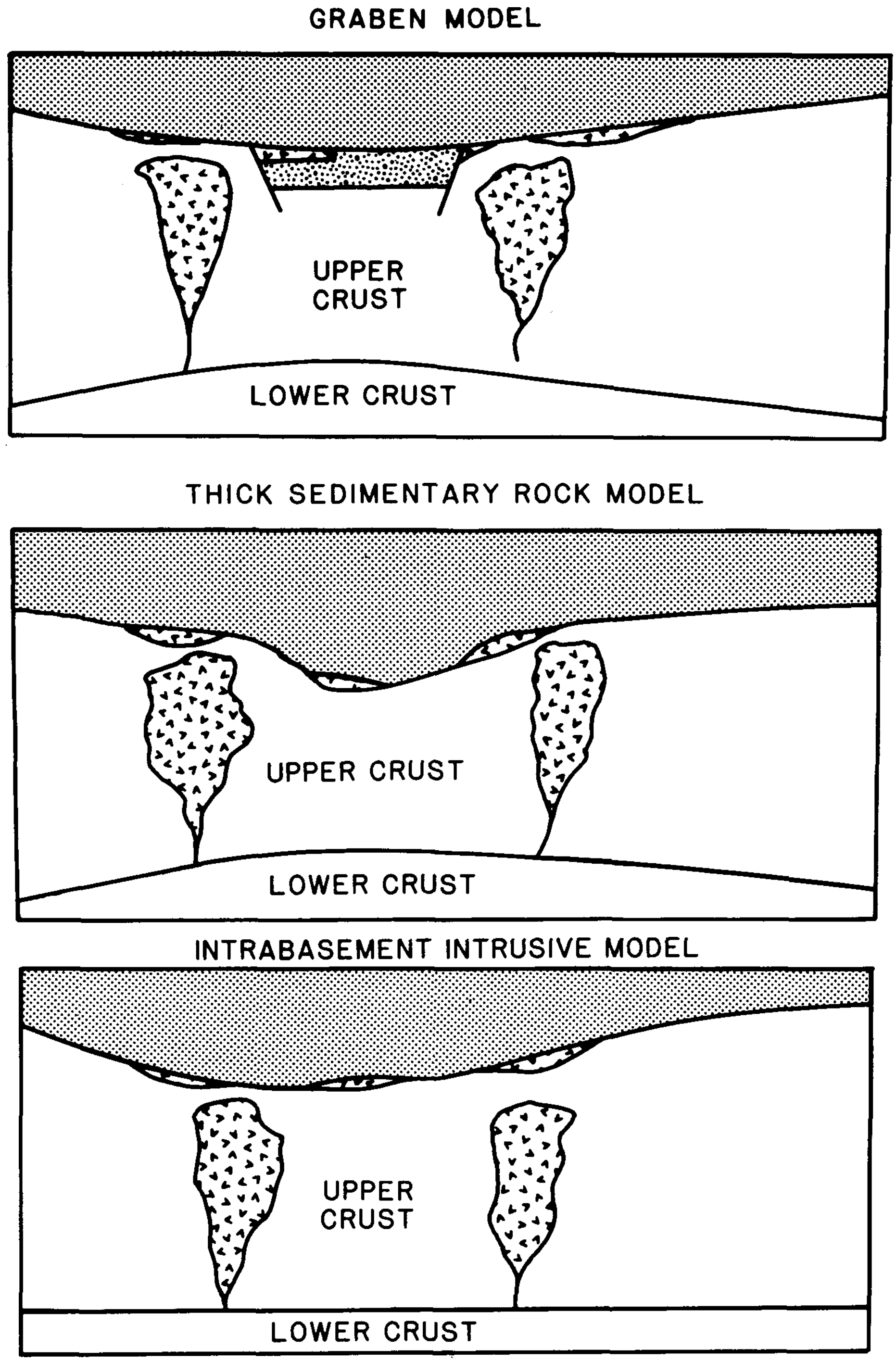


Figure 15. Schematic representation of tectonic models under investigation.

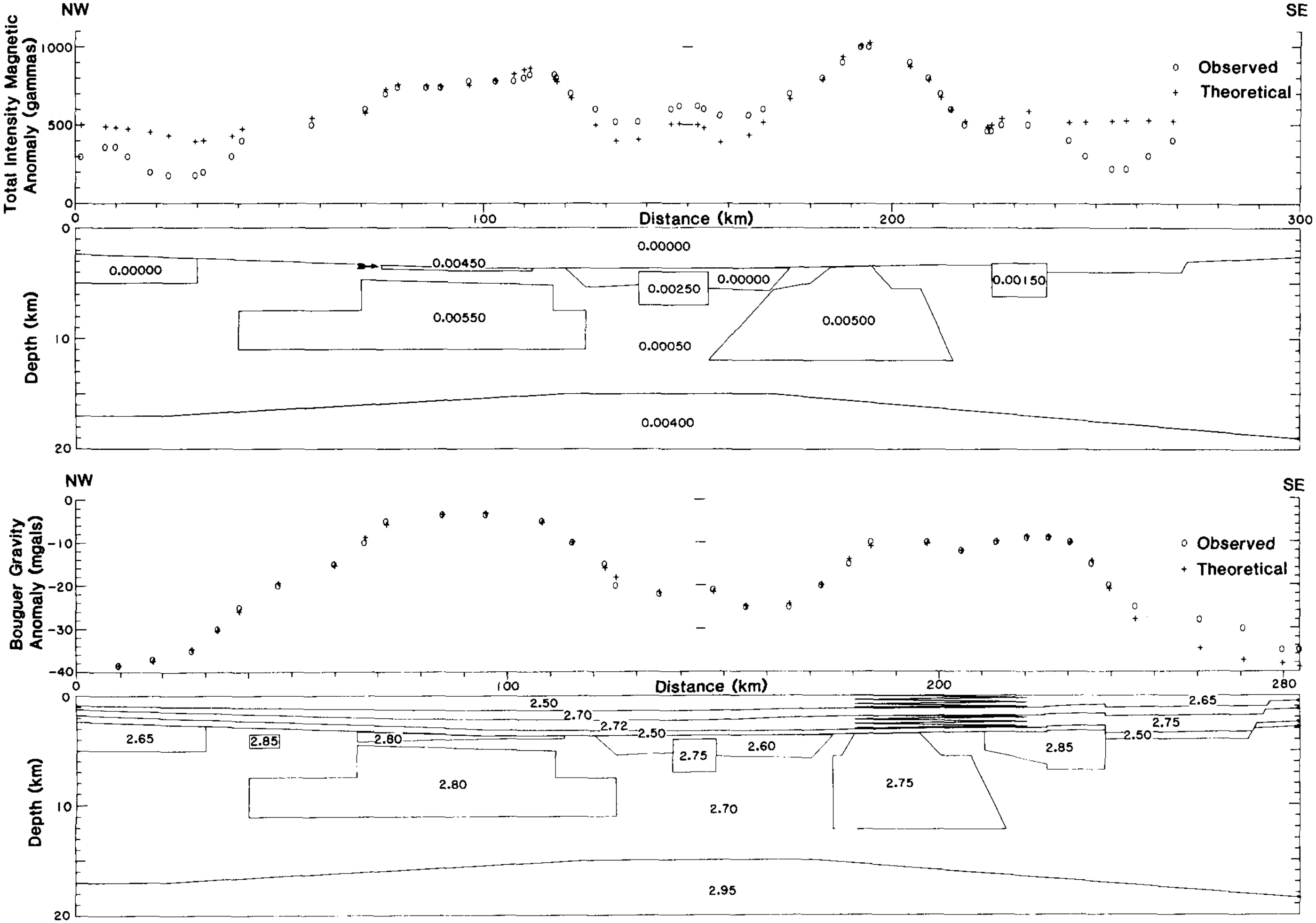


Figure 16. Profile A magnetic (top) and gravity (bottom) graben models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field -57,000γ, declination - 0°, and inclination - 72°.

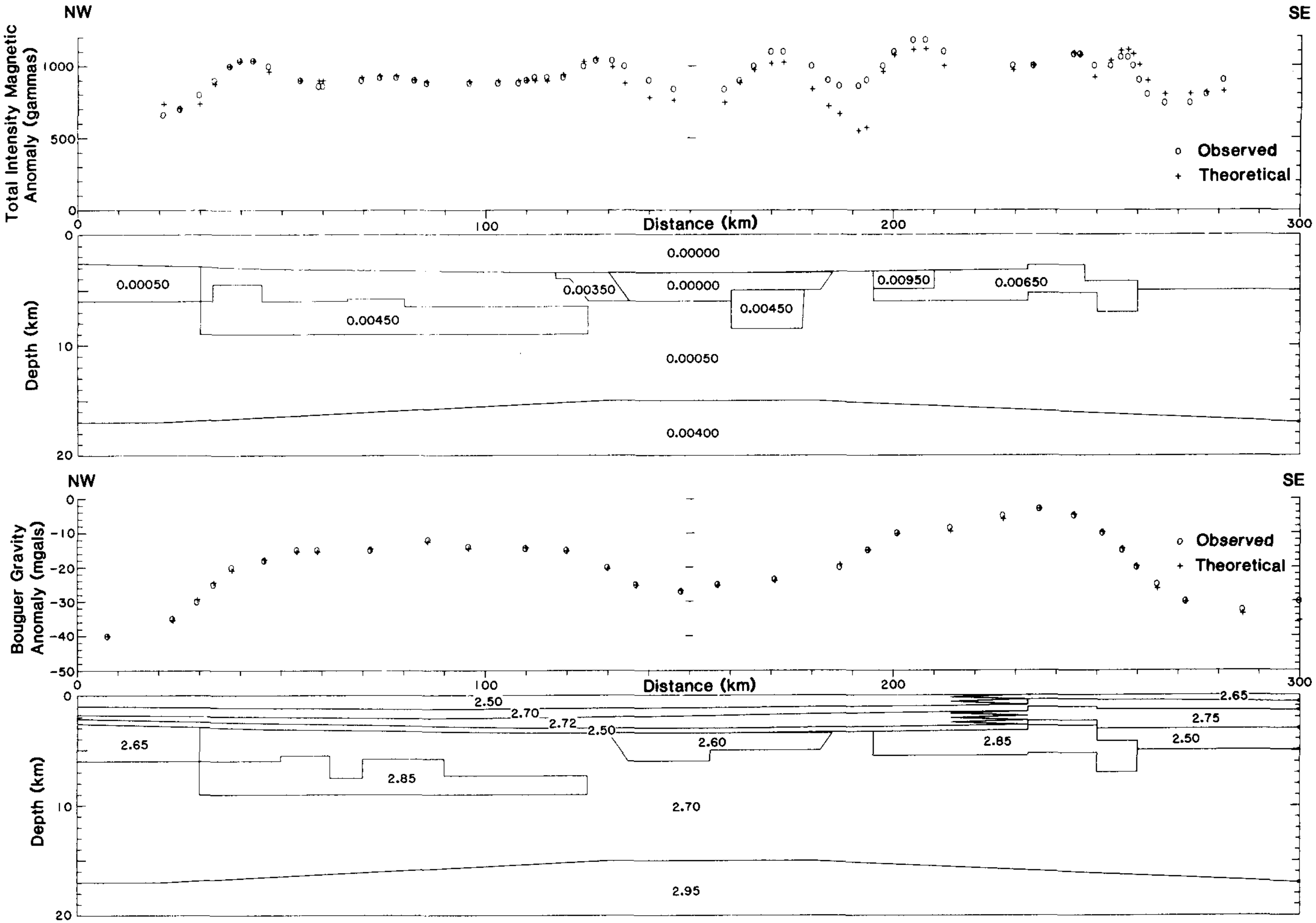


Figure 17. Profile B magnetic (top) and gravity (bottom) graben models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000γ, declination - 0^o, and inclination - 72^o.

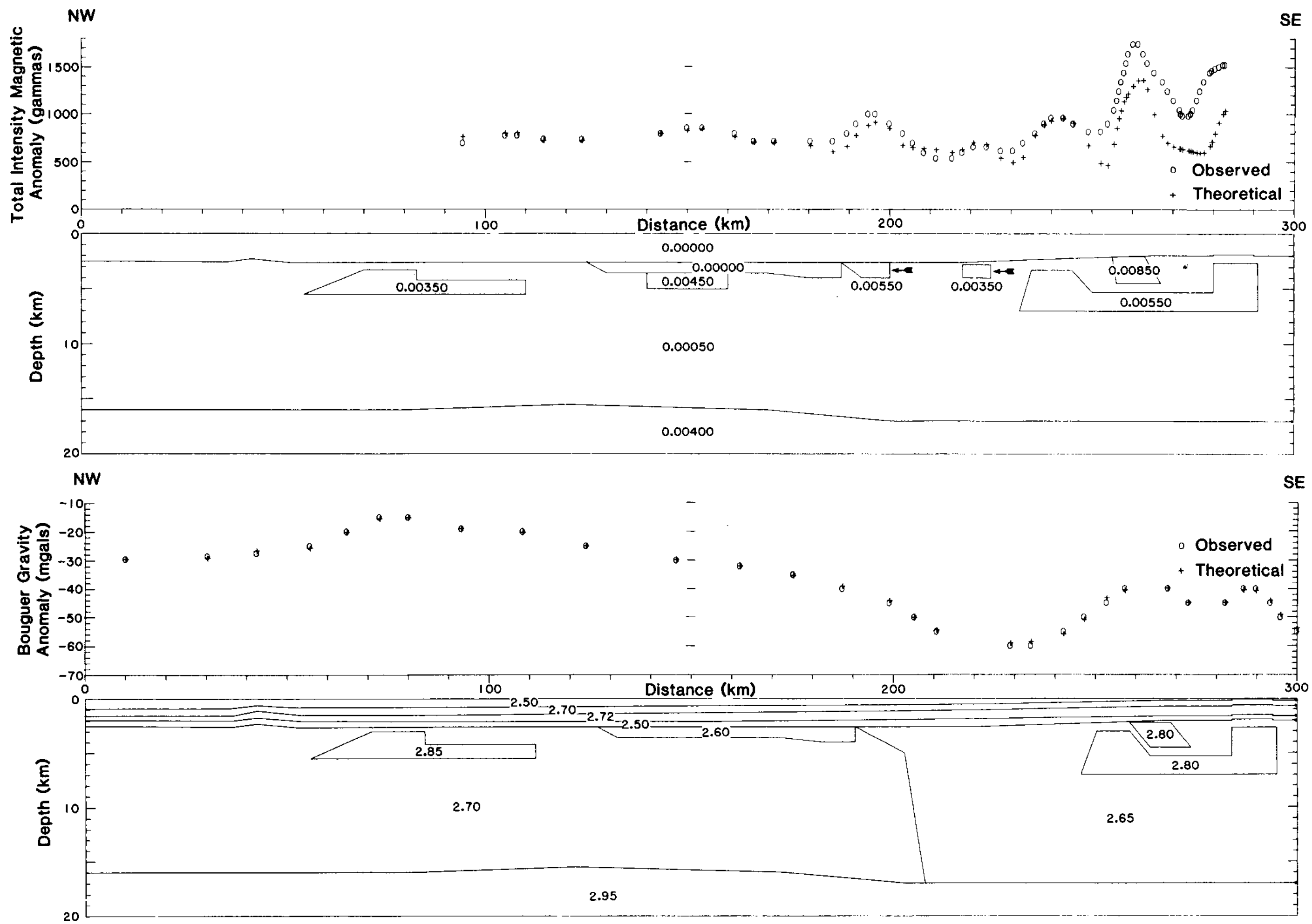


Figure 18. Profile C magnetic (top) and gravity (bottom) graben models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000 γ, declination - 0°, and inclination - 72°.

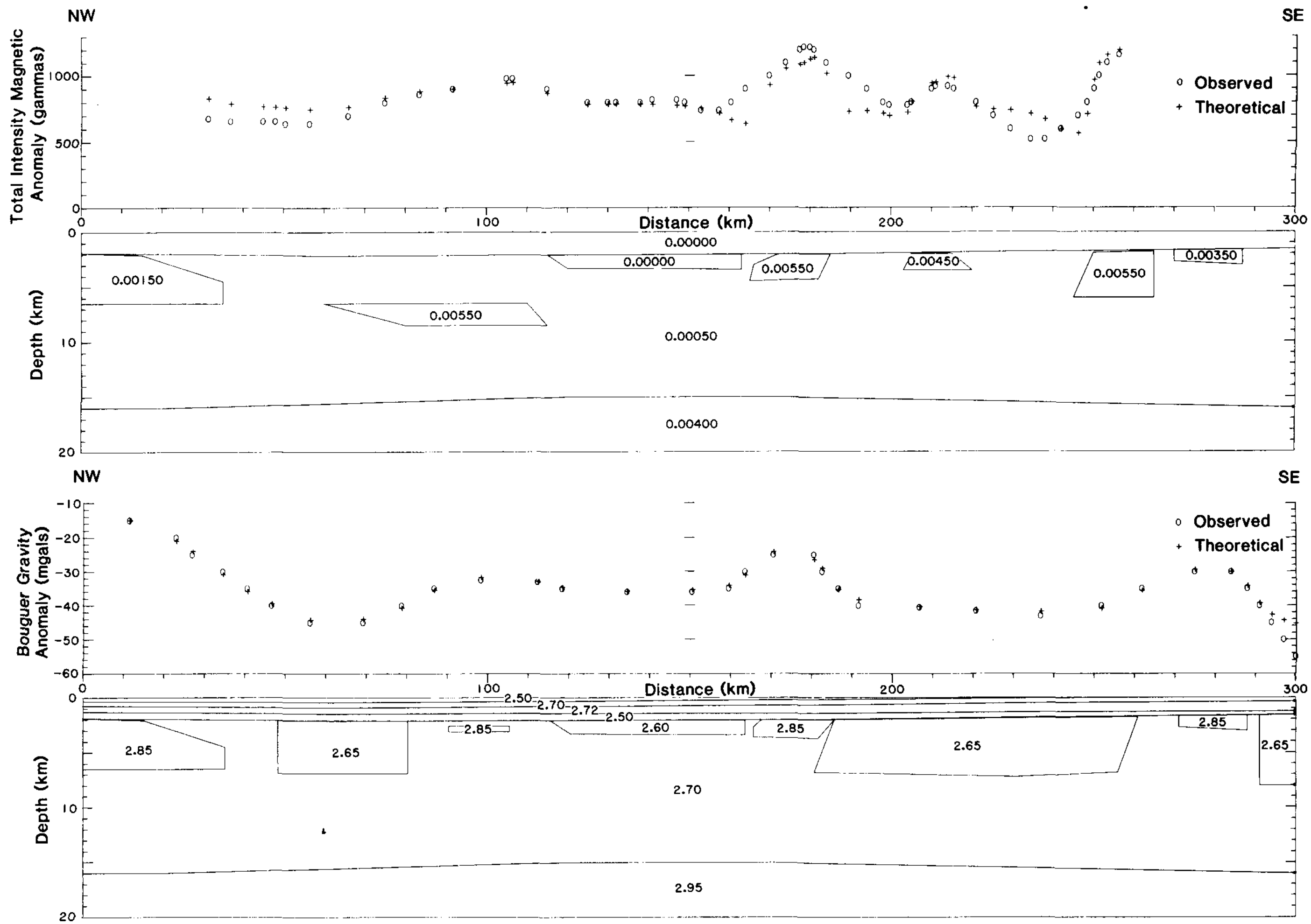


Figure 19. Profile D magnetic (top) and gravity (bottom) graben models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000γ, declination - 0°, and inclination - 72°.

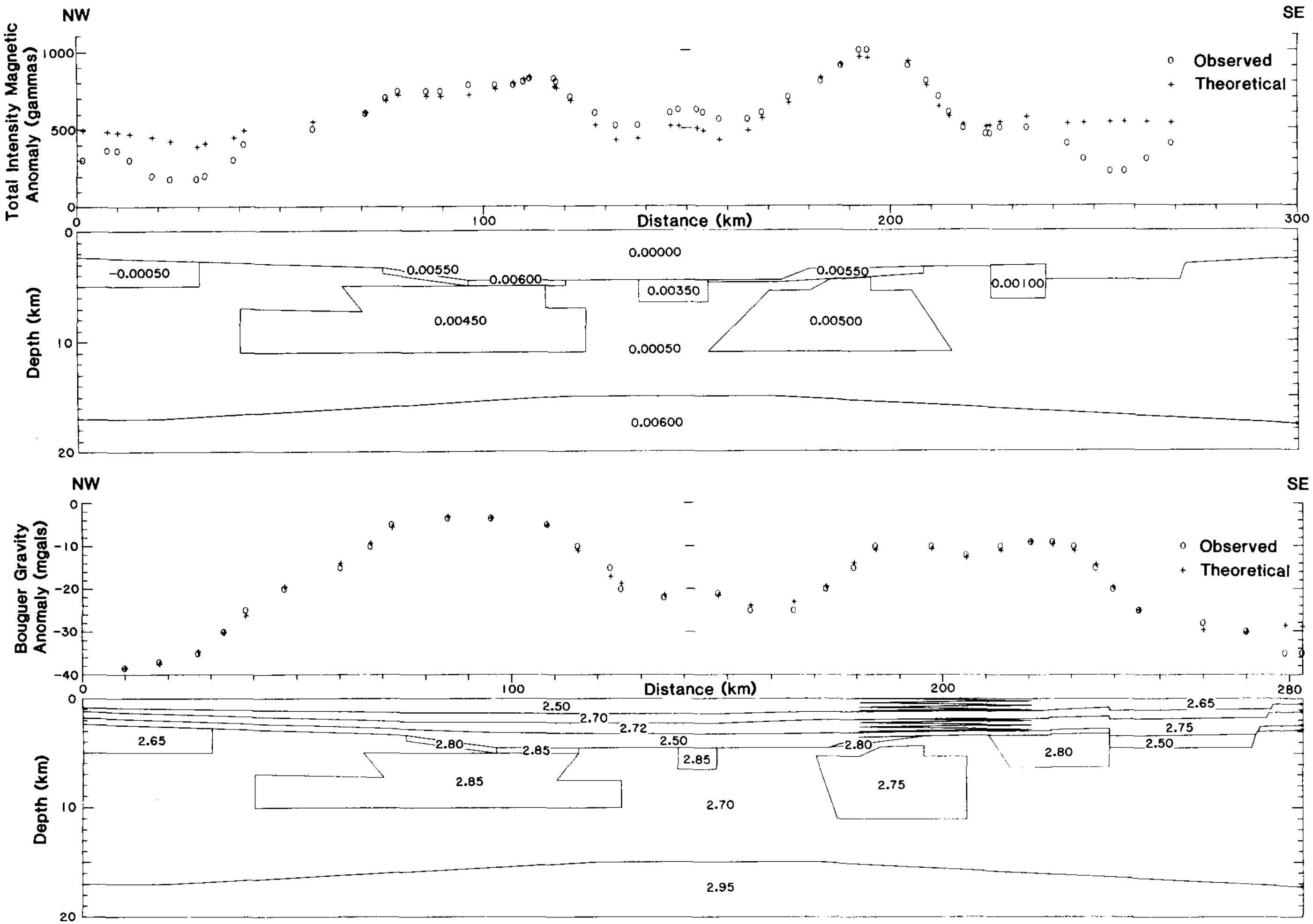


Figure 20. Profile A magnetic (top) and gravity (bottom) thick sedimentary rock models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000γ, declination - 0^o, and inclination - 72^o.

