UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D. C. 20555

JUN 30 1986

MEMORANDUM FOR: Harold Denton, Director
Office of Nuclear Reactor Regulation

FROM: Robert B. Minogue, Director
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER NUMBER 146, RESULTS OF NEW MADRID SEISMOTECTONIC RESEARCH PROGRAM

ABSTRACT

The New Madrid earthquakes of the Central Mississippi River Valley (1811-1812) were among the strongest known seismic events in North America. Their intensity has been estimated at XI-XII on the Modified Mercalli scale and the felt area extended eastward as far as Charleston, SC, Washington, DC, New York City, and Hartford, CT. The earthquakes are unusual in that they occurred within a continental plate rather than at a plate margin as is the case for most large earthquakes. Using only surficial geology and historic seismicity, it was not possible to relate the New Madrid earthquakes to a specific geologic structure or capable fault. To resolve uncertainty in the causative mechanism of these earthquakes, a multidisciplinary program of investigations was begun by the NRC in 1976 called the New Madrid Seismotectonic Research Program. This program is now at a stage where a conceptual model can be constructed that explains the recurring intraplate seismicity of the Central Mississippi River Valley. The earthquakes are spatially associated with fault movement within an ancient rift complex called the New Madrid Rift complex. This rift complex can be delineated based on geological, geophysical, and seismic evidence. This is significant to NRC regulatory activities because it means that seismicity in the area can be linked to a tectonic structure of finite extent.

The rift complex formed in late Precambrian to Cambrian time (1,500 to 500 million years ago). The contemporary stress regime is quite different (compressional as opposed to tensile) from the one that produced the original zones of weakness. Several generalizations can be made that would be significant in drawing a seismic hazards map for the New Madrid area: (1) the Reelfoot Rift is seismically the most hazardous portion of the rift complex; (2) the recurrence interval for events large enough to cause liquefication in the area is about 600 years; and (3) the remaining portions of the rift complex (i.e., the St. Louis and Indiana arms and Rough Creek Graben) should be considered seismically active but to a lesser extent than the Reelfoot Rift.

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INTRODUCTION

Background

The series of earthquakes which occurred in the Central Mississippi River Valley near New Madrid, Missouri, in the winter of 1811-1812 were among the strongest known earthquakes in North America. Three major earthquakes, plus 203 damaging aftershocks, occurred in the 3-month interval from December 16, 1811 through March 15, 1812 (Nuttli, 1982). They are unusual in that they happened in the interior of a continental plate (North American Plate) rather than at a plate margin. Thus we are dealing with "intraplate tectonics." The intensity of the earthquakes was extremely high. Nuttli (1982) estimates an epicentral Modified Mercalli Intensity (MMI) of XII and a body wave magnitude of 7.2, 7.3, and 7.5 for the three major earthquakes. The zone of greatest deformation (i.e., fissuring, sandblows, landslides, subsidence) extended over an area of 48,000 square kilometers (approximately the area of West Virginia), and the earthquakes were felt as far away as Hartford, CT, Washington, DC, Charleston, SC and New Orleans, LA.

Since 1812 there have been at least 20 damaging earthquakes of MMI intensity VI-VII to XI (Nuttli, 1982, p.15) in the Central Mississippi River Valley (see Figure 2 for their location) making this one of the most seismically active areas in the United States east of the Rocky Mountains. Although the frequency and severity of earthquakes in this area are high, until very recently, the earthquakes could not be directly linked to geologic structures as can be done in some areas such as California. This is due to: (1) deep burial of the causative structures, (2) the fact that most of them do not extend to the earth's surface, (3) vegetative cover which obscures faults and rock exposures, and (4) the fact that until about 1974 there was very little geophysical data available for the Central Mississippi River Valley that could provide a basis for interpreting subsurface structure. The lack of definitive evidence linking seismicity with geologic structures was a matter of serious concern for, in the absence of this evidence, Appendix A to Part 100 requires nuclear power plant license applicants to design the facility to withstand the largest earthquake which could occur in the tectonic province where the power plant is located. In licensing actions going back to the early 1970's the AEC/NRC licensing staff dealt with the New Madrid earthquakes as an anomalous zone of high seismicity within the Mississippi Embayment portion of the Gulf Coastal Plain and the adjacent Wabash River Valley. In the early 1970's the staff had to rely principally on the pattern of seismicity which centered on the Central Mississippi River Valley, the frequent recurring earthquakes in the area, and surficial geology. With this limited evidence the licensing staff treated the New Madrid earthquakes as being linked to buried unidentified structure. The zone of New Madrid seismicity was presumed to extend from Memphis, Tennessee, to Vincennes, Indiana. To resolve the causative mechanism, that is, to see if the New Madrid earthquakes could be linked with geologic structure the Office of Nuclear Regulatory Research initiated in 1976 a program of confirmatory research. The purpose of the research was to provide the licensing staff with information to support regulatory decisions. The research program was a cooperative multidisciplinary effort called the New Madrid Seismotectonic Research Program and funding was shared by 7 State Geological Surveys, and several academic institutions in cooperation with the U.S. Geological Survey, National Science Foundation, and Tennessee Valley Authority.

Description of the Program

The New Madrid Seismotectonic Research Program was a coordinated program of geological, geophysical, and seismological investigations of the area within a 200-mile radius of New Madrid, Missouri, which concluded in FY 1986. The location of the New Madrid Area is shown in Figure 1 and the contributions of the participants is summarized in NUREG/CR-4632 (Buschbach, 1986). The program was designed to define the structural setting and tectonic history of the area in order to evaluate earthquake hazards, particularly to nuclear facilities. Specific program objectives are: (1) to identify the earthquake source and source mechanisms for the numerous recurring earthquakes in the Central Mississippi River Valley; (2) to delineate the zone of high seismic activity; and (3) to determine the recurrence interval of potentially damaging earthquakes in the area.

Participants in the program have included scientists from the State Geological Surveys of Illinois, Indiana, Kentucky, Tennessee, Alabama, Arkansas, and Missouri; faculty members of Earth Science Departments at Saint Louis University, Vanderbilt University, Purdue University, Memphis State University, Eastern Kentucky University, the University of Pittsburgh, the University of Kentucky, the University of Wisconsin at Milwaukee, and the University of Texas at El Paso; and staff members of the U.S. Geological Survey, U.S. Army Corps of Engineers, and the Tennessee Valley Authority.

RESULTS OF THE PROGRAM

Integration of Results into a Conceptual Model

The program has produced significant results which led to the formulation of a conceptual model that explains the New Madrid seismicity based on many lines of evidence. For an historical review of key developments in the formulation of the conceptual model see USGS Open File Report 84-770, pp. 6-10. Among them are: seismic history, contemporary seismicity, geophysical exploration techniques (particularly gravity and aeromagnetic data and seismic reflection profiles), subsurface geology, surface geology, stress measurement data, and hydrogeochemical data.

The conceptual model relates the New Madrid earthquakes to the reactivation of basement structures within a rift complex that formed in late Precambrian to Cambrian time. (A geologic time scale is provided in Figure 13.) The model relates the seismicity to a contemporary compressional stress regime greatly different from the tensional stress field which originally produced the rift complex. Thus the research has reduced uncertainty for the licensing process by relating seismicity to geologic structures which have a finite extent.

The conceptual model is shown schematically in Figures 3, 4, and 5. Braile, Keller, Hinze, and Lidiak (1982) named overall rift complex the New Madrid Rift funding was shared by 7 State Geological Surveys, and several academic institutions in cooperation with the U.S. Geological Survey, National Science Foundation, and Tennessee Valley Authority.

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Complex and the term is accepted by many researchers