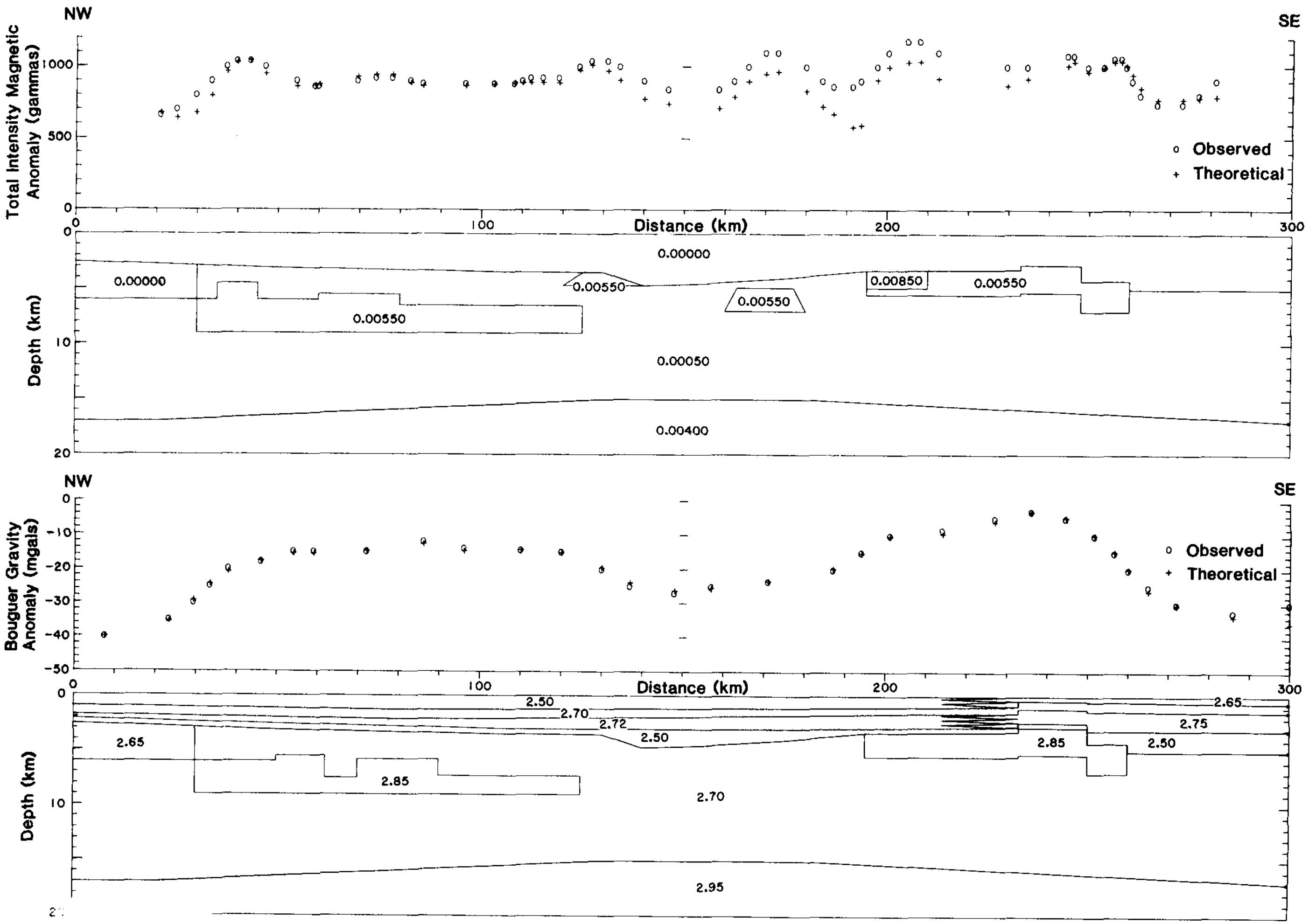


Figure 21. Profile B magnetic (top) and gravity (bottom) thick sedimentary rock models. Densities are measured in g/cm^3; suscetpibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000 γ, declination - 0°, and inclination - 72°.

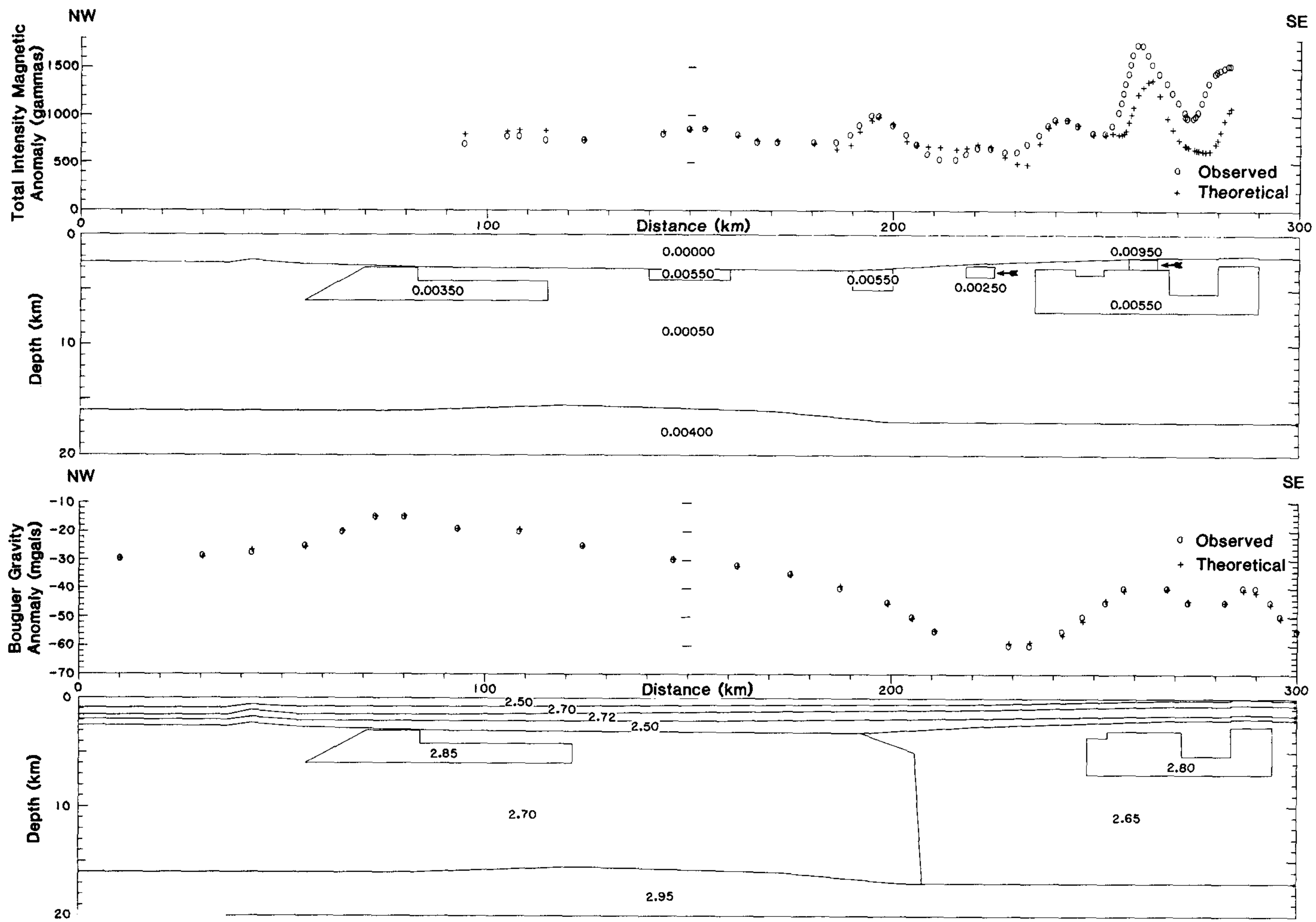


Figure 22. Profile C magnetic (top) and gravity (bottom) thick sedimentary rock models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000γ, declination - 0^{o}, and inclination - 72^{o}.

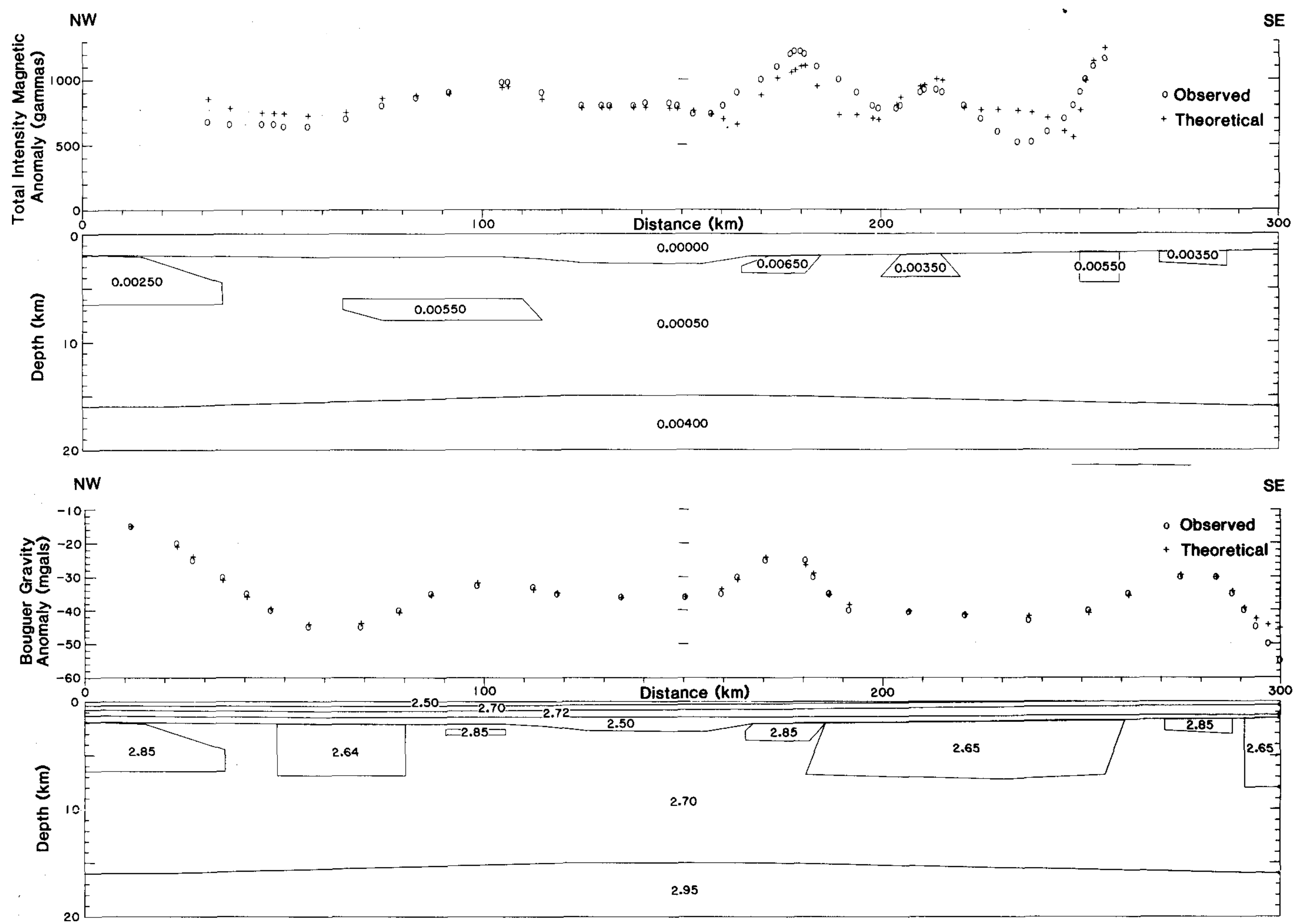


Figure 23. Profile D magnetic (top) and gravity (bottom) thick sedimentary rock models. Densities are mearured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000γ, declinatinn - 0^o, and inclination - 72^o.

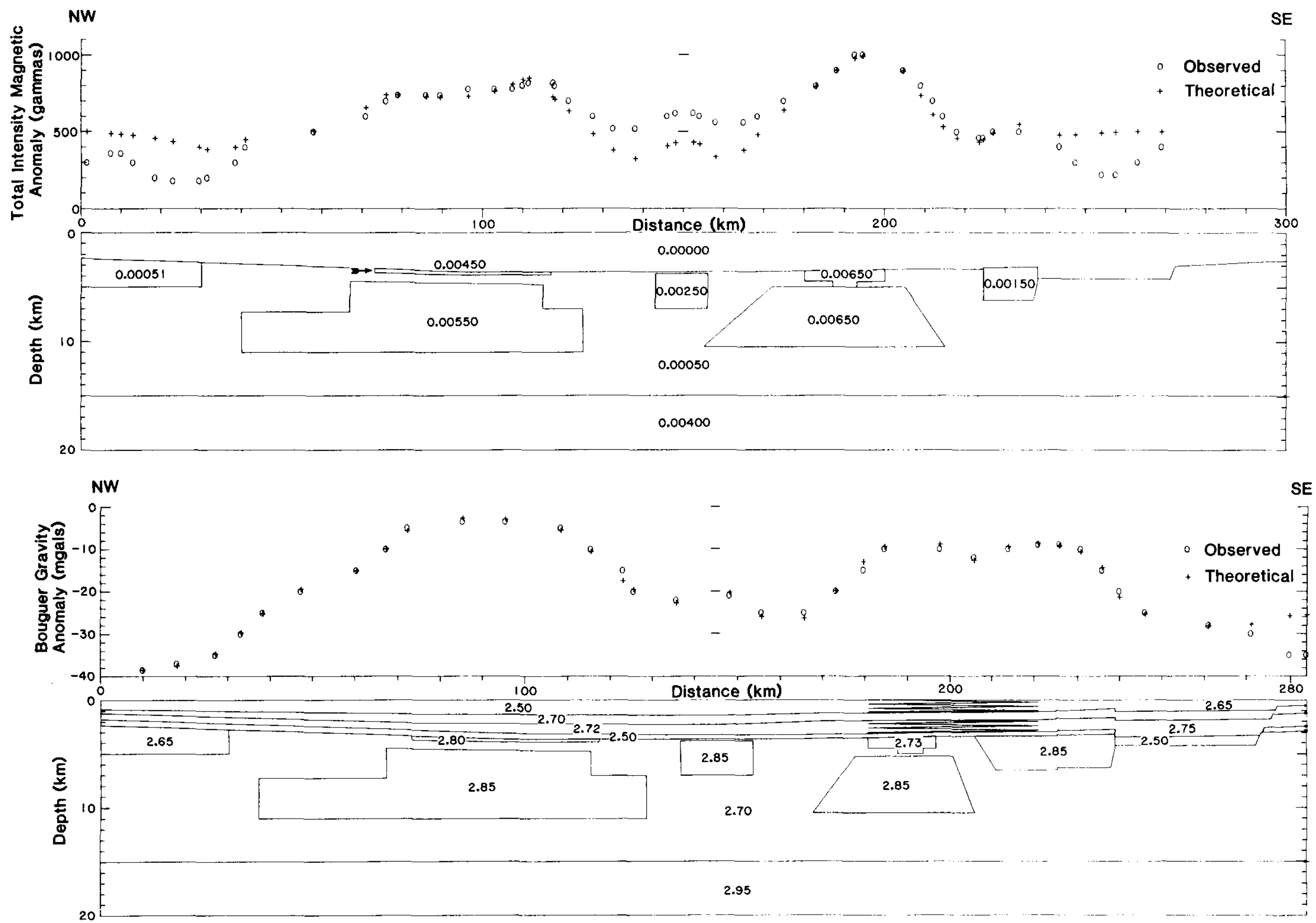


Figure 24. Profile A magnetic (top) and gravity (bottom) intrabasement intrusive models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000γ, declination - 0°, and inclination - 72°.

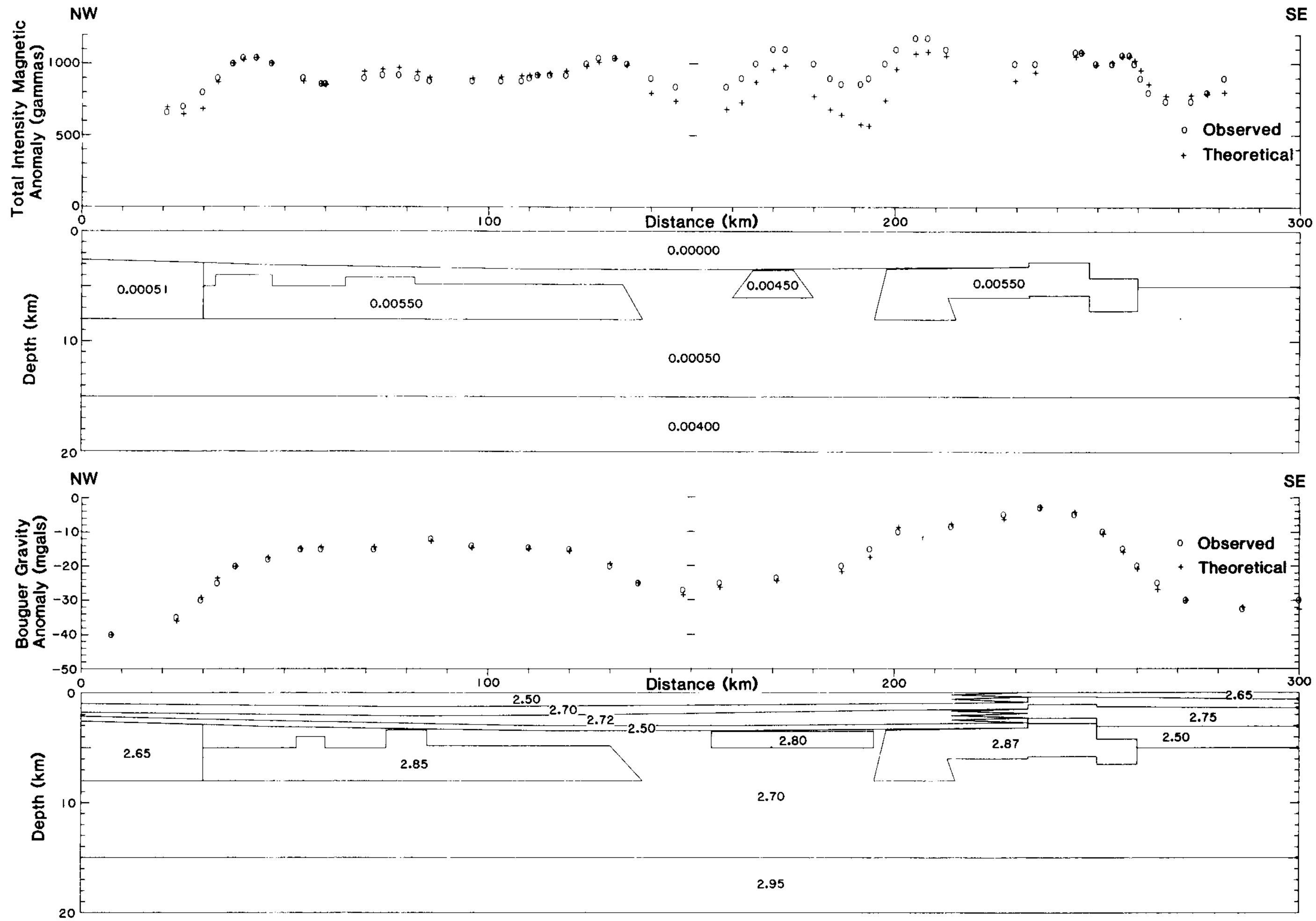


Figure 25. Profile B magnetic (top) and gravity (bottom) intrabasement intrusive models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000γ, declination - 0^{o}, and inclination - 72^{o}.

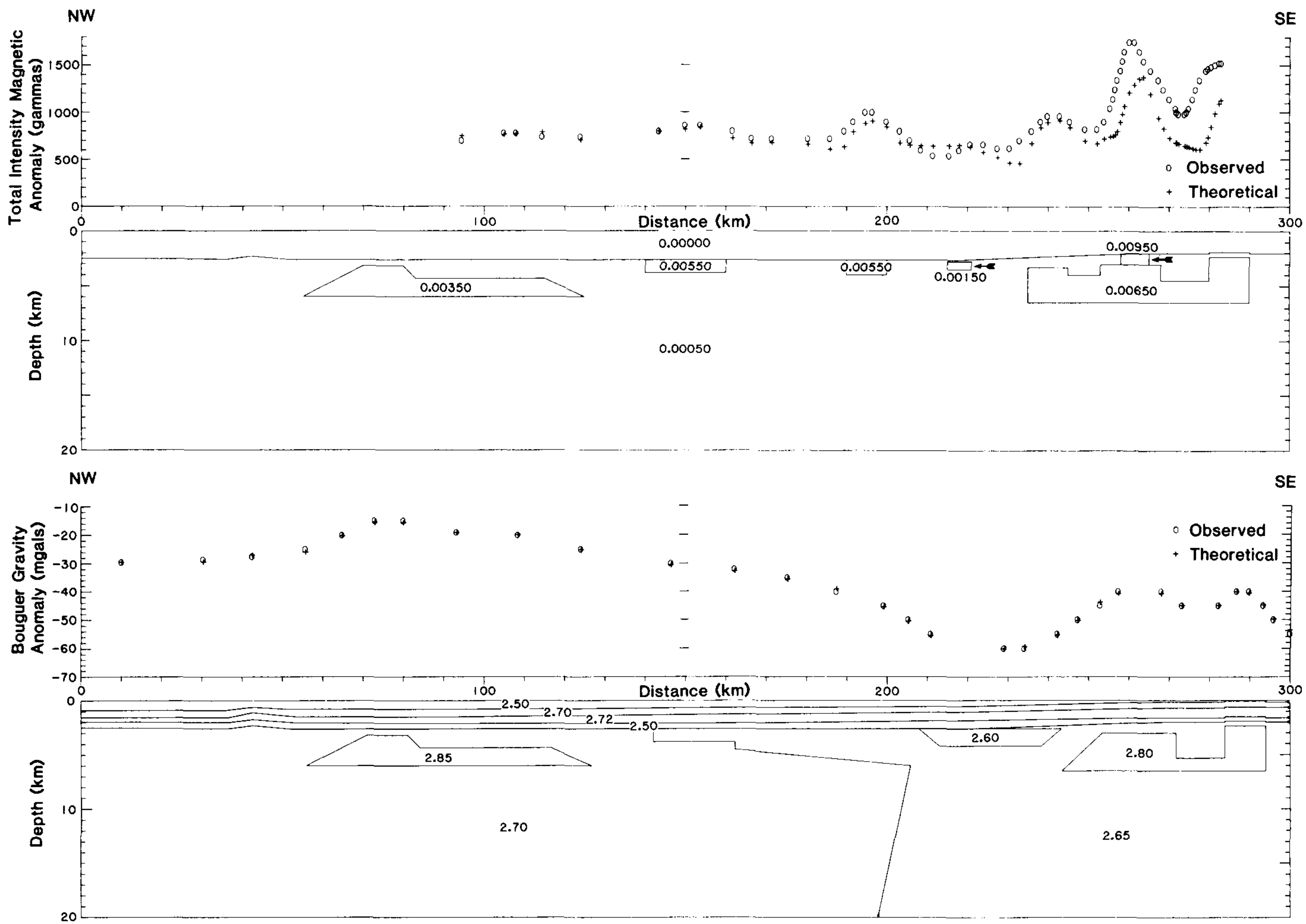


Figure 26. Profile C magnetic (top) and gravity (bottom) intrabasement intrusive models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000γ, declination - 0°, and inclination - 72°.

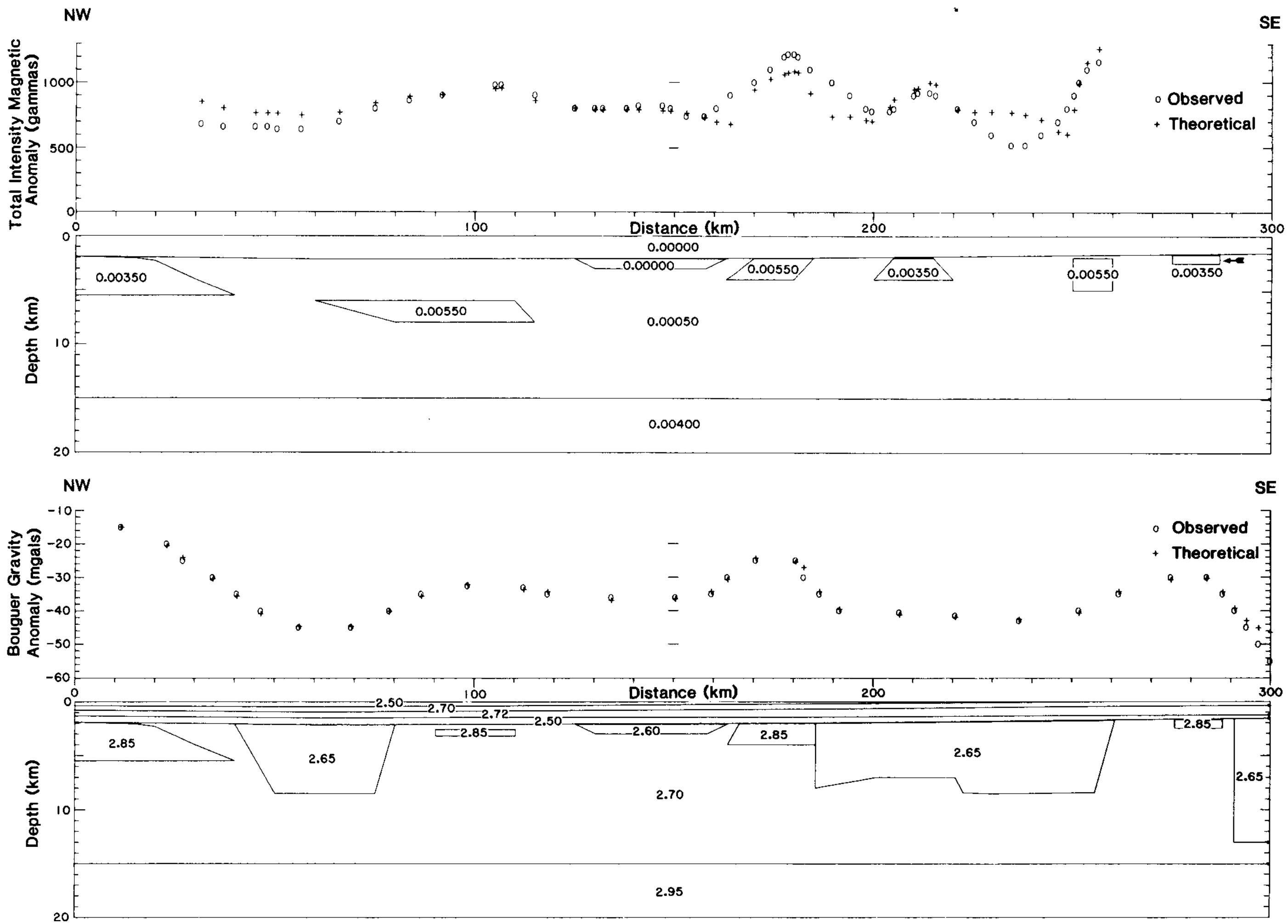


Figure 27. Profile D magnetic (top) and gravity (bottom) intrabasement intrusive models. Densities are measured in g/cm^3; susceptibilities are measured in emu/cm^3. Magnetic parameters are: total field - 57,000γ, declination - 0^{o}, and inclination - 72^{o}.

but this zone is unnecessary if the intrabasement intrusive model is assumed. 4) A variety of contrasting anomalous upper crustal bodies lie between the two positive anomaly zones, suggesting complex geologic relationships. 5) The regions of less than -40 mGal gravity anomalies appear to be related to a decrease in crustal density and a possible thickening of the upper crust.

The ambiguity of potential field data prevent discrimination between the three tectonic models posed in Figure 15, but modeling suggests a low density upper crustal feature associated with the northeast arm of the New Madrid Rift Complex flanked by high density/high magnetization zones (Fig. 28). Further refinement of the modeling will be based on constraints imposed by the interpretation of the seismic reflection data obtained in the Wabash River Valley area.

THE ANNA, OHIO SEISMIC AREA

The preliminary nature of the seismo-tectonic investigations in the Anna, Ohio area makes any interpretive discussion of the present investigation of this area highly tentative, bordering on the speculative. However, the lack of a viable mechanism for the neotectonism of the area is in contradiction to other seismic areas of the midcontinent and the available data suggest interesting structural relationships which provide working tectonic hypotheses worthy of continued investigation. It is no longer necessary to accept without question the suggestion that the Anna area seismicity is an isolated occurrence without structural control.

Basement geology (Figs. 5 and 6) and geophysical data (Figs. 9, 10, 11, and 13) testify to the variability of the Precambrian upper crust and the complexity of its geological history. The position of the Grenville Front south of Michigan has been the subject of considerable speculation (e.g., McLaughlin, 1954; Rudman et al., 1965), but recent geologic studies

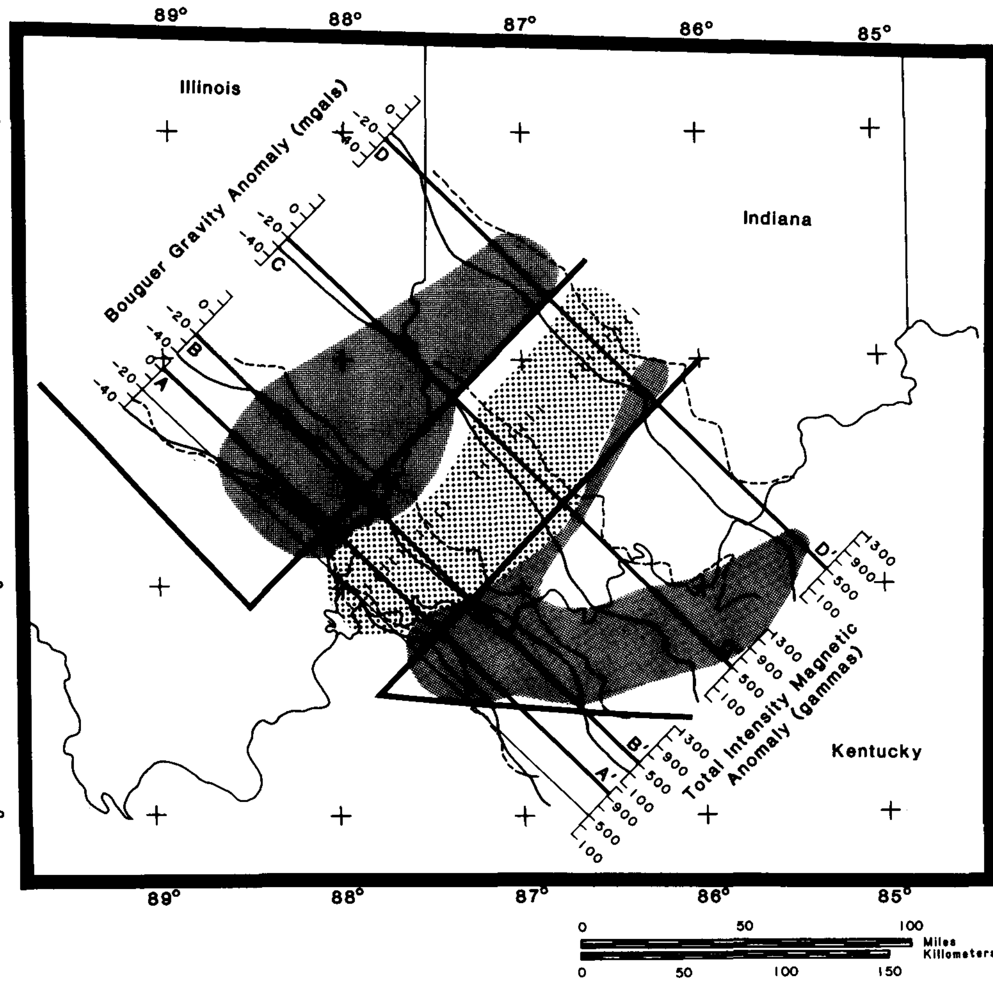


Figure 28. Overlay of areas of modeled high density/ high susceptibility (shaded region) and low density (dotted region) bodies from the graben models. The quadruple-junction boundaries are expressed by the thick lines.

of the basement rocks sampled in deep drill holes suggest a location in western Ohio as discussed previously. Tentatively, this interpretation is supported by the regional gravity and magnetic anomaly data. O'Hara and Hinze (1980) have mapped the location of the Grenville Front in Lake Huron on the basis of a marginal gravity high and a related positive magnetic anomaly which is bordered within the Grenville Province by a broad regional minimum. The positive gravity anomalies along the eastern margin of the Grenville Front in the Canadian Shield are indicated in Figure 29 together with a series of disconnected positives which appear to mark the sub-Phanerozoic extension of the Grenville Front into western Ohio. By analogy with the area in Canada where these sources outcrop, the positive anomalies originate from a mafic complex of high-grade metamorphic rocks. It is also significant to note that the gravity anomalies have a considerably different character east and west of the Grenville Front. The gravity anomalies west of the Front are dominated by linear features, while to the east in Ontario, eastern Ohio, western New York, and Pennsylvania the anomalies are more equidimensional and the gradients are subdued. Farther east, the northeast-trending Appalachian trends predominate. Similarly, the regional magnetic anomaly pattern supports the interpretation that the Grenville Front extends north-south across western Ohio. Relative positive and negative magnetic anomalies related to the Front in Canada and their possible extension to the south are interpreted on Figure 30. They indicate a western Ohio location for this major tectonic feature along and immediately east of the Front the magnetic anomalies are generally parallel to the feature. Further to the east, they exhibit a complex, alternating, equidimensional, positive-negative anomaly ('birdseye') pattern. West of the Front the magnetic anomalies are more linear and exhibit a markedly different strike than those observed to the east.

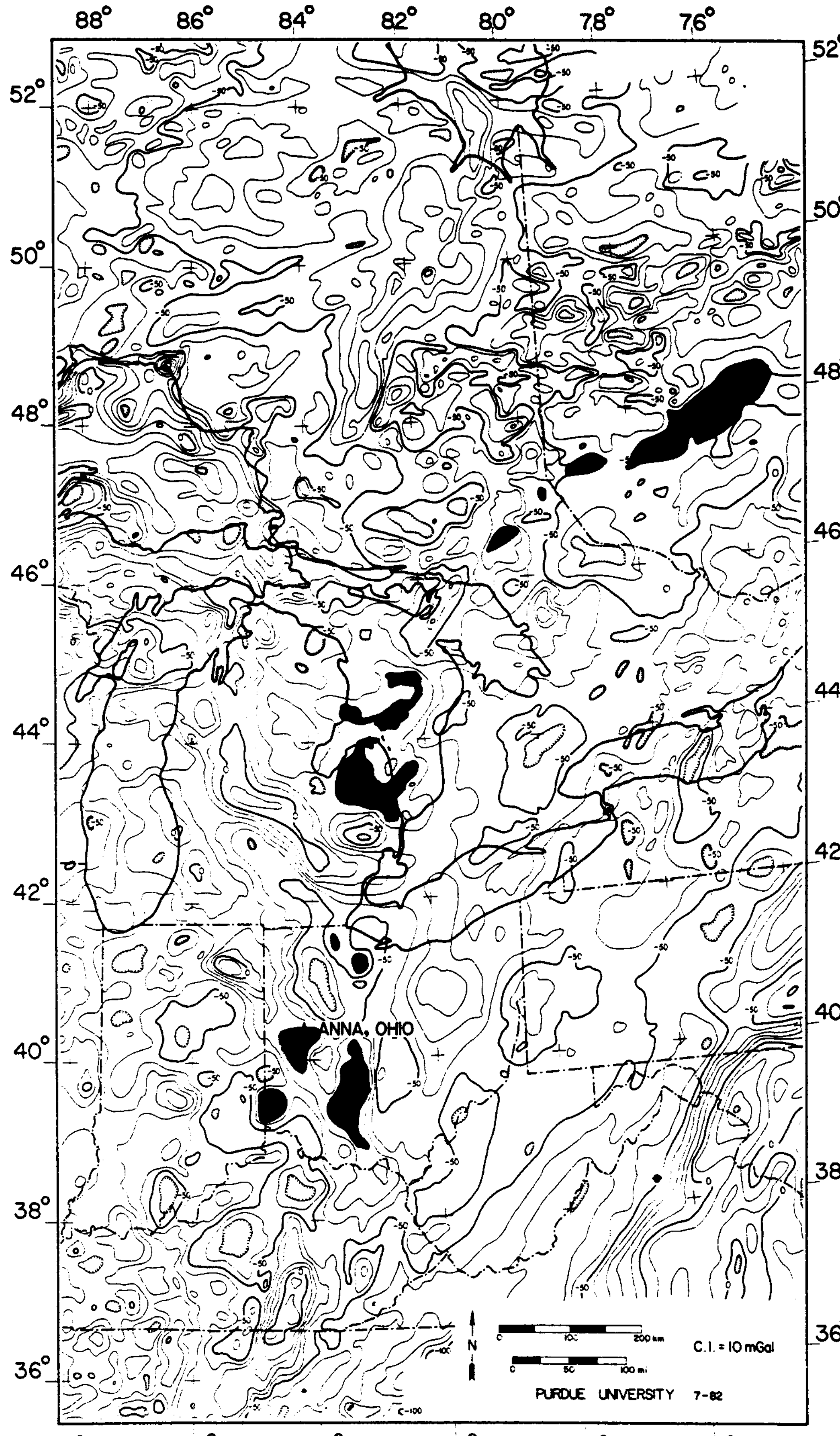


Figure 29. Simple Bouguer gravity anomaly map of the greater Anna, Ohio region with interpreted positive gravity anomalies along the Grenville Front indicated in solid black.

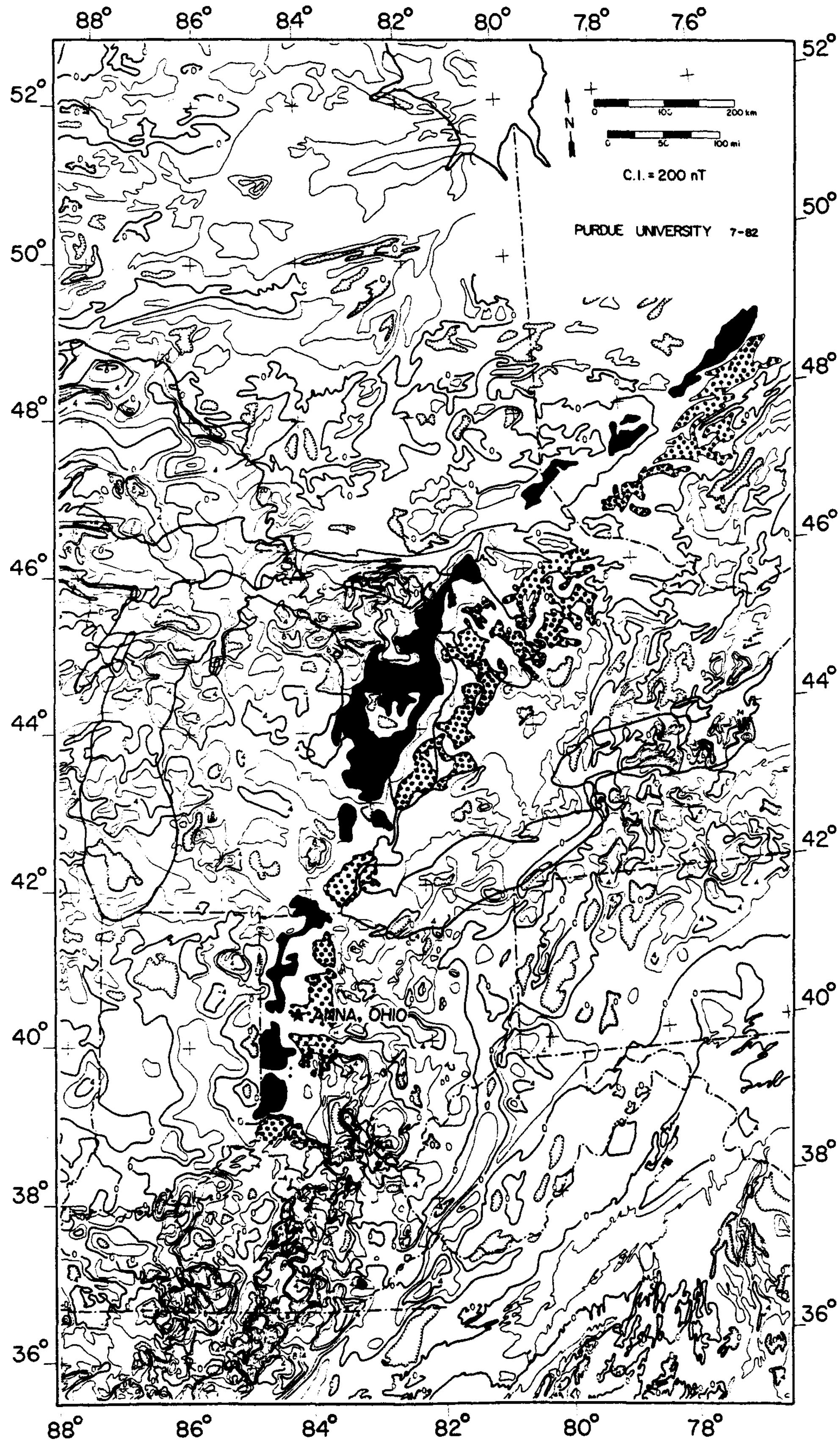


Figure 30. Aeromagnetic anomaly map of the greater Anna, Ohio region with interpreted positive (solid black) and negative (dotted pattern) magnetic anomalies along the Grenville Front.

Another feature which intersects the Anna area is evident in Figure 9. A broad regional Bouguer positive gravity anomaly strikes southeast from central Lake Michigan across southwestern Michigan, northeastern Indiana into the Anna area. This anomaly which reaches absolute amplitudes in excess of zero milligals is correlated with a series of intense magnetic anomalies which directly correspond to the highest amplitude/gradient gravity anomalies. This feature has been interpreted by Hinze et al. (1975) as originating from a rift zone subparallel to the Midcontinent Rift System in Michigan which did not develop as extensively as the principal segments of the rift system. Rather, the lower crust of the area was pervasively intruded by upper mantle material which today is reflected in the broad regional gravity high. The local gravity and magnetic anomalies along its trend indicate the limited areas where the differentiating upper mantle reached into the upper crust. Evidence for this interpretation is present in the form of volcanic rocks encountered locally in the basement drill holes of the region. The age of this feature is unknown, but by analogy with the Midcontinent Rift Complex, it is dated as Keweenawan. However, its origins could date as far back as the volcanism dated at 1.5 b.y. ago which is the age of the Central Province felsic terrane.

A third feature which may intersect the Anna seismic region is the extension of the northeast arm of the New Madrid Rift Complex. The possible connection between the Anna and New Madrid seismicity areas has been the focus of considerable speculation (e.g., McLaughlin, 1954; Woollard, 1958), but little evidence has been presented. A major focus of the present research is to search out evidence for this possible connection. None is available from the bedrock Phanerozoic rocks or their structure, but it is interesting to note that the Fortville Fault extends northeast along the extension of this arm of the New Madrid Rift Complex (Fig. 31) and the Anna seismic region occurs along the southeast margin of the

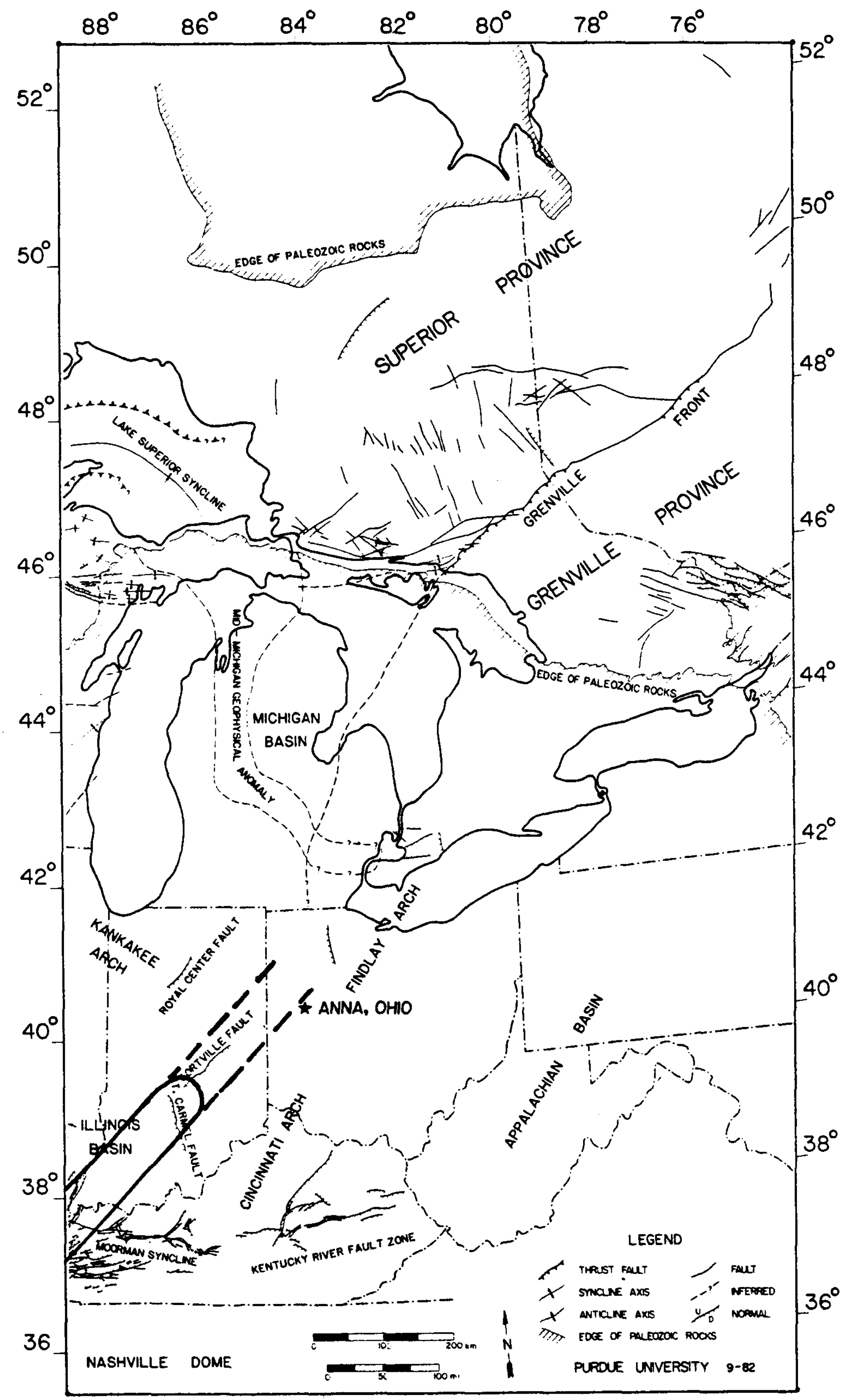


Figure 31. Simplified map of the major structural features showing the Northeast Arm of the New Madrid Rift Complex and its extension to the northeast.

northeast arm. It is clear that the gravity and magnetic anomaly pattern (Figs. 9 and 10) is not an obvious extension of the anomalies observed over the New Madrid Rift Complex (Braile et al., 1982a). However, the extension of the feature manifested in a more subtle anomaly pattern remains a possibility that will be investigated by a variety of derived enhancement maps. The potential utility of these maps is indicated in Figure 32 which is a map of the gravity anomaly pattern obtained by removing all anomaly wavelengths greater than 250 km (Hildenbrand et al., 1982a). It is worthy to note that a minor, but nonetheless obvious, gravity positive anomaly extends northeast from the limit of the presently mapped northeast arm into the Anna area. The margins of this anomaly are straight, northeast-trending linear segments which appear to be fault controlled.

Thus, it is possible that three major tectonic features intersect in the Anna, Ohio seismic region resulting in a zone of weakness which could be reactivated under the present stress regime. Furthermore, these tectonic regimes produce a complex basement lithologic regime as evidenced in the magnetic anomaly map of the Anna, Ohio area with the drillhole basement lithology (Fig. 33) superimposed. The earthquake epicenters superimposed on the gravity anomaly (Fig. 34) and magnetic anomaly (Fig. 35) maps show a random distribution of epicenters with a concentration along the southern margin of and within a broad gravity and magnetic minimum and associated with a local gravity and magnetic anomaly high located immediately northwest of 41°N, 83°W. The occurrence of epicenters along the margins of the anomalies opens up the possibility of block tectonics as the control on the seismicity. McGinnis and Ervin (1974) have speculated that the earthquakes in Illinois are localized along the margins of basement blocks which are reflected in the potential field anomaly patterns. A similar control may be in effect in Ohio. This hypothesis will be investigated in future studies.

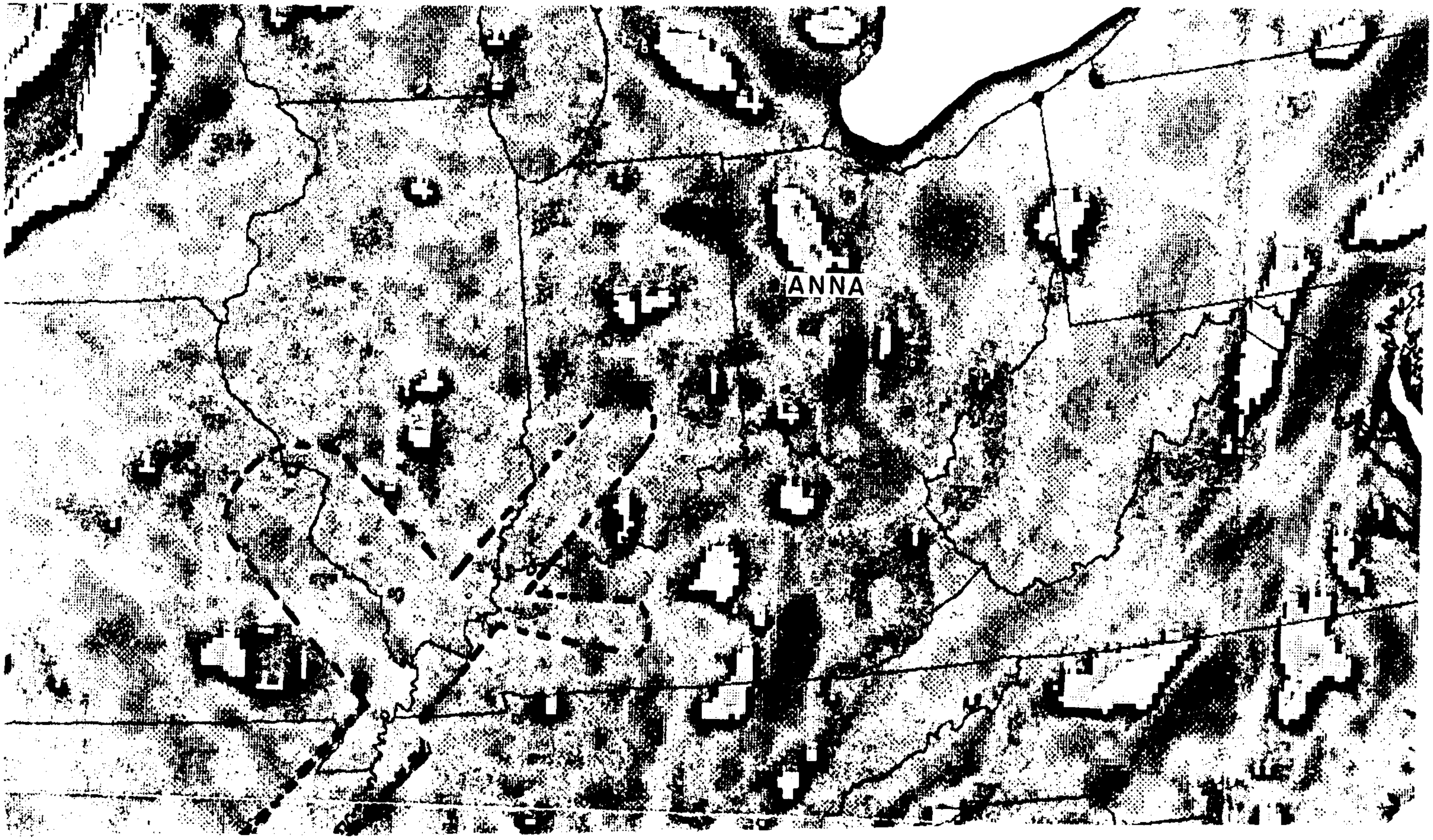


Figure 32. Photocopy of colored filtered gravity map which excludes all wavelengths greater than 250 km (after Hildenbrand et al., 1982) and position of New Madrid Rift Complex (white areas are minima).

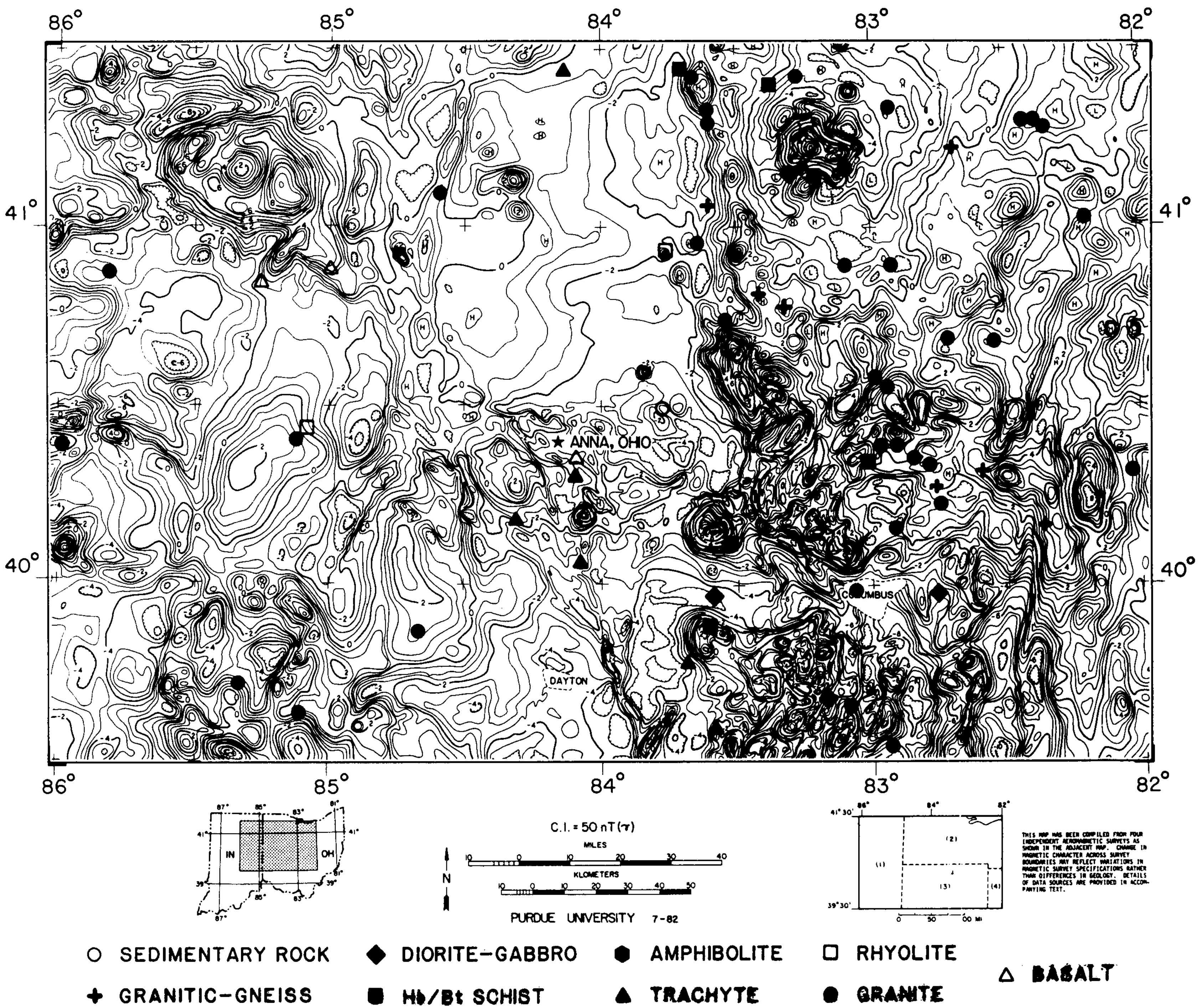


Figure 33. Composite aeromagnetic anomaly map of the Anna, Ohio area with basement drillhole lithologies.

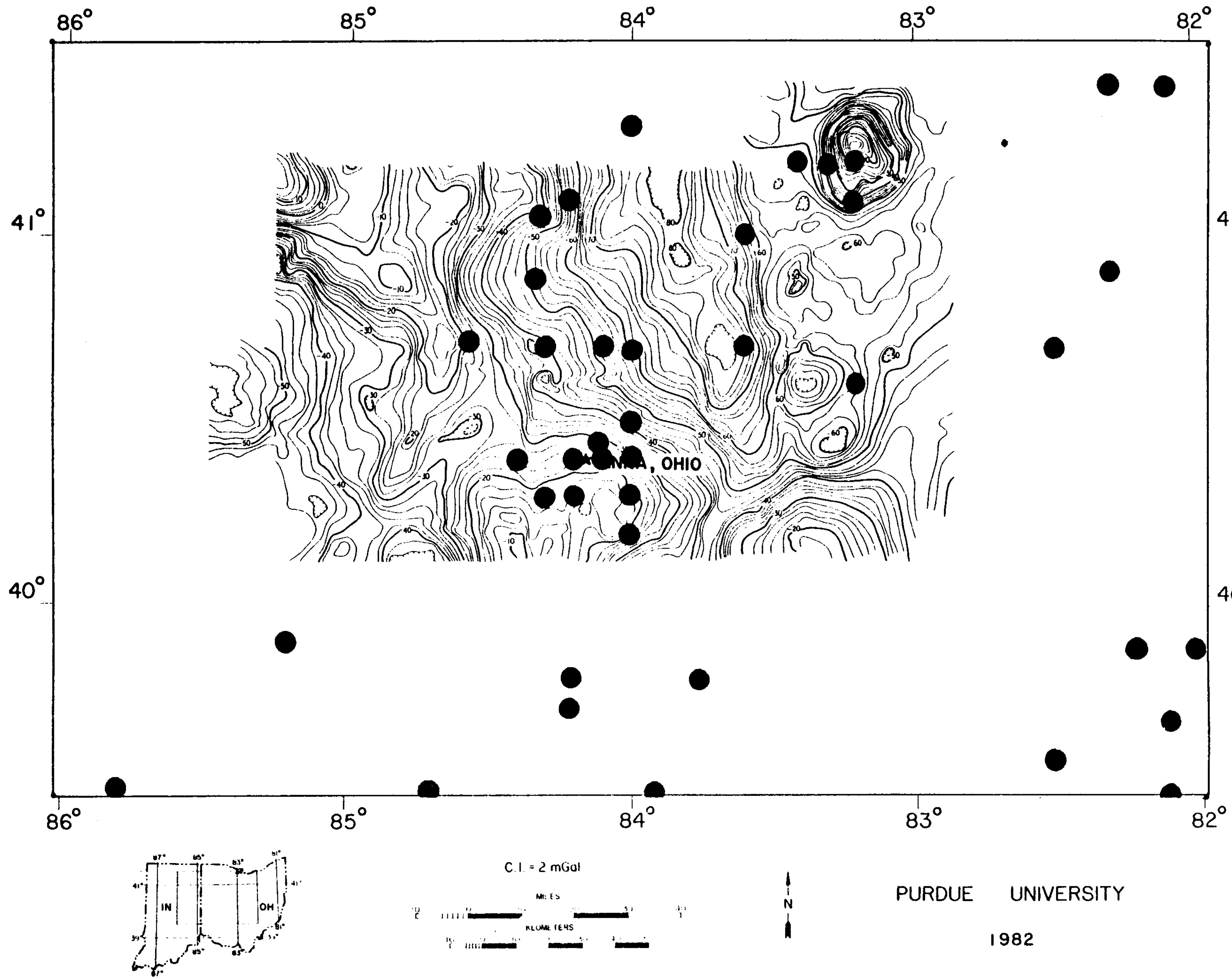


Figure 34. Simple Bouguer gravity anomaly map of the Anna, Ohio area with earthquake epicenters.

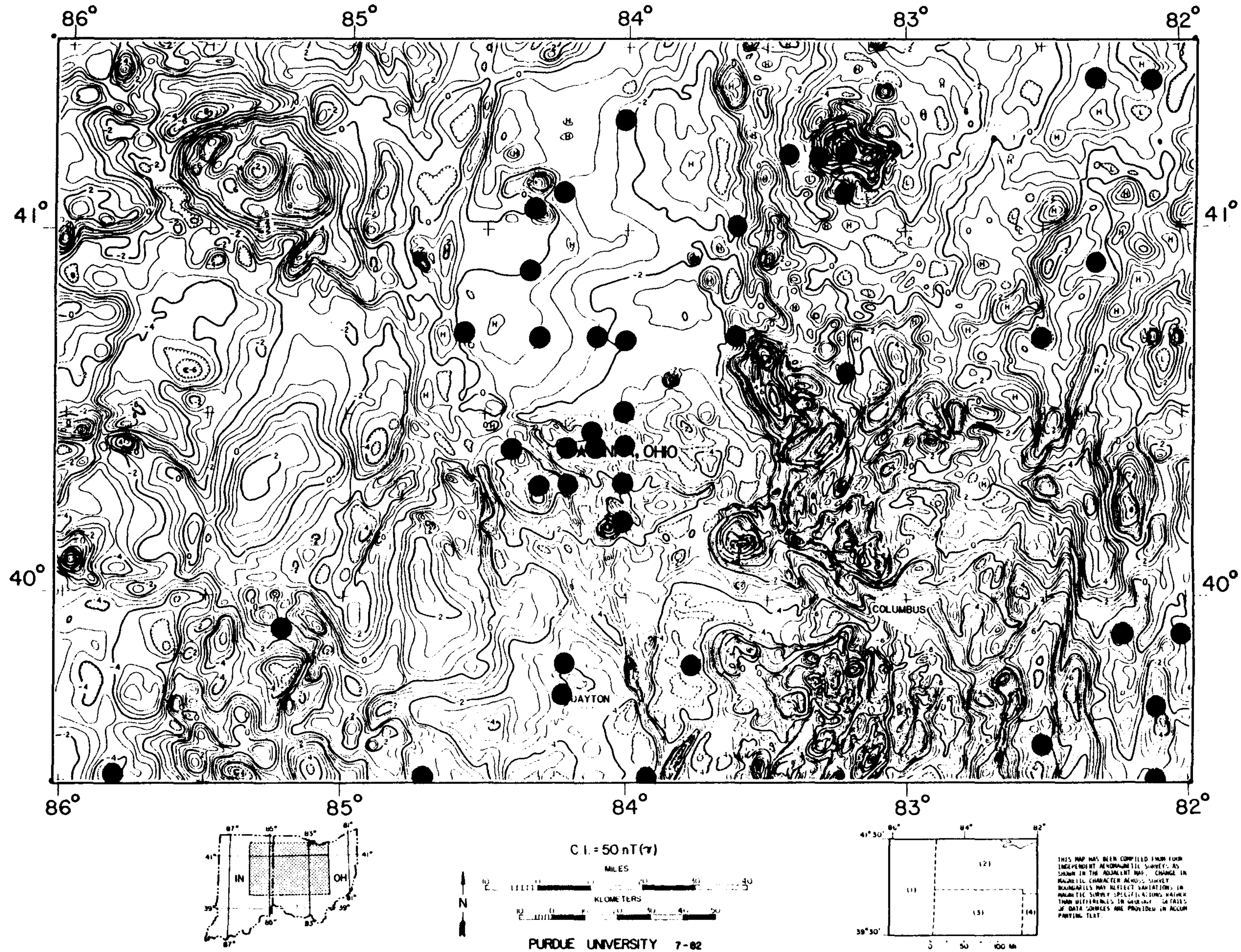


Figure 35. Composite magnetic anomaly map of the Anna, Ohio area with earthquake epicenters.

References

Barstow, N.L., K.G. Brill, Jr., O.W. Nuttli, and P.W. Pomeroy, An approach to seismic zonation for siting nuclear electric power generating facilities in the eastern United States, NUREG/CR-1577, 143 p., 1981.

Braile, L.W., G.R. Keller, W.J. Hinze, and E.G. Lidiak, An ancient rift complex and its relation to contemporary seismicity in the New Madrid Seismic Zone, Tectonics, 1, 225-237, 1982a.

Braile, L.W., W.J. Hinze, J.L. Sexton, G.R. Keller, and E.G. Lidiak, Seismicity and tectonics of the midcontinent United States, Proceedings 3rd International Conference on Microzonation, in press, 1982b.

Dames and Moore, Interpretation of mechanism for the Anna, Ohio Earthquakes for the Marble Hill generating station, Public Service Indiana: Dames & Moore report, John S. Trapp, Project Geologist, 1975.

Hadley, J.B., and J.F. Devine, Seismotectonic map of the eastern United States, U.S. Geol. Surv. Map MF-620, 1974.

Hildenbrand, T.G., M.F. Kane, and W. Stauder, S.J., Magnetic and gravity anomalies in the northern Mississippi Embayment and their spatial reation to seismicity, U.S. Geol. Surv. Map MF-914, 1977.

Hildenbrand, T.G., R.W. Simpson, R.H. Godson, and M.F. Kane, Digital colored residual and regional Bouguer gravity maps of the conterminous United States with cut-off wavelengths of 250 km and 1000 km, U.S. Geol. Surv. Map GP-953-A, 1982.

Hinze, W.J., R.L. Kellogg and N.W. O'Hara, Geophysical studies of basement geology of Southern Peninsula of Michigan, Am. Assoc. Petroleum Geologists Bull., 59, 1562-1584, 1975.

Hinze, W.J., L.W. Braile, G.R. Keller, and E.G. Lidiak, A tectonic overview of the central midcontinent, U.S. Nuclear Regulatory Commission Report NUREG/CR-0382 (RGA), 106 p., 1977.

Hinze, W.J., L.W. Braile, G.R. Keller, and E.G. Lidiak, Models for midcontinent tectonism: in "Continental Tectonics", National Academy of Science/National Research Council, Spec. Publ. Series "Studies in Geophysics", p. 73-80, 1980.

Jackson, P.L., D.H. Christensen, and F.H. Mauck, Geophysical investigation of the Western Ohio-Indiana Region, Final Report, NUREG/CR-2484, 41 p., 1982.

Johnson, R.W., C. Haygood, W.J. Hinze, T.G. Hildenbrand, and P.M. Kunselman, Aeromagnetic map of the East-Central Midcontinent of the U.S., U.S. Nuclear Regulatory Commission Report NUREG/CR-1662, 12 p., 1980.

Keller, G.R., D.R. Russell, W.J. Hinze, J.E. Reed, and P.J. Geraci, Bouguer gravity anomaly map of the East-Central Midcontinent of the U.S., U.S. Nuclear Regulatory Commission Report NUREG/CR-1663, 12 p., 1980.

Kersting, J.J., The petrology and petrography of the Mt. Simon and pre-Mt. Simon Sandstones: Evidence for possible Precambrian rifting in the central midcontinent, Unpub. M.S. Thesis, Univ. of Pittsburgh, 179 p., 1982.

Kisslinger, Carl, Evaluation of S to P amplitude ratios for determining focal mechanisms from regional network observations, Bull. Seis. Soc. of Am., 70, 999-1014, 1980.

Kisslinger, C., J.R. Bowman, and K. Koch, Procedures for computing focal mechanisms from local $(SV/P)_z$ data, Bull. Seis. Soc. of Am., 71, 1719-1729, 1981.

Lidiak, E.G., and W.J. Hinze, Pre-Upper Cambrian sedimentary rocks of the northern midcontinent, (EOS) Trans. Am. Geophys. Un., 61, 1980.

McGinnis, L.D., and P.C. Ervin, Earthquake and block tectonics in the Illinois Basin, Geology, 2, 517-519, 1974.

McLaughlin, D.B., Suggested extension of the Grenville orogenic belt and the Grenville Front, Science, 120, 287-289, 1954.

O'Hara, N.W., and W.J. Hinze, Regional basement geology of Lake Huron, Geol. Soc. Am. Bull., 91, 348-358, 1980.

O'Hara, N.W., Great Lakes Area. Great Lakes Region - Bouguer Gravity Map, Great Lakes Region - Total Magnetic Intensity Map, and Great Lakes Region - Free-air Gravity Map, Geol. Soc. of Am. Map Series MC-41, 1:2,500,000 scale, 1981.

Pawlowicz, E.F., Earthquake statistics for Ohio, Ohio Jour. Science, 75, 103-111, 1975.

Peregrine, K.A., Potential field enhancement and two-dimensional gravity and magnetic modeling of the northwest extension of the New Madrid Tectonic Feature, Unpub. M.S. Thesis, Purdue Univ., 217 p., 1982.

Rudman, A.J., C.H. Summerson, and W.J. Hinze, Geology of basement in mid-western United States, Am. Assoc. Petroleum Geologists Bull., 49, 894-904, 1965.

Schwalb, H.R., Paleozoic geology of the New Madrid area, NUREG/CR-2909, 61 p., 1982.

Woollard, G.P., 1958, Areas of tectonic activity in the U.S. as indicated by earthquake epicenters, Trans. Am. Geophys. Un., 39, 1135-1150, 1958.

APPENDIX I

"The Role of Rifting in the Tectonic Development of the Midcontinent, USA"

abstract

Paper to be published in

Ttectonophysics (in press)

THE ROLE OF RIFTING IN THE TECTONIC DEVELOPMENT OF THE MIDCONTINENT, U.S.A.

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

ABSTRACT

Keller, G.R., Lidiak, E.G., Hinze, W.J. and Braile, L.W., 1983. The role of rifting in the tectonic development of the midcontinent, U.S.A. In: P. Morgan and B.H. Baker (Editors), Processes of Continental Rifting. *Tectonophysics,* 94. Paper published.

Recent studies have proposed the existence of several major ancient rift zones in the midcontinent region of North America. Although the dating of some of these rifts (and even the rift interpretations) are subject to question, an analysis of these "paleo-rifts" reveals three major episodes of rifting: Keweenawan (~1.1 b.y.B.P.), Eocambrian (~600 m.y.B.P.), and early Mesozoic (~200 m.y.B.P.). The extent of these events documents that rifting has played a major role in the tectonic development of the midcontinent region. This role goes well beyond the initial rifting event because these features display a strong correlation with Paleozoic basins and a strong propensity for reactivation. For example, the Eocambrian Reelfoot rift was reactivated in the Mesozoic to form the Mississippi embayment and is the site of modern seismicity which suggests reactivation in a contemporary stress field of ENE compression. Even though the importance of rifting can be established, recognition of rifts and delineation of their complexities remain a major problem which requires more study.

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APPENDIX II

"Evidence for a Major Late Precambrian Tectonic Event (Rifting?) in the Eastern Midcontinent U.S."

abstract

Paper published in

Tectonics, v. 1, no. 2, April 1982, p. 213-223

EVIDENCE FOR A MAJOR LATE PRECAMBRIAN TECTONIC EVENT (RIFTING?) IN THE EASTERN MIDCONTINENT REGION, UNITED STATES

G.R. Keller[1], A.E. Bland[2] and J.K. Greenberg[3]

ABSTRACT

Recently acquired gravity and aeromagnetic data delineate a large linear gravity anomaly which extends through eastern Kentucky and Tennessee and coincides with a zone of complex, high-amplitude magnetic anomalies. Basement lithologies in the area can be interpreted as a bimodal volcanic suite which is locally peralkaline in nature. These volcanics appear to be metamorphosed where they lie east of the Grenville front, suggesting they predate the Grenville metamorphic event. The available gravity, aeromagnetic, seismic refraction, and petrologic data, along with regional correlations, suggest that the best tectonic interpretation of these data is that a Keweenawan rift zone extended through the area. This rift can be roughly outlined by the gravity high, which is locally offset, suggesting the presence of transform faults. The boundaries of this rift have been locally reactivated and, in fact, a recent earthquake was located along its western boundary in northern Kentucky.

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APPENDIX III

'Geologic Significance of Regional Gravity
and Magnetic Anomalies in the East-Central Midcontinent'

an expanded abstract

GEOLOGIC SIGNIFICANCE OF REGIONAL GRAVITY AND MAGNETIC ANOMALIES IN THE EAST-CENTRAL MIDCONTINENT

by

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ABSTRACT

Recently compiled Bouguer gravity and magnetic anomaly maps of the east-central midcontinent covering the area approximately between 35°-39°N latitude and 82°-92°W longitude provide the opportunity to study the tectonic framework of the basement rocks which lie buried beneath generally low-dipping Phanerozoic sedimentary rocks. A variety of wavelength filters, including continuation, wavenumber, derivative, and directional filters, are useful in isolating and identifying particular attributes of anomalies associated with the basement rocks. These maps in conjunction with lithologic information and isotopic age dates obtained from the few widely distributed drill holes which reach the basement rocks are used to define four principal basement zones. The southeastern corner is marked by long, linear, northeast-striking anomalies which correlate with Appalachian Mountain structural trends. Immediately to the west are the more northerly trends of the subsurface continuation of the Grenville Province. West of the Grenville Front, which is poorly defined in Tennessee, lies the roughly 1500 Ma felsic basement rocks of the Central Province. A generally subtle, west-northwest pattern of anomalies pervades the Central Province probably due to a more ancient basement which underlies the felsic rocks. Transecting this region is a series of parallel, correlative gravity and magnetic anomalies which are interpreted to mark the margins of a late Precambrian rift complex centered over the confluence of the Mississippi and Ohio Rivers.

A critical element of the New Madrid Seismotectonic Study Program sponsored by the U.S. Nuclear Regulatory Commission is the investigation of the tectonic framework of the basement rocks of the east-central midcontinent. The identification of the tectonic elements of the basement rocks and in particular the potential zones of weakness is useful in characterizing potential earthquake hazards especially when combined with information on the prevailing stress field and seismicity of the region. To study the basement rocks, Bouguer gravity (Figure 1) and total intensity magnetic anomaly (Figure 2) maps have been prepared of Tennessee, Kentucky, and portions of adjoining states.

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Gravity observations were made in selected areas to supplement existing data coverage to obtain stations along existing roads at roughly a 2 km interval. The resulting file of approximately 50,000 gravity measurements tied to the IGSN-71 gravity datum were reduced to simple Bouguer anomaly values using a sea level datum, a reduction density of 2.67 gm/cc, and the 1967 theoretical gravity formula.

The total intensity magnetic anomaly map was compiled from 28 aeromagnetic surveys by visual comparison and manual adjustment of adjoining anomaly maps. The surveys were generally flown along roughly 2 km flight paths at a mean elevation above the surface of approximately 300 meters. The core derived magnetic field was removed from the observations by subtracting an appropriate, up-dated geomagnetic reference field. All data were adjusted upward by 1000 gammas (nT) to minimize the occurrence of negative contour values.

Both the gravity and magnetic observation data sets were gridded on a registered 2 km orthogonal array. This grid was used for hand contouring the gravity anomaly map, machine contouring the magnetic map, and wavenumber filtering both data sets. The magnetic anomaly data were reduced-to-pole to eliminate the effect of inclined induced magnetization, and both data sets were selectively band-passed, high-passed, and low-passed filtered, upward continued, and subject to derivative and strike-reject and strike-pass filtering to emphasize particular characteristics of the anomaly fields. An example of these filtered maps is shown in Figure 3 which was prepared by passing gravity anomaly wavelengths between roughly 8 to 100 kms. This map isolates the local gravity anomalies within the upper crust from the broad positive gravity anomaly over the Mississippi Embayment and the regional negative anomaly associated with the Appalachian Mountains. The filtered maps are primarily useful for qualitative analysis, in identifying and extending subtle anomalies through areas of complex and conflicting patterns, in isolating anomalies from either longer or shorter wavelength anomalies, and in modifying anomaly data to enhance the correlation of the gravity and magnetic anomaly fields.

The gravity anomaly map is dominated by a broad positive feature locally reaching absolute amplitudes in excess of +25 mGals associated with the Mississippi Embayment and negative values of less then -100 mGals related to the Appalachian Mountains. Upon removal of these long wavelength components of the gravity field, four basic anomaly patterns emerge (Figure 3). The interpretation of the geological significance of these patterns is assisted by lithologic information and isotopic age dates obtained from basement rock samples retrieved from the widely separated deep drill holes. Several basement geological provinces are evident in the gravity and associated magnetic anomalies.

Northeast striking elongate gravity and magnetic anomalies in the southeast corner of the map (Fig. 2,3) parallel the structural trends of the Appalachian Mountains. This pattern is terminated abruptly along a northeast line passing through Knoxville and Chattanooga, Tennessee. West of this line the major gravity anomalies are positive and strike roughly north-south. The magnetic anomalies associated with the positive gravity features exhibit a "birds-eye" pattern of intense positive amplitude. This zone is identified as a continuation of the roughly 1000 Ma Grenville Province which crops out in the Canadian Shield. The western margin of this province, (Figure 4) the Grenville Front, is placed along the western limit of the most prominent of the northerly striking anomalies with the aid of geologic information from basement drill hole samples. The intense gravity anomalies which occur along the Grenville Front are interpreted as originating from metamorphosed mafic igneous rocks that may be a relic of a rift system extending south from Ohio into Kentucky and Tennessee. West of the Grenville Front, the basement consists largely of felsic rocks of the roughly 1500 Ma Central Province. Sporadic basalts occur within this granite/rhyolite terrane.

A west-northwest pattern of gravity and magnetic anomalies pervade the Central Province. Generally this pattern is rather subtle, but a major anomaly having this trend strikes across the southern tip of Illinois into Missouri as well as into Kentucky and on into Tennessee. This pattern of anomalies may reflect petrologic variations in a more ancient basement which underlies the felsic rocks of the Central Province. Transecting this province is a series of parallel, northeast-striking correlative gravity and magnetic anomalies which are interpreted to mark the margins of a late Precambrian rift, the Reelfoot rift, which was reactivated in Mesozoic time and is currently the site of the most intense seismicity in the mid-continent, the New Madrid seismic zone. This feature splits into a series of rift arms (Figure 4) near the confluence of the Mississippi and Ohio Rivers. The series of structural features observed in the Phanerozoic sedimentary rocks along the 38th parallel of latitude and commonly referred to as the 38th-parallel lineament may be the result of reactivation of east-west-trending faults of the New Madrid rift complex and the Rome trough which lie roughly along the 38th parallel.

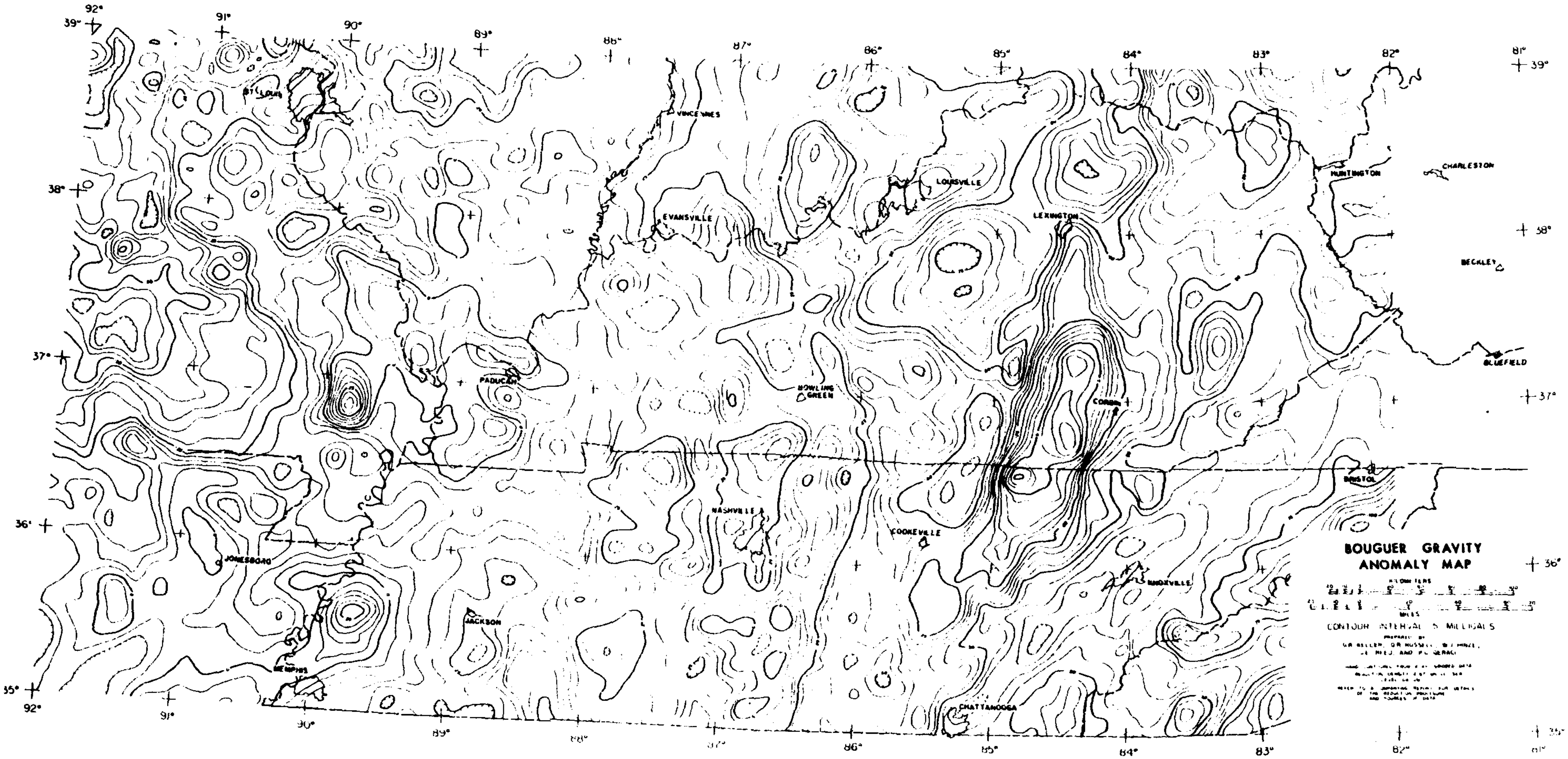


Figure 1. Bouguer gravity anomaly map of east-central midcontinent of the United States. Contour interval is 5 mGals (after Keller et al., 1980).

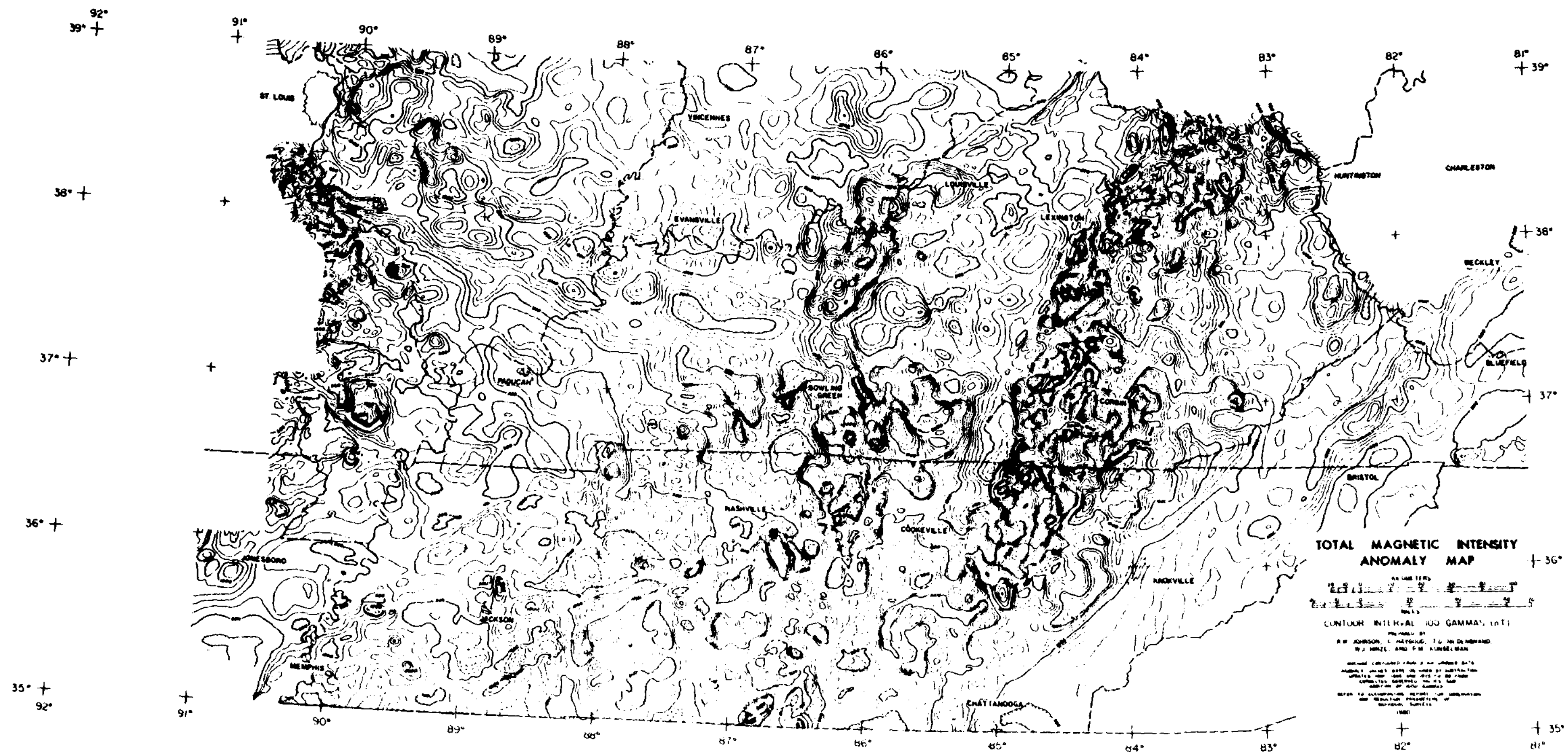


Figure 2. Total intensity magnetic anomaly map of east-central midcontinent of the United States. Contour interval is 100 gammas (nT) (after Johnson et al., 1980).

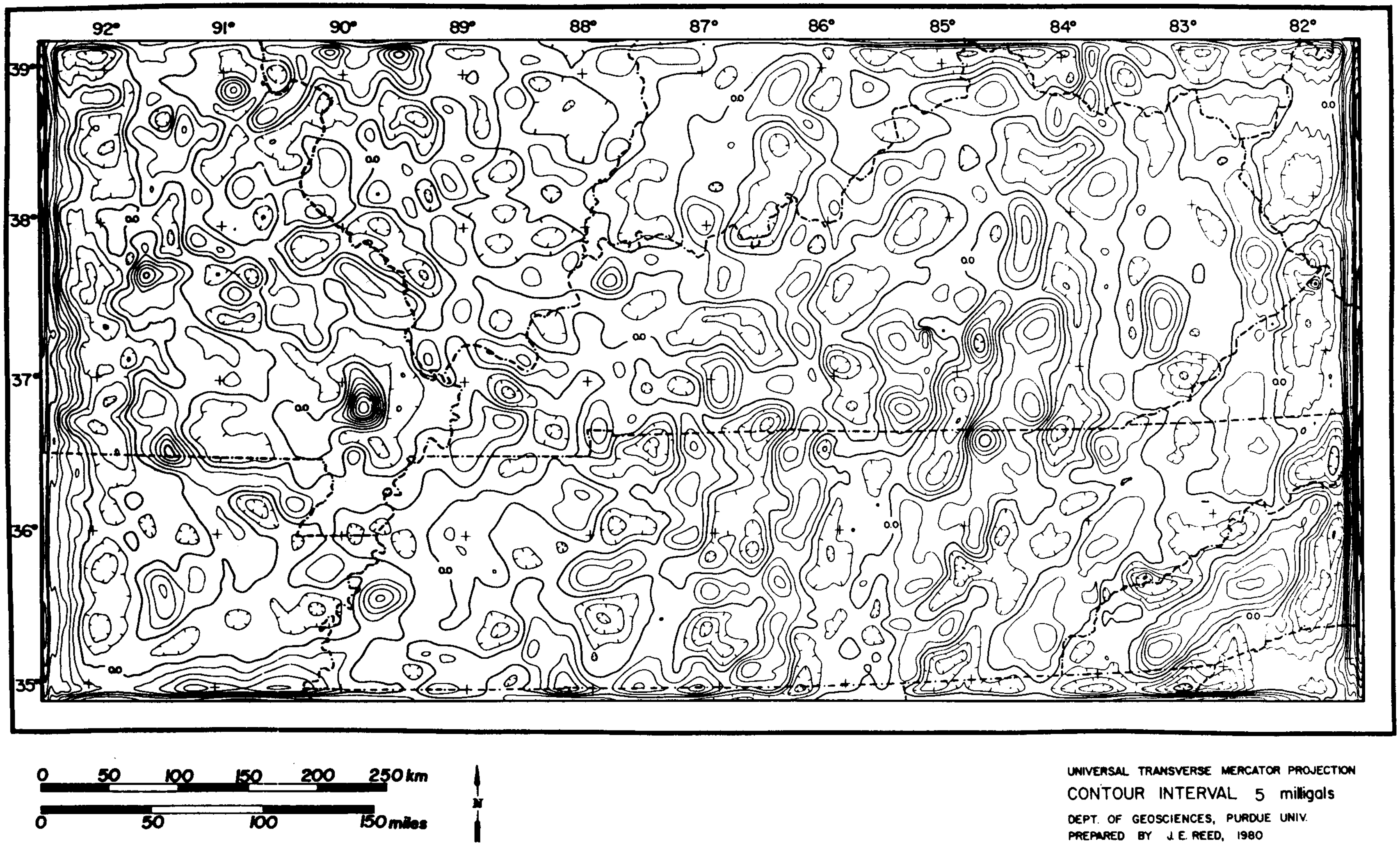
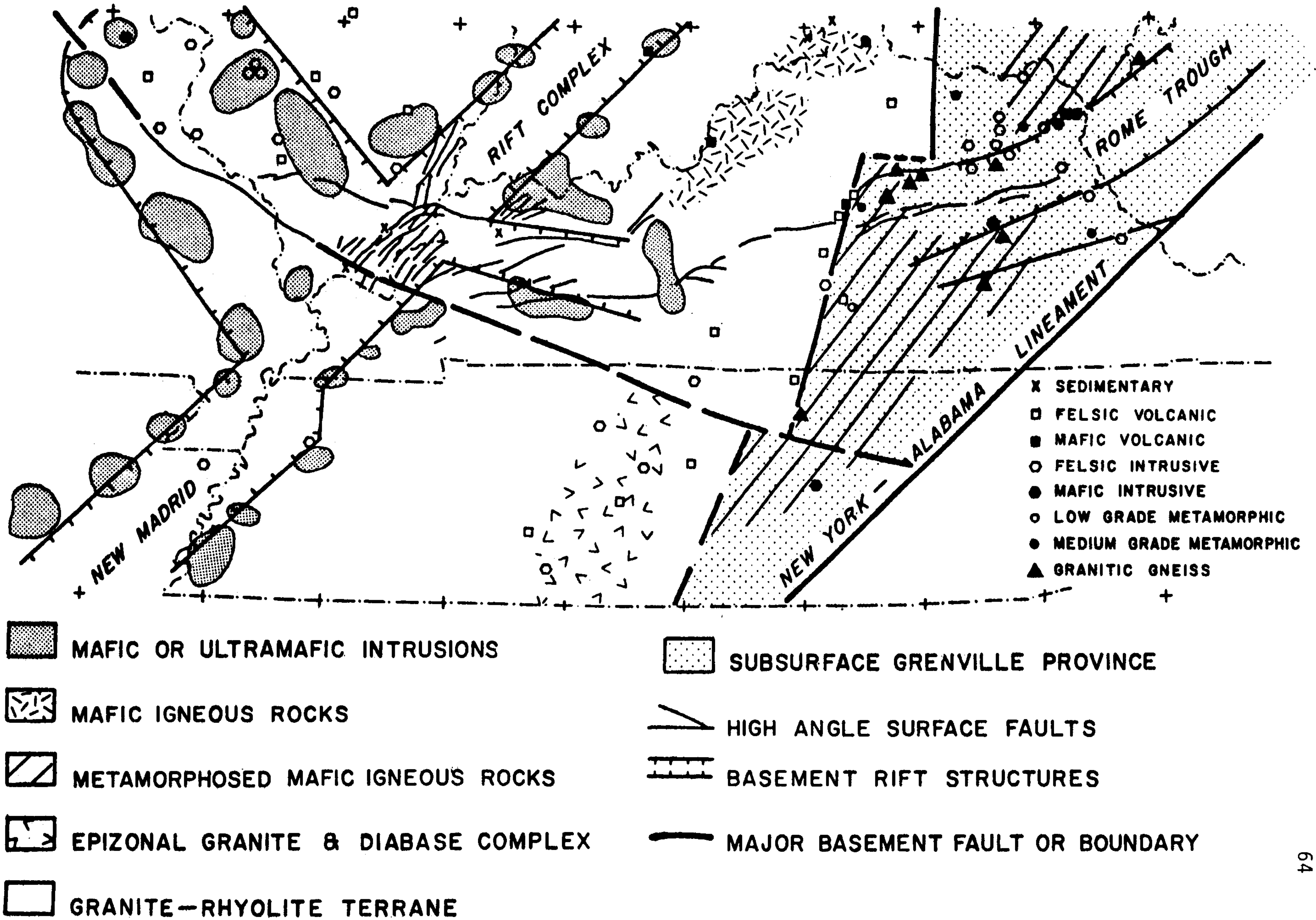


Figure 3. Bandpassed, Bouguer gravity anomaly map of east-central Midcontinent, North America. Wavelengths from 100 to 8 km are passed.

Figure 4. Basement rock map of east-central midcontinent of the United States.



APPENDIX IV

'Relation Between Drill-Hole Basement Lithology and Magnetic and Gravity Anomalies in the East-Central Midcontinent'

an expanded abstract

RELATION BETWEEN DRILL-HOLE BASEMENT LITHOLOGY AND MAGNETIC AND GRAVITY ANOMALIES IN THE EAST-CENTRAL MIDCONTINENT

by

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Regional aeromagnetic anomaly and Bouguer gravity anomaly maps are widely used in conjunction with samples from deep drill holes to basement to interpret the tectonic development of the buried basement and to construct basement rock maps. However, little emphasis has been given thus far to detailed study of the relation between the lithology and physical parameters of buried basement rock samples and the magnitude and amplitude of magnetic and gravity anomalies that occur in the immediate vicinity of the drill holes to basement. For this reason a study was undertaken to determine just how accurately samples from the basement reflect the magnetic and gravity signatures and to evaluate the factors that lead to ambiguities in correlation. Wells to basement were plotted according to rock types on recently compiled aeromagnetic and long wave-length cut Bouguer gravity anomaly maps of the east-central Midcontinent, and anomaly values coinciding with each well location were determined. In general, there is rather poor correlation between rock type and both magnitude of total intensity magnetic anomalies and Bouguer gravity anomalies (100-8 km bandpassed data). There is, however, some tendency for mafic igneous rocks to coincide with positive Bouguer anomalies and for felsic intrusive rocks and granitic gneisses, although variable, to be associated with lower Bouguer values. Similarly, the magnetic susceptibility of basement samples plotted against total magnetic intensity shows no clear distinction among the main rock types. Metamorphic rocks do display a good positive correlation of these two parameters for most samples, as do, to a lesser extent, felsic igneous rocks and possibly mafic igneous rocks. The causes of the generally poor correlations are varied and include such factors as the drill hole not encountering the main causative anomaly both laterally and at depth, general basement inhomogeneity, physical properties inhomogeneity, basement layering, sample alteration, and lack of definitive geophysical properties.

The correlations can best be assessed on a series of diagrams. Figure 1 shows that there is considerable overlap in total intensity magnetic values for all the main rock types. Mafic intrusive rocks occur in areas of higher magnetic intensity, but surprisingly, mafic extrusive rocks do not. Considering metamorphic rocks, which include both low and medium metamorphic grades and mafic and silicic compositions, there is no relation to grade of metamorphism or composition. Also surprising is the fact that most felsic intrusive rocks occur in areas of relatively high magnetic intensity.

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Figure 2 indicates that there is also wide variation in Bouguer gravity anomalies (100-8 km bandpassed data) associated with all the main rock types. Both extrusive and intrusive mafic igneous rocks occur in areas of higher Bouguer gravity values. Of the metamorphic rocks, two amphibolites reflect higher Bouguer anomalies than do lower grade rocks and more silicic compositions. The felsic extrusive and intrusive igneous rocks occur in areas of widely different Bouguer gravity anomalies, although many of the rocks do occur in areas of generally lower intensity anomalies than do the mafic rocks. The occurrence of about one-half of the felsic igneous rocks in areas of higher anomalies is clear indication that additional causative factors contribute to the gravity anomalies.

On Figure 3 are plotted by rock type the total intensity magnetic anomalies versus 100-8 bandpassed Bouguer gravity anomalies. As with the previous figures, there is considerable overlap in geophysical anomalies among the rock types. Mafic igneous rocks occur in areas of consistently high gravity anomalies (0 to +11 mgals), but of wide variation in magnetic signature. Felsic volcanic rocks similarly occur in areas having widely different magnetic intensities. Gravity anomalies for most of these volcanics cluster at about 0 mgals. Felsic intrusive rocks show the greatest variation in gravity anomalies, most samples occurring between -10 mgals and +10 mgals. These rocks also display a crude positive correlation between gravity and magnetic intensities. Metamorphic rocks also vary considerably, particularly in magnetic intensity. Most granitic gneisses occur in areas containing gravity anomalies between 0 and -10 mgals. Most mafic schists, both low and medium metamorphic grade, occur in areas of 0 to +6 mgal values.

Magnetic susceptibility measurements were carried out on basement rock samples from the study area. The results, plotted against total intensity magnetic anomalies, are shown on Figure 4. Each rock type shows considerable variation within groups and overlapping values among groups, making characterization difficult. A major feature on Figure 4 is the excelent positive linear correlation of six of the eight metamorphic rocks. Such correlations are expected if the measured sample is representative of the basement rock body in place and if the total intensity magnetic value accurately reflects that body. Felsic igneous rocks show some tendency toward a broad, poorly defined positive correlation. Mafic igneous rocks may show a similar trend, but the data points are too few to be definitive. Felsic volcanic rocks show no direct relation between the two plotted parameters.

The reasons why the rocks do not display distinct magnetic and gravity signatures or magnetic susceptibility contrasts are varied. It must be kept in mind that rocks are not classified on the basis of susceptibility and density, and thus 1:1 correlation should not be expected. This commonly results in contrasting rock types not having definitive geophysical signatures. There are other important factors as well. The geophysical maps used in this study are regional maps and record anomalies at a larger scale than the individual drill hole localities. Thus, the drilled sample may have missed laterally the body causing the anomaly, or the drill may not have penetrated deeply enough into the basement to encounter the causative body. Depth to basement is a clearly related factor. In this area of the east-central Midcontinent (Kentucky, Tennessee, southern Indiana, and southern Illinois) the basement typically is buried to a depth of 5,000-10,000 ft. Another factor is basement and physical properties inhomogeneity. This is a particular problem in steeply dipping rock bodies and gneissic complexes. Flat-lying layered bodies or surface alteration can also result in the recovered basement rock not accurately reflecting the body that produced the observed anomaly. Finally, it must be kept in mind that filtered or derivative geophysical maps can create apparent anomalies that are not related to basement features. A consideration of the various factors discussed here is a clear indication that considerable caution needs to be exercised in comparing geophysical data with basement rock samples obtained from widely separated drill holes.

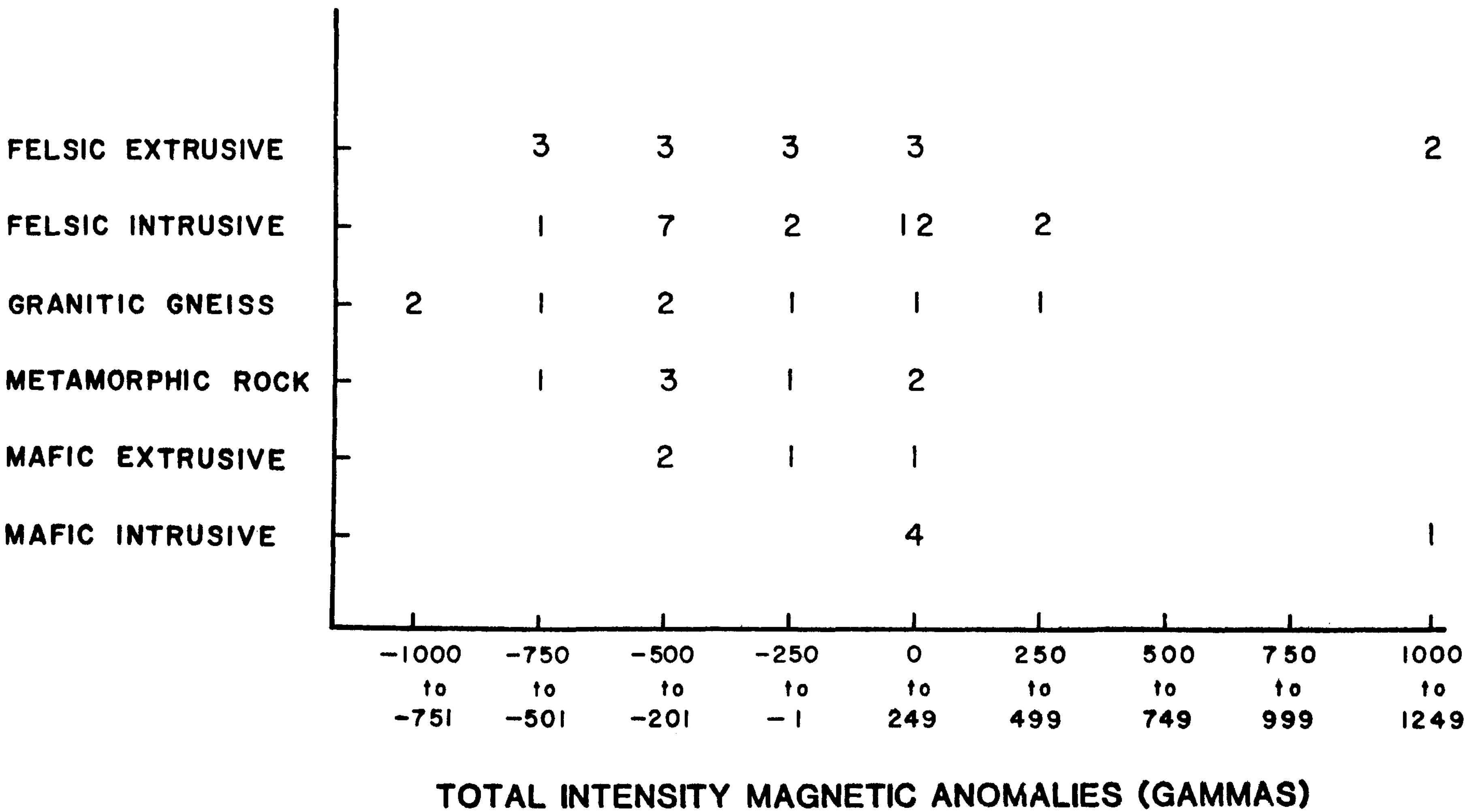

Figure 1. Total intensity magnetic anomalies (gammas) vs. basement rock types, east-central midcontinent, United States.

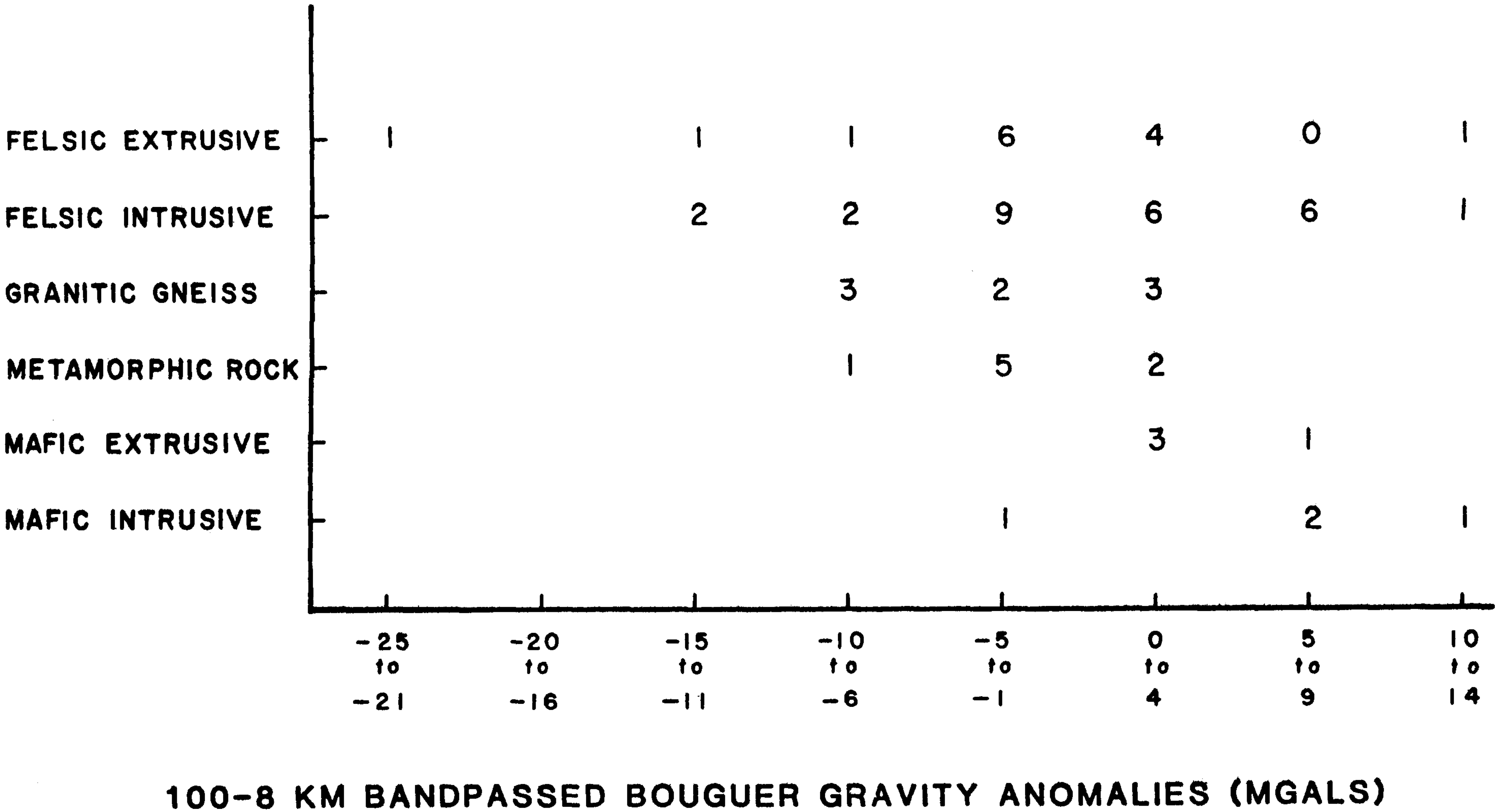

Figure 2. 100-8 Km bandpassed Bouguer gravity anomalies (mgals) vs. basement rock types, east-central midcontinent, United States.

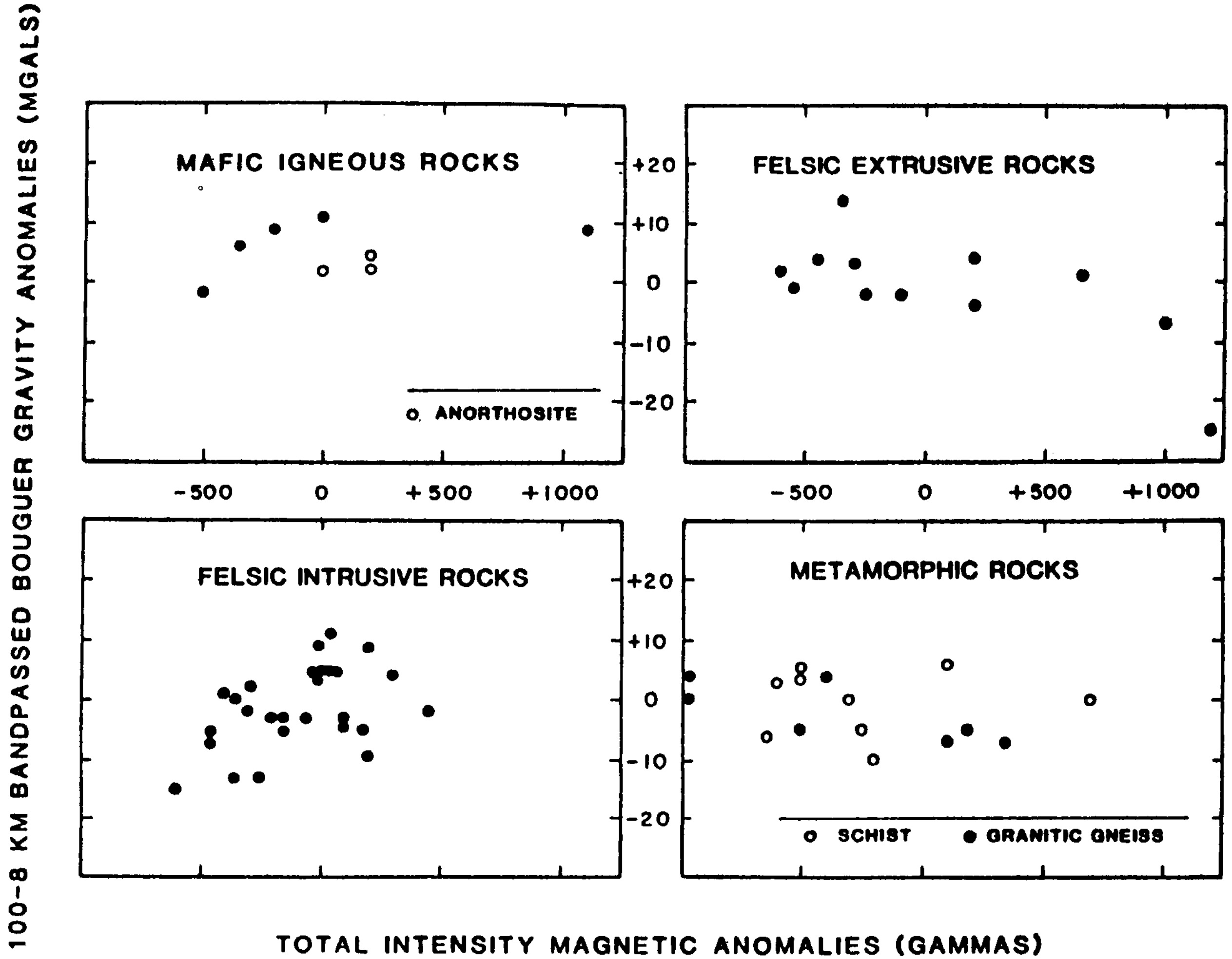

Figure 3. Total intensity magnetic anomalies (gammas) vs. 100-8 Km bandpassed Bouguer gravity anomalies (mgals) associated with basement rocks encountered in drill holes, east-central midcontinent, United States.

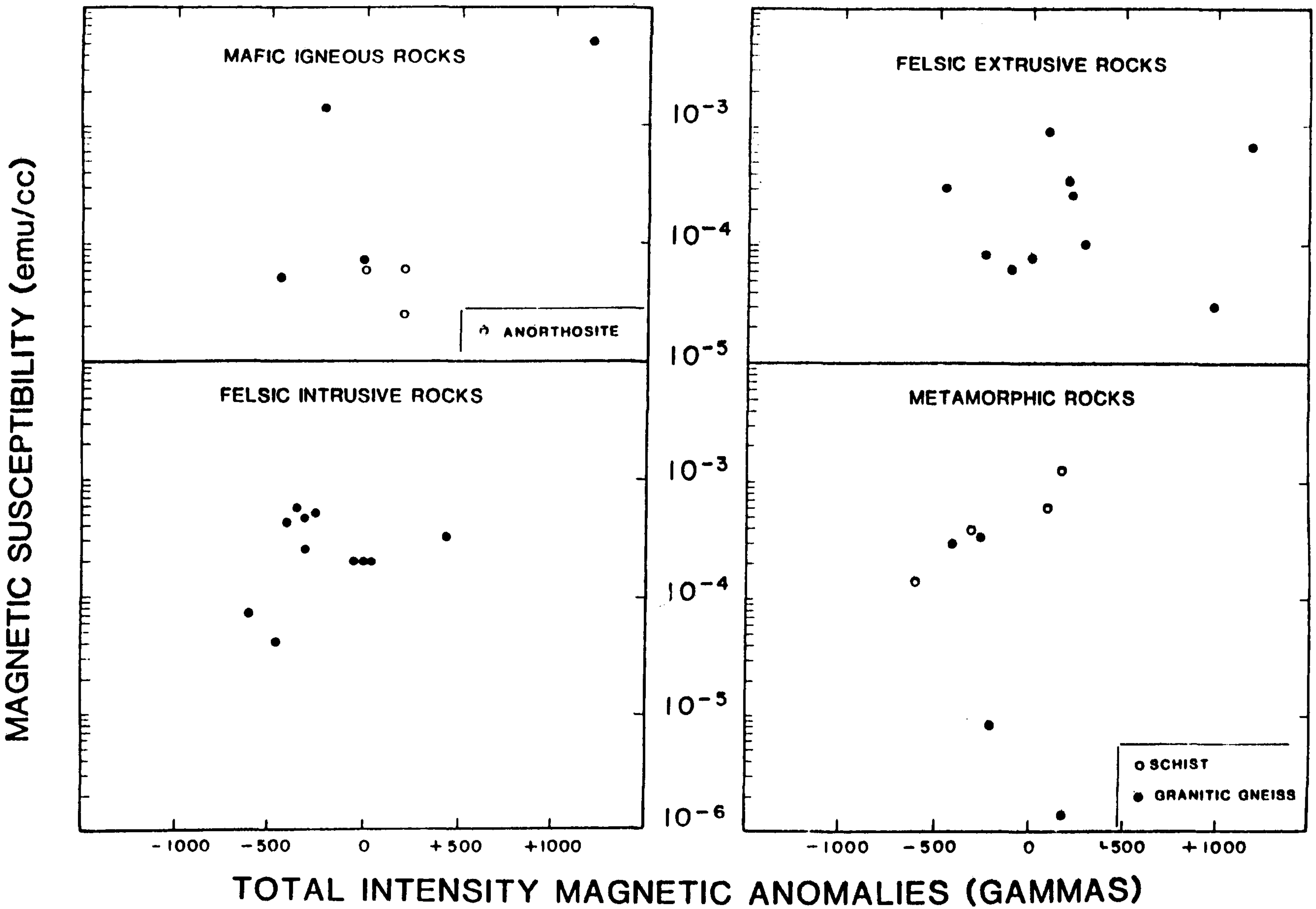

Figure 4. Total intensity magnetic anomalies (gammas) vs. magnetic susceptibility (emu/cc) of basement rocks encountered in drill holes, east-central midcontinent, United States.

APPENDIX V

"Seismicity and Tectonics of the Midcontinent United States"

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SEISMICITY AND TECTONICS OF THE MIDCONTINENT UNITED STATES

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The historical earthquake record indicates that moderate earthquake activity has occurred throughout the midcontinent United States. Larger earthquakes and more frequent activity are associated with discrete seismic zones within the central United States. Several of these zones are coincident with major geologic structural zones which are located at the margins of the ancient continental craton or are major intracratonic structures. The most intense seismicity in the midcontinent occurs in the New Madrid seismic zone where the trends of earthquake epicenters correlate with a geologically and geophysically mapped rift complex which dates from at least late Precambrian time. The ancient structures associated with the rift complex are apparently reactivated as zones of weakness to control the locations of contemporary earthquakes. Thus the significant intraplate earthquake activity in the New Madrid area can be explained in terms of a relatively simple plate tectonics model in which ancient structures of plate tectonic origin may be reactivated by the contemporary stress field which is caused by current plate motion. Comparison of the trends of major geologic structures and active seismic zones in the midcontinent suggests that the orientation of ancient structures, which may be subject to reactivation in the contemporary stress field, is a primary control on intraplate seismicity in the midcontinent of the United States.

INTRODUCTION

The eastern North American continent is an intraplate region in which earthquake activity occurs in a diffuse pattern throughout the continent with zones of concentrated activities such as the New Madrid area, the western Quebec region and the southern Appalachians. Although the frequency of occurrence of large magnitude earthquakes in this intraplate region is relatively low compared to seismic zones at plate boundaries, the occurrence of several large magnitude events during historic time attests to the significance of the earthquake hazard in the eastern North American continent. These events include the 1638 and 1755 earthquakes off the coast of Massachusetts, the 1663 and 1870 earthquakes in the St. Lawrence River valley, the 1886 Charleston, South Carolina earthquake and the three large New Madrid events in southeastern Missouri in 1811-1812. Understanding of the causes of eastern North American earthquake activity is impeded by the limited occurrences of large events during the short historical seismicity record and by the absence of recognized surface tectonic elements (such as plate boundaries) associated with the seismicity.

Compilations of the seismicity of eastern North America have been provided by several authors including Smith (1966), Fox (1970), York and Oliver (1976) and Nuttli (1979). Several investigators have attempted to relate the patterns of earthquake epicenters in eastern North American continent to tectonic features (Woollard (1958), Kanasewich (1965), Sbar and Sykes (1973), Sykes (1978) and Wesnousky and Scholz (1980)). Hinze et al. (1980) have reviewed the tectonic models which have been proposed to explain the seismicity in eastern North America. Of the models they

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discuss, the zones of weakness hypothesis has received the most recent attention and appears to be the model that best fits the available data. The zones of weakness hypothesis as a model for intraplate seismicity was proposed by Sbar and Sykes (1973) for eastern North America and extended to several areas of active intraplate seismicity by Sykes (1978). In the zones of weakness hypothesis, contemporary earthquake activity in intraplate regions is caused by the presence of ancient structures which act as zones of weakness in the presence of a regional stress field which is generated by contemporary plate motions. The zones of weakness serve as slip planes along which earthquakes occur to relieve strains generated by the regional stress field. Most of the intraplate activity, therefore, represents slip along ancient weakness planes and does not represent concurrent fracturing.

In this paper, we will examine the zones of weakness hypothesis as an explanation for earthquake activity in the midcontinent of eastern North America. Although the data are sparse, we will attempt to relate patterns of earthquake epicenters to major ancient tectonic features as indicated by mapped geologic structures as well as structures indicated by gravity and magnetic anomaly patterns. We will use the New Madrid area as a type example for this study because this region has recently received considerable attention and a large amount of new geophysical and geological data are available which help elucidate the seismotectonics of this active seismic zone. We believe that the results of study of the New Madrid area may be applicable to earthquake activity in other zones throughout eastern North America. We have chosen the midcontinent region (approximately from the Rocky Mountain Front to the Appalachians) because this area contains a large number of intraplate seismic zones including the New Madrid region and because the regional stress pattern within this area appears to be relatively uniform (Zoback and Zoback, 1980). Although we refer to seismic zones in the Appalachian and New England area in our analyses, our intent is not to concentrate on these areas. This is because the seismotectonics of the New England area has recently been reviewed by Yang and Aggarwal (1981) and the compilation of regional stress direction data (Zoback and Zoback, 1980) suggest that the New England region and the area to the east of the Appalachian Mountains may represent different regional stress provinces as compared to the central midcontinent area of eastern North America.

SEISMICITY DATA

Historic earthquake epicenters for the eastern North American continent are shown in Figure 1 from York and Oliver (1976) along with major tectonic features generalized from the tectonic map of North America (King, 1969). Virtually all of the structural features shown in Figure 1 are pre-Tertiary in age. Zones of more concentrated earthquake activity are also indicated mostly as defined by previous studies. There is a rough correlation between zones of concentrated seismicity and mapped tectonic features. However, there are many areas in which earthquake epicenters do not appear to be correlated with mapped geologic features and similarly mapped structures are present which do not appear to be seismically active. Because the structures shown in Figure 1 are primarily pre-Tertiary in age, they represent features caused by tectonic events which were associated with a completely different regional stress pattern from the current stress pattern. Thus, the correlation of earthquake epicenters with some of the mapped stuctural elements may be an indication of slip along pre-existing zones of weakness rather than a strict reactivation of the ancient structure. For example, structures which resulted from a prior tensional stress environment (for example normal faults), may under the current stress pattern actually be associated with strike-slip or thrust faulting.

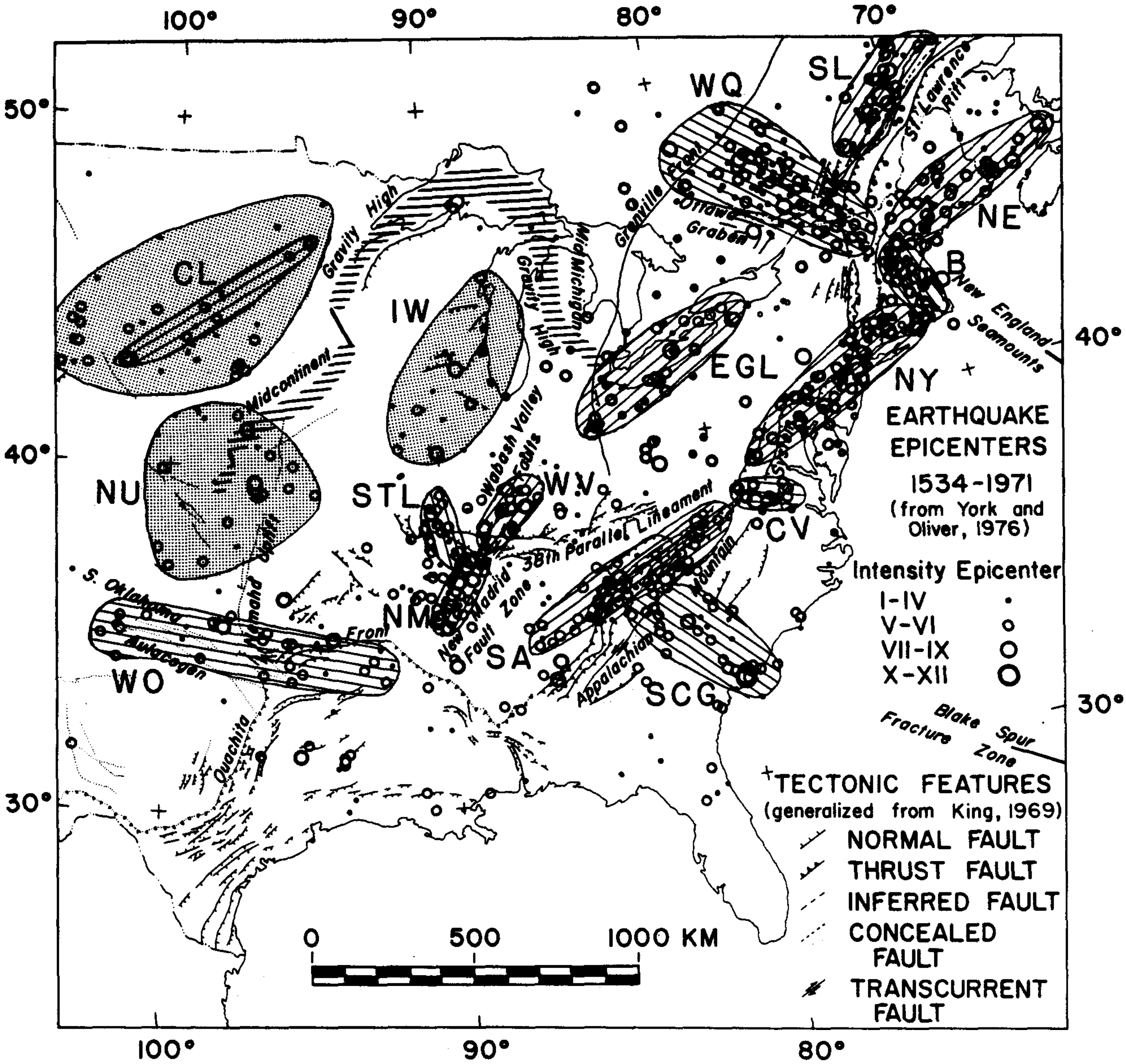

Figure 1. Earthquake epicenters (York and Oliver, 1976), regional tectonic features (King, 1969) and zones of concentrated earthquake activity for eastern North America. The zones of earthquake activity are shaded for diffuse zones for which no linear trend can be assigned and ruled for zones in which there is an approximate linear alignment of epicenters. The earthquake zones are Colorado Lineament (CL), Nemaha Uplift (NU), Wichita-Ouachita (WO), Wabash Valley (WV), and New Madrid (NM) from Barstow et al. (1981); Southern Appalachian (SA), South Carolina-Georgia (SCG), and Central Virginia (CV) from Bollinger (1973); St. Lawrence (SL), and Western Quebec (WQ) from Basham et al. (1979); Boston (B) from Sbar and Sykes (1973); and St. Louis (STL) from Braile et al. (1982). Other seismic areas defined here are Illinois-Wisconsin (IW), Eastern Great Lakes (EGL), New York (NY), and New England (NE).

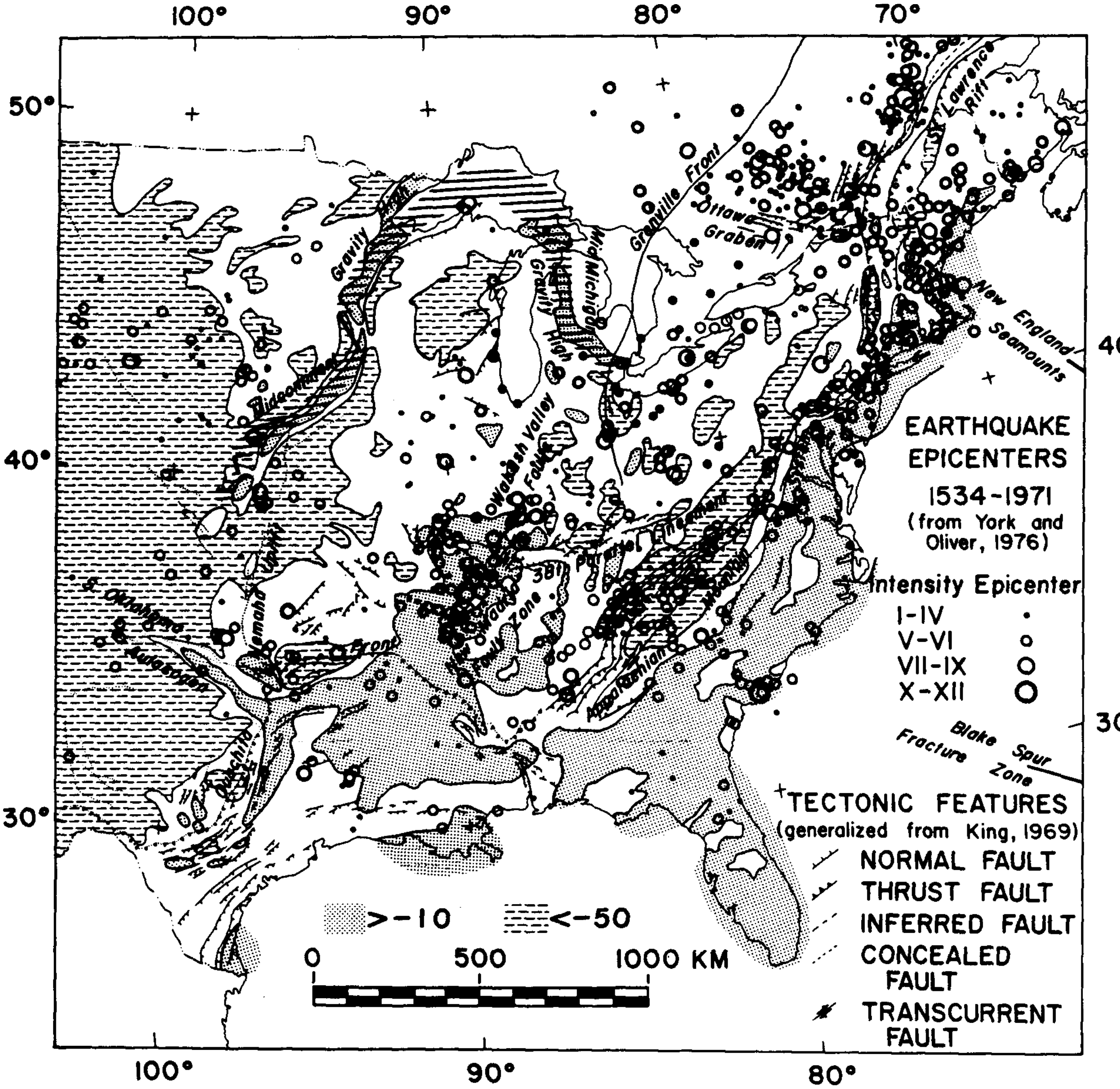

Figure 2. Earthquake epicenters and tectonic features for eastern North America and regional gravity anomalies generalized from Woollard and Joesting, 1964. The shaded areas indicate relative positive gravity anomalies with values greater than -10 mgals. The dashed areas indicate areas of relative negative gravity anomalies with values less than -50 mgals.

There are several reasons to explain why one would not expect a perfect correlation between earthquake epicenters and tectonic features as mapped in Figure 1 including the fact that not all tectonic structures may be reactivated either due to metamorphic healing or improper orientation of the structure with respect to the regional stress direction. In addition, important tectonic features may not be evident from mapping due to lack of surface exposures yet such deeply buried structures might be significant zones of weakness within the cyrstalline crust. In addition, many features which are evident on surface mapping may not extend to great depth and, therefore, may not be related to contemporary earthquake activity. To investigate the existence of deep-seated structural elements within the midcontinent of the United States, we have prepared regional gravity (Figure 2) and magnetic (Figure 3) maps of the eastern United States and plotted

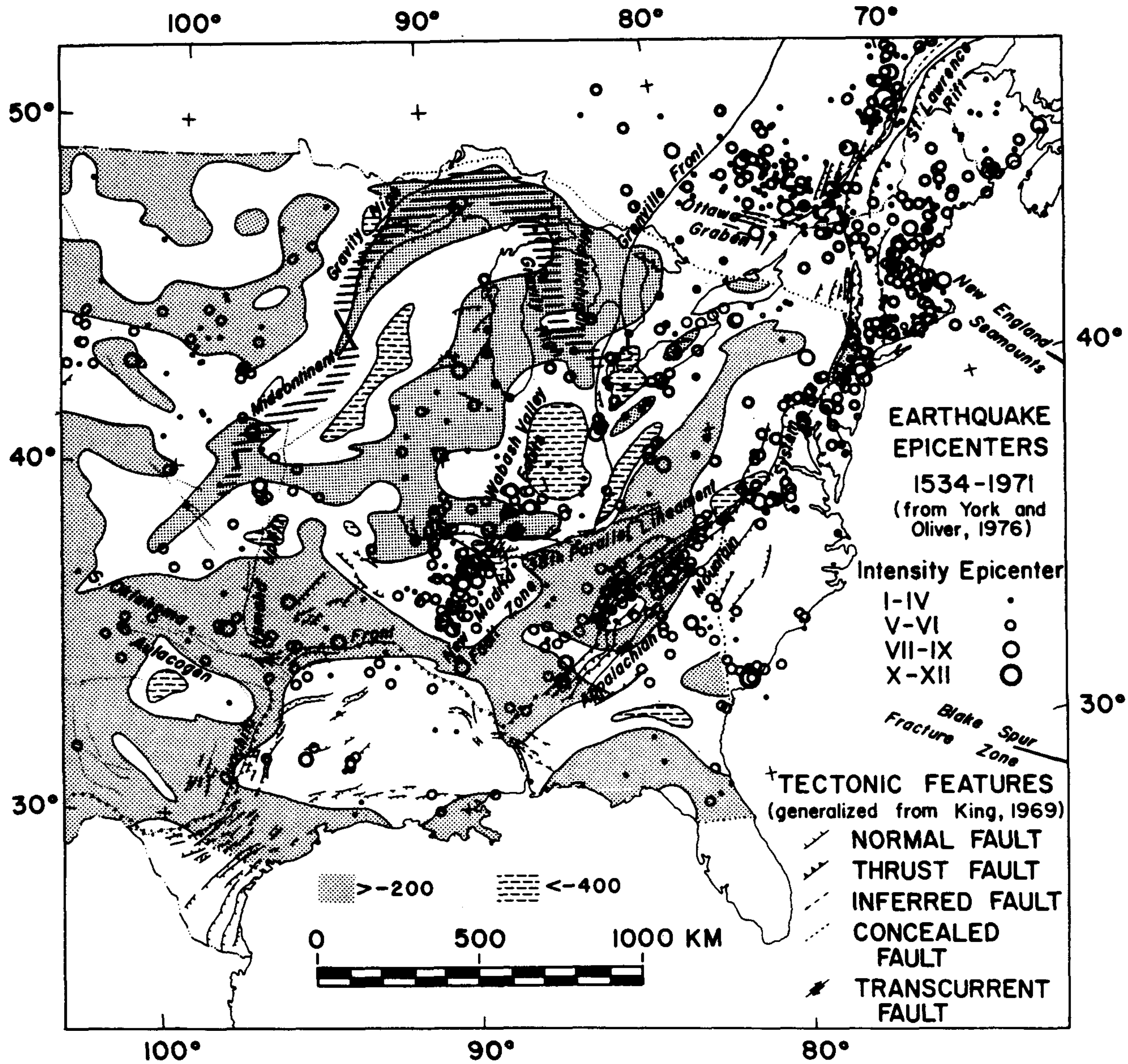

Figure 3. Earthquake epicenters and tectonic features in eastern North America and generalized regional aeromagnetic map of the eastern United States. Shaded area indicates relative positive magnetic anomalies with intensities greater than -200 gammas and the dashed areas are negative anomalies with intensities less than -400 gammas. Magnetic data have been low-pass filtered. The map includes wavelengths greater than about 100 km. Magnetic anomaly data from Sexton et al. (1982).

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them on the same base map as the seismicity data and the surface geological features shown in Figure 1. Comparison of the zones of earthquake epicenters in eastern North America with the regional gravity and magnetic anomalies indicates many interesting correlations. A northeasterly trend of the gravity and magnetic anomalies in the Appalachian region correlates with the observed earthquake epicenter patterns. In addition, prominent gravity anomalies (Figure 2) and magnetic highs (Figure 3) correlate with the earthquake epicenters in the southern Oklahoma aulacogen and Ouachita Front area. Diffuse seismicity zones southwest of Lake Michigan and west of the midcontinent gravity high correlate with magnetic highs and the

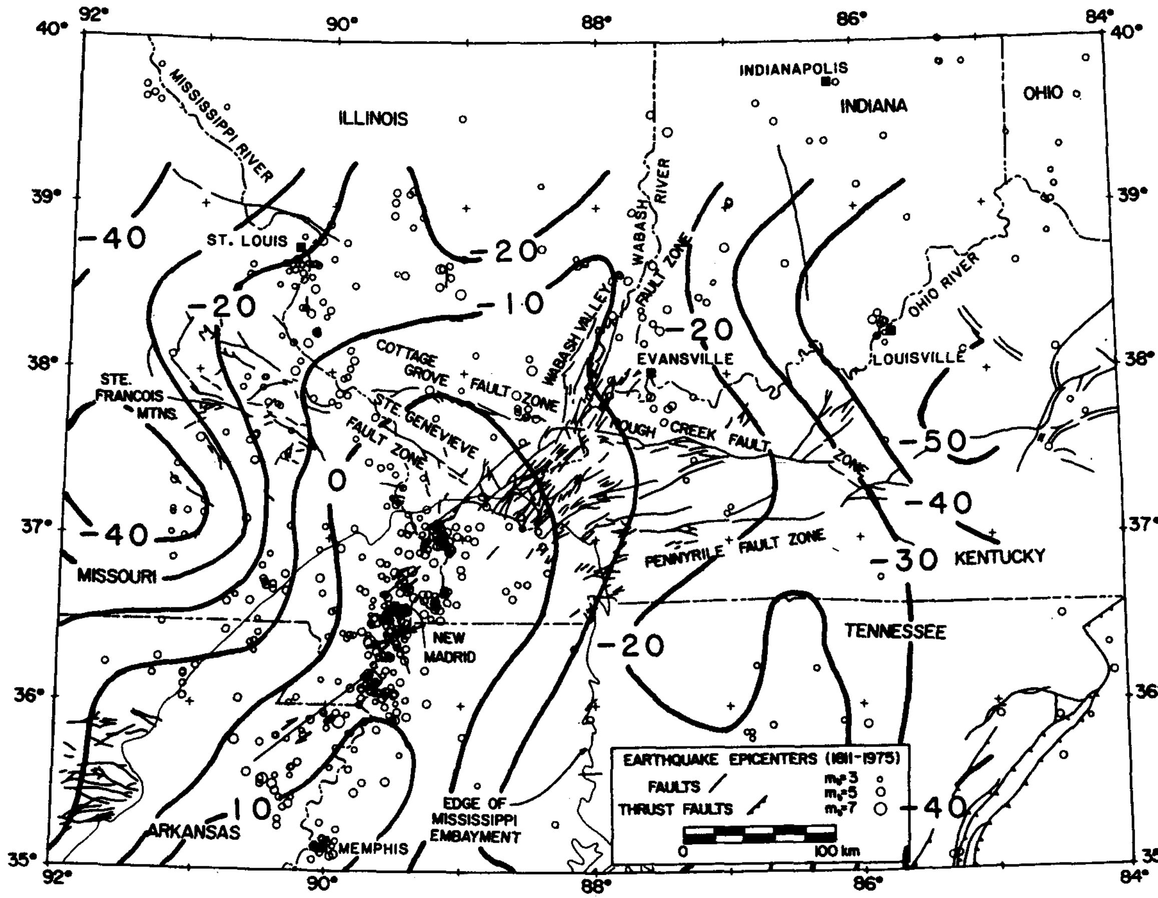

Figure 4. Historical earthquake epicenters in the New Madrid area of the central midcontinent from the historical data file of Otto Nuttli. The solid lines in the New Madrid region indicate the trends of linear micro-earthquake epicenter zones from Stauder et al. (1977) and the arrows indicate inferred earthquake focal mechanisms for the fault zones (Herrmann and Canas, 1978). Tectonic features are from Heyl (1972); Heyl and McKeown (1978); Bristol and Treworgy (1979); and Ault et al. (1980). The gravity anomaly contours (in mgals) are from the geologic corrected regional Bouguer gravity anomaly on data presented by Cordell (1977).

New Madrid area and adjacent seismic zones are correlative with a regional gravity high which is centered along the upper Mississippi Embayment. Some investigators (Long, 1976; Kane, 1977; and McKeown, 1978) have previously noted the correlation of earthquake epicenters with positive gravity anomalies and have suggested a causative relationship in which the gravity anomalies are indicative of density differences within the continental crust which could generate differential stresses resulting in earthquake activity. However, we interpret the gravity and magnetic anomalies to indicate ancient structures within the continental crust which in many cases represent sharp contrasts in physical properties which may result in zones of weakness. Slip along these zones of weakness could result from stresses applied by the regional compressive stress field.

NEW MADRID AREA

The New Madrid area in the midcontinent United States is of particular interest to our analysis of the correlation of tectonic features and earthquake activity because it represents the most active seismic area in eastern North America and is the site of the 1811 and 1812 magnitude 7.1 to 7.4 events (Nuttli, 1973). Also significant new geological and geophysical

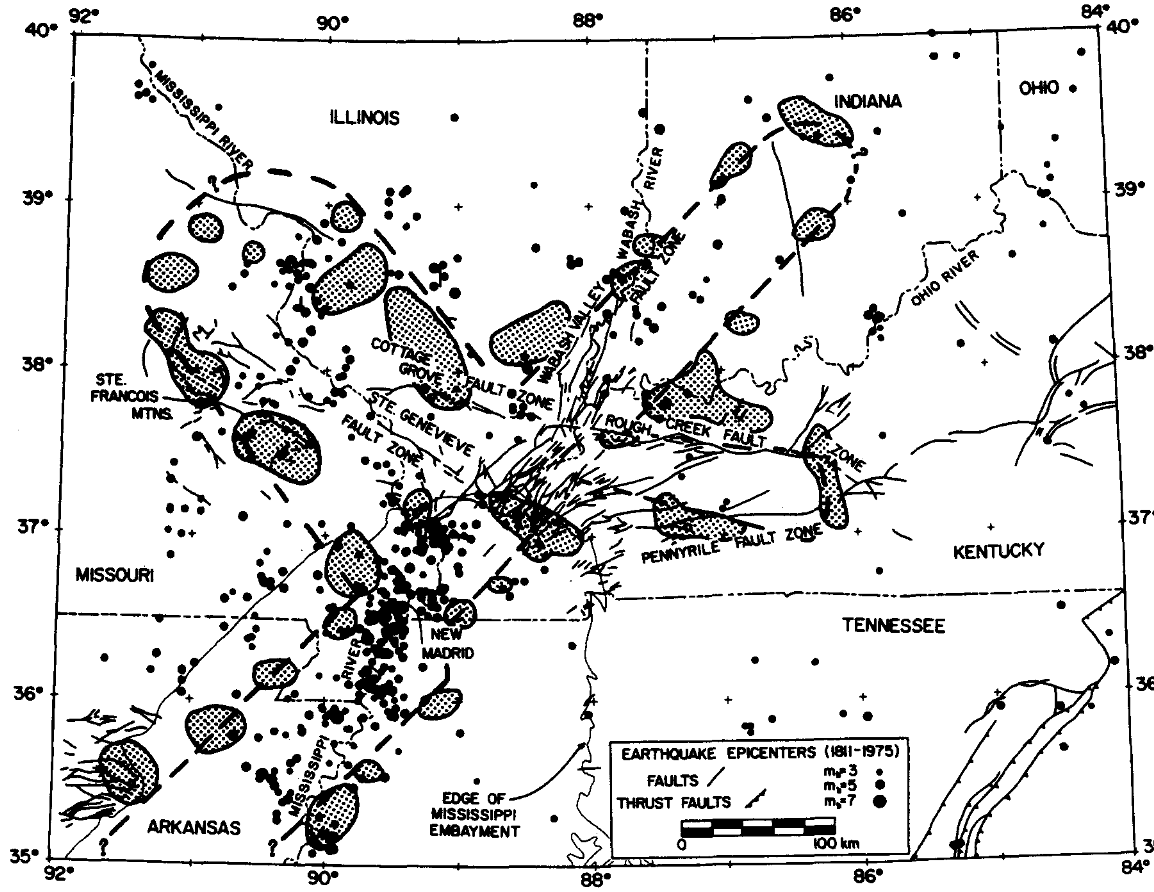

Figure 5. Earthquake epicenters, tectonic features and inferred boundaries of an ancient rift complex in the northern Mississippi embayment (Braile et al., 1982). The shaded regions are areas of correlated positive gravity and magnetic anomalies which have been used by Hildenbrand et al. (1977) and Braile et al. (1982a,b) to infer the boundaries of the rift complex.

data have been obtained in this area in the last decade. A microearthquake seismograph network (Stauder et al., 1977) has shown the existence of a linear trend of microearthquake epicenters just south of New Madrid in southeastern Missouri and northeastern Arkansas. Historic earthquake epicenters for the New Madrid region are shown in Figure 4 along with a contour map of the regional gravity field associated with the Mississippi Embayment from Cordell (1977). It is clear that the zone of greatest historical earthquake activity, which also coincides approximately with the region defined by microearthquake epicenters, is correlative with a regional positive gravity anomaly trending approximately northeasterly which extends along the northern Mississippi Embayment. The gravity anomaly branches near 37° latitude and extends northward to at least 39°N latitude as a positive anomaly trending toward St. Louis along the Mississippi River and as an additional positive anomaly approximately coincident with the Wabash River Valley faults. Hildenbrand et al. (1977) used detailed gravity and magnetic data in the New Madrid area to infer the existence of a buried Precambrian rift whose extent is nearly coincident with the microearthquake epicenters. Their results supported the suggestion by Ervin and McGinnis (1975) that the Reelfoot rift in the northern Mississippi Embayment represents a buried Precambrian structure which is currently acting as a zone of weakness to localize the earthquake activity in the New Madrid area. The northeasterly trending gravity and magnetic anomaly patterns identified by Hildenbrand et al. probably reflect geologic features associated with

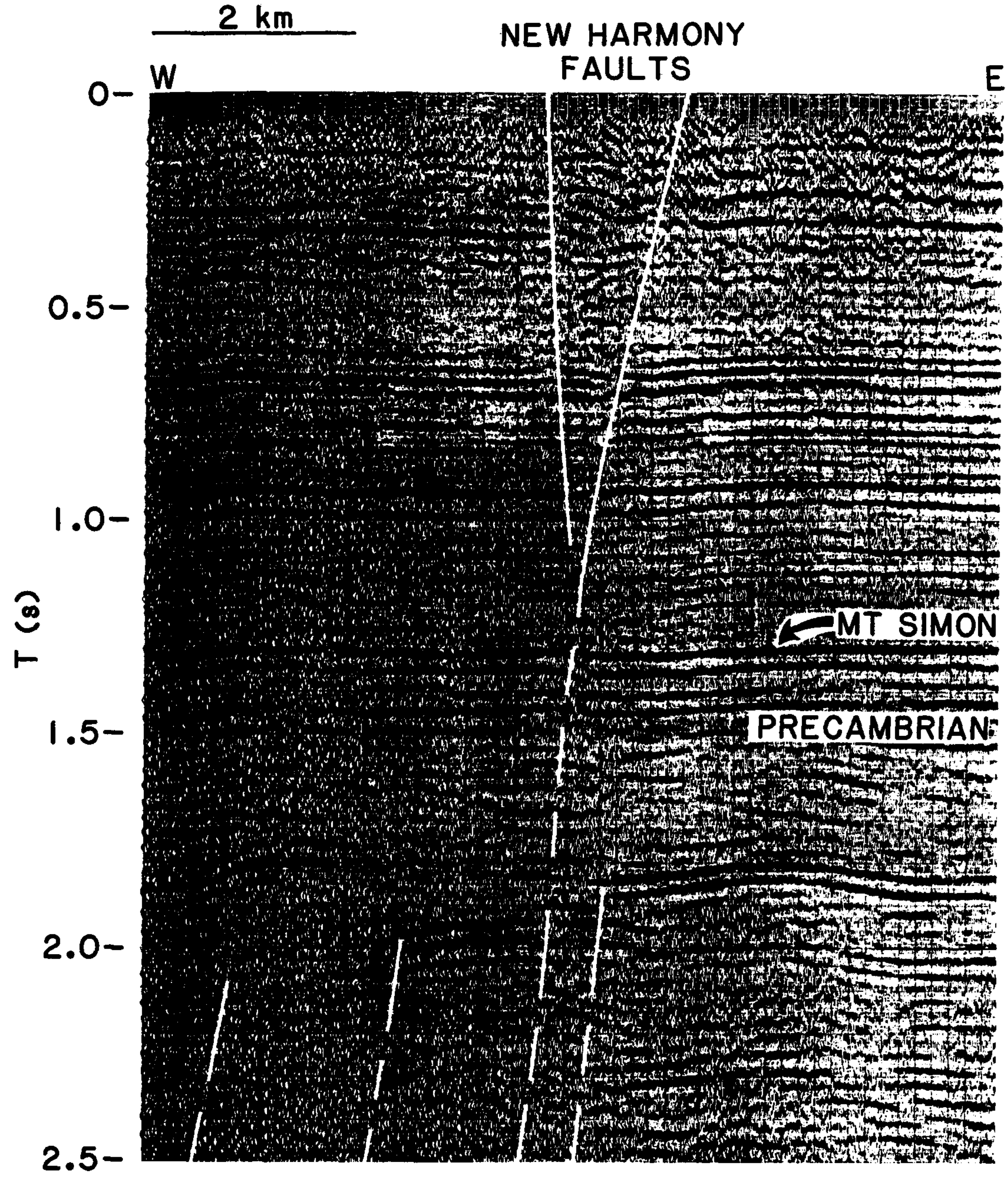

Figure 6. A portion of a seismic reflection profile recorded over the New Harmony faults which are a part of the Wabash Valley Fault System. The profile is located approximately 5 km east of the Wabash River in Indiana adjacent to Grayville, Illinois. The profile is oriented east-west. Mt. Simon formation is the base of the Phanerozoic sedimentary section at a depth of approximately 3.7 km. Reflections in the Precambrian are inferred to be due to late Precambrian volcanic/sedimentary rocks in a graben-like structure with boundary faults as shown on the diagram (from Sexton et al., 1982).

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normal fault structures which were active during rifting. Today, these northeasterly trending structures are acting as zones of weakness in which the regional compressive stress direction has caused right-lateral strike-slip motion with a fault plane trending approximately N45°E. Focal mechanism studies in the area (Herrmann and Canas, 1978; and Herrmann, 1979) have shown results consistent with this interpretation. Braile et al. (1982a,b) have utilized regional gravity and magnetic data to extend the geophysical

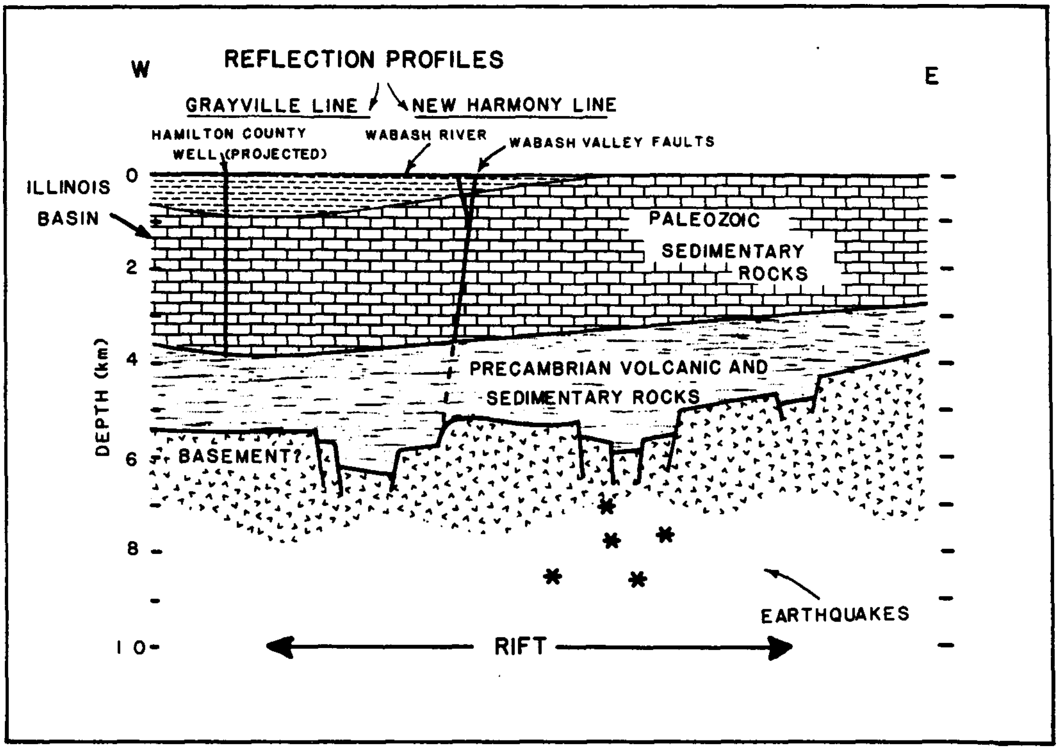

Figure 7. Schematic diagram showing inferred late Precambrian rift structures beneath the Wabash River Valley faults in southeastern Illinois and southwestern Indiana. The locations of the seismic reflection profiles (Sexton <u>et al</u>., in preparation) are shown. The western one-third of the reflection profile for the New Harmony line is shown in Figure 6.

anomalies associated with the New Madrid area to the northwest and northeast along arms of an ancient rift complex. The approximate boundaries of this rift complex are indicated in Figure 5 along with historical earthquake epicenters. The earthquake epicenter patterns show a much better correlation with the location of the rift complex (epicenters being approximately located near the central part of the rift complex) than they do with the mapped surface geological features.

Additional confirmation of the zones of weakness model in the New Madrid area has recently been derived from deep seismic reflection studies in the northern Mississippi Embayment by Zoback <u>et al</u>. (1980) and in the Wabash River Valley area by Sexton <u>et al</u>. (in preparation). Results of a portion of the deep seismic reflection profiling experiment in the Wabash River Valley area are shown in Figure 6. The reflection data indicate that the Phanerozoic sedimentary rock section is relatively flay-lying and undisturbed with the exception of small-offset faults in the New Harmony fault zone which is part of the Wabash River Valley Fault System. However, within the Precambrian beneath the Wabash River Valley area, prominent normal faults exist as evidenced by offsets in Precambrian volcanic and/or sedimentary units. The example shown in Figure 6 is one side of a graben structure which has been mapped beneath the Wabash River Valley area. It is also interesting to note that the New Harmony faults may be localized due to the underlying Precambrian faults thus indicating a reactivation of ancient structures. Although only a very small portion of the seismic reflection data for the Wabash River Valley area are shown in Figure 6, the seismic reflection data together with the regional basement geology and gravity and magnetic surveys (as prepared by Braile <u>et al</u>., 1982a,b) are suggestive of the existence of a major Precambrian rift zone extending

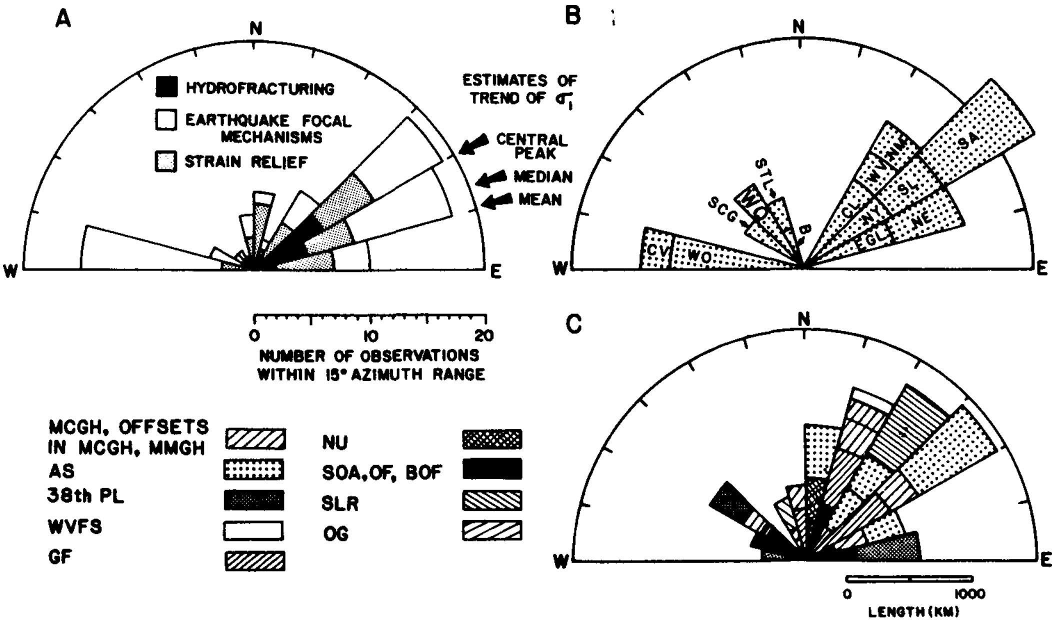

Figure 8. (A) Azimuthal histogram of the trends of the horizontal direction of the maximum compressive stress from hydrofracture, earthquake focal mechanism and strain relief measurements in eastern North America. (B) Azimuthal histogram of the trends of earthquake zones shown in Figure 1. The length associated with each zone is plotted according to the scale shown in C. (C) Azimuthal histogram of the trends of segments of major tectonic features from the tectonic map of North America (Figure 1). Segments are Midcontinent gravity high (MCGH), Appalachian system (AS), 38th Parallel Lineament (38th PL), Wabash Valley Fault System (WVFS), Grenville front (GF), Nemaha Uplift (NU), Southern Oklahoma aulacogen (SOA), Ouachita front (OF), buried Ouachita front (BOF), St. Lawrence river valley (SLR) and Ottawa graben (OG).

from the northern Mississippi Embayment into the Wabash River Valley area (Figure 7) and northwesterly along the Mississippi River to near St. Louis.

SEISMOTECTONIC MODEL

The correlation of earthquake zones with geologically and geophysically mapped ancient structures supports the hypothesis of zones of weakness as a seismotectonic model to explain the occurrence of earthquake activity in the intraplate midcontinent United States and perhaps all of eastern North America. If this model is correct, there will be two important factors in determining whether or not an ancient structure acts as a zone of weakness in the regional stress field. The first factor will be the physical properties of the zone of weakness itself which can best be thought of as the effective coefficient of friction along the plane of the structure. Ancient structures will only act as zones of weakness or slip planes if the coefficient of friction along the potential fault plane is small relative to the strength of the surrounding rock. In addition, the orientation of the plane of the ancient structure with respect to the regional stress direction will be a controlling factor in determining whether or not the structure will result in slippage and, therefore, earthquakes. Although detailed data such as that which exists in the New Madrid area will be required to analyze the effect of the direction of orientation completely, we will attempt a preliminary analysis of the effect of the orientation of structures with the respect to the prevailing regional stress patterns by comparing the directions of major structural trends in eastern North America with the directions of the seismicity zones which have been defined for eastern North America. In addition, we will compare these directions with predictions from the slippage direction which would be expected from the zones of weakness hypothesis based on the direction of maximum compressive stress in the area.

We have compiled data on stress directions for eastern North America and have plotted them as an azimuthal histogram in Figure 8A. Most of the data summarized here are contained in Zoback and Zoback (1980). The stress data for eastern North America consistently indicate a regional compressive stress environment in which the maximum compressive stress direction is nearly horizontal. The horizontal trend of the maximum compressive stress is plotted in Figure 8A and shows a regional trend for eastern North America of approximately N60°E. Raleigh et al. (1972) consider the conditions for fracturing of intact rock versus slip along pre-existing zones of weakness for the case of an applied compressive stress. Although the exact results are dependent on the three component stress field which is applied as well as the rock properties, their analysis indicates that slip along pre-existing zones of weakness will be preferred over fracturing of intact rock for those cases in which the plane of the zone of weakness is oriented in a direction within the range of approximately 10°-40° from the direction of the maximum compressive stress. Thus for the case of eastern North America, with maximum compressive stress being nearly horizontal and with a trend of N60°E, we would expect that nearly vertical structures with strike directions within approximately N20°E to N100°E could result in strike-slip motion along the zone of weakness due to the applied stress field. Similarly, structures of relative shallow dip (10°-40°) with strikes of approximately N30°W would be expected to result in thrust fault slippage along the zone of weakness. A combination of dip-slip and strike-slip movement would be expected for orientation of zones of weakness between these extremes. Although this description is basically a two-dimensional simplification, it probably represents an adequate representation of the expected directions of slip along pre-existing zones of weakness for eastern North America.

The trends of major seismic zones in eastern North America are shown in Figure 1 and the azimuthal orientation of these trends are plotted in the histogram in Figure 8B. We realize that the delineation of these seismic zones is somewhat arbitrary, but we have followed the definitions proposed by previous investigators wherever possible in defining the direction of a seismic zone. In some cases, areas of seismicity may be connected within a single zone for which there is no evidence other than the visual pattern of the epicenter map. However, our experience with the New Madrid area suggests that as more and more detailed information about the seismotectonics of an area are gathered, the linear patterns will emerge as being significant. Although many general trends of the orientation of earthquake epicenter zones exist in eastern North America, there is a predominance of orientation of the earthquake trends in a direction approximately northeast to east and north-northwest similar to the direction which would be expected based on the zones of weakness hypothesis and the orientation of the regional compressive stress field in eastern North America. Trends of mapped structures in eastern North America are shown in the azimuthal histogram in Figure 8C. Although there are more structures which trend approximately northeast than any other direction, structures do exist which trend in nearly every azimuthal range. The comparison of the azimuthal histograms for the orientation of active seismic zones and mapped structures for eastern North America (Figures 8B and 8C) support the hypothesis that those structures which are oriented in the appropriate direction to act as zones of weakness will experience earthquake activity. For example, notice the absence of seismic zones trending approximately north whereas there are a large number of ancient structures within eastern North America which trend in this direction. It is suggested that the north trending features are not active due to their orientation with respect to the direction of the regional stress field.

CONCLUSIONS

Seismicity zones in the eastern United States show a rough correlation with ancient tectonic features evidenced by mapped geologic structures and/or gravity and magnetic anomaly trends. The correlation of earthquake epicenter patterns with ancient zones of weakness suggests that the hypothesis of localization of earthquake activity in the intraplate region of eastern North America along reactivated zones of weakness is a viable model to explain earthquake activity. It is suggested that orientation of pre-existing structures with respect to the prevailing regional compressive stress pattern in eastern North America is a primary control on the location of earthquakes in this area. The detailed seismotectonic model which has been developed for the New Madrid area is suggested to be a type example of intraplate earthquake activity in eastern North America and earthquake activity in similar intraplate zones may result from buried structures. Earthquake focal mechanism studies are a critical element necessary to confirm the applicability of the zones of weakness model to seismic zones throughout eastern North America. Although discrepancies due to secondary faulting and local stress direction patterns are to be expected, the zones of weakness model and the existence of the prevailing compressional stress direction of N60°E in eastern North America suggest that earthquake activity will be primarily along strike-slip fault zones oriented approximately northeast to east and along reverse faults for structures oriented approximately north-northwest. The seismotectonic model presented here for midcontinent North America suggests a viable mechanism consistent with current plate tectonic theory to explain the earthquake activity in this broad intraplate continental region and represents a useful model for the assessment of earthquake hazards in eastern North America.

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REFERENCES

Ault, C.H., D.M. Sullivan, and G.T. Tanner, Faulting in Posey and Gibson Counties, Indiana: Proceedings of the Indiana Academy of Science for 1979, 89, 275-289, 1980.

Barstow, N.L., K.G. Brill, O.W. Nuttli, and P.W. Pomeroy, An approach to seismic zonation for siting Nuclear Electric Power generating facilities in the eastern United States, U.S. Nuclear Regulatory Commission Technical Report NUREG/CR-1577, 143 p., 1981.

Basham, P.W., D.H. Weichert, and M.J. Berry, Regional assessment of seismic risk in Eastern Canada: Seis. Soc. Am. Bull., 69, 1567-1602, 1979.

Bollinger, G.A., Seismicity of the southeastern United States: Seis. Soc. Am. Bull., 63, 1785-1808, 1973.

Braile, L.W., W.J. Hinze, G.R. Keller, and E.G. Lidiak, The northeastern extension of the New Madrid seismic zone: U.S. Geol. Surv., Prof. Paper 1236, in press, 1982a.

Braile, L.W., G.R. Keller, W.J. Hinze, and E.G. Lidiak, An ancient rift complex and its relation to contemporary seismicity in the New Madrid Seismic Zone: Tectonics, 1, in press, 1982b.

Bristol, H.M., and J.D. Treworgy, The Wabash Valley Fault System in southeastern Illinois: Illinois State Geological Survey, Circular 509, 1979.

Cordell, L., Regional positive gravity anomaly over the Mississippi embayment: Geophys. Res. Ltrs., 4, 285-287, 1977.

Ervin, C.P., and L.D. McGinnis, Reelfoot Rift: reactivated precursor to the Mississippi embayment: Geol. Soc. Am. Bull., 86, 1287-1295, 1975.

Fox, F.L., Seismic geology of eastern United States: Assoc. Eng. Geol. Bull., 7, 21-43, 1970.

Herrmann, R.B., and J.A. Canas, Focal mechanisms studies in the New Madrid seismic zone: Seis. Soc. Am. Bull., 68, 1095-1102, 1978.

Herrmann, R.B., Surface wave focal mechanisms for eastern North American earthquakes with tectonic implications: J. Geophys. Res., 84, 3543-3552, 1979.

Heyl, A.V., The 38th parallel lineament and its relationship to ore deposits: Econ. Geol., 67, 879-894, 1972.

Heyl, A.V., and F.A. McKeown, Preliminary seismotectonic map of central Mississippi valley and environs: U.S. Geol. Surv. Misc. Field Studies Map MF-1011, 1978.

Hildenbrand, T.G., M.F. Kane, and W. Stauder, Magnetic and gravity anomalies in the northern Mississippi embayment and their spatial relation to seismicity: U.S. Geol. Surv. Map MF-914, 1977.

Hinze, W.J., L.W. Braile, G.R. Keller, and E.G. Lidiak, Models for midcontinent tectonism, in Continent Tectonics: National Acad. Sci., 73-83, 1980.

Kanasewich, E.R., Seismicity and other properties of geological provinces: Nature, 208, 1275-1278, 1965.

Kane, M.F., Correlation of major eastern earthquake centers with mafic/ultramafic basement masses: U.S. Geol. Surv. Prof. Paper 1028-O, 199-204, 1977.

King, P.B., compiler, Tectonic map of North America: U.S. Geol. Surv. Map, scale 1:5,000,000, 1969.

Long, L.T., Speculations concerning southeastern earthquakes, mafic intrusions, gravity anomalies, and stress amplifications: Earthquake Notes, 47, 29-35, 1976.

McKeown, F.A., Hypothesis: many earthquakes in the central and southeastern United States are casually related to mafic intrusive bodies: J. Res. U.S. Geol. Surv., 6, 41-50, 1978.

Nuttli, O.W., The Mississippi valley earthquakes of 1811 and 1812, intensities, ground motion, and magnitudes: Seis. Soc. Am. Bull., 63, 227-248, 1973.

Nuttli, O.W., Seismicity in the central United States: Geol. Soc. Am. Rev. Eng. Geol., 4, 67-93, 1979.

Raleigh, C.B., J.H. Healy, and J.D. Bredehoeft, Faulting and crustal stress at Rangely, Colorado, in Flow and Fracture of Rocks: Am. Geophys. Union Monograph 16, 275-284, 1972.

Sbar, M.L., and L.R. Sykes, Contemporary stress seismicity in New York and adjacent areas: J. Geophys. Res., 82, 5771-5786, 1977.

Smith, W.E.T., Earthquakes of eastern Canada and adjacent areas 1928-1959: Publ. 32, 87-121, Dominion Observ., Ottawa, Ont., 1966.

Stauder, W., M. Kramer, G. Fischer, S. Schaefer, and S. Morrissey, Seismic characteristics of southeast Missouri as indicated by a regional telemetered microearthquake array: Seis. Soc. Am. Bull., 66, 1953-1964, 1977.

Sykes, L.R., Intraplate seismicity, reactivation of pre-existing zones of weakness, alkaline magmatism, and other tectonism postdating contrinental fragmentation: Rev. Phys. Space Phys., 16, 621-688, 1978.

Wesnousky, S.G., and C.H. Scholz, The craton: Its effect on the distribution of seismicity and stress in North America: Earth, Planet. Sci. Lett., 48, 348-355, 1980.

Woollard, G.P., Areas of tectonic activity in the U.S. as indicated by earthquake epicenters: EOS Trans. Am. Geophys. Union 39, 1135-1150, 1958.

Woollard, G.P., and H.R. Joesting, Bouguer gravity anomaly map of the United States: Am. Geophys. Union, 1:2,500,000 scale, 1964.

Yang, Jih-Ping, and Y.P. Aggarwal, Seismotectonics of northeastern United States and Adjacent Canada: J. Geophys. Res., 86, 4981-4998, 1981.

York, E., and E. Oliver, Cretaceous and Cenozoic faulting in eastern North America: Geol. Soc. Amer. Bull., 87, 1105-1114, 1976.

Zoback, M.L., and M. Zoback, State of stress in the conterminous United States: J. Geophys. Res., 85, 6113-6156, 1980.

Zoback, M.D., R.M. Hamilton, A.J. Crone, D.P. Russ, F.A. McKeown, and S.R. Brockman, Recurrent intraplate tectonism in the New Madrid seismic zone: Science, 209, 971-976, 1980.

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An integrated geophysical/geologic program is being conducted to evaluate the rift complex hypothesis as an explanation for the earthquake activity in the New Madrid Seismic Zone and its extensions, to refine our knowledge of the rift complex, and to investigate the possible northern extensions of the New Madrid Fault Zone, especially its possible connection to the Anna, Ohio seismogenic region. Geologic studies are being used to confirm the existence of rift zones suggested by geophysical signatures with identification of pre-upper Cambrian sedimentary rocks in the subsurface. Drillhole basement lithologies are being investigated to aid in tectonic analysis and geophysical interpretation, particularly in the Anna, Ohio area. Gravity and magnetic modeling combined with limited seismic reflection studies in southwest Indiana are interpreted as confirming speculation that an arm of the New Madrid Rift Complex extends northeasterly into Indiana. Sufficient evidence are unavailable to test the hypothesis that this feature extends into the Anna, Ohio area. The geological and geophysical evidence confirm that the basement lithology in the Anna Ohio area is highly variable reflecting a complex geologic history. The data indicate that as many as three major Late Precambrian tectonic features intersect within the basement of the Anna area suggesting that the seismicity may be related to basement zones of weakness.

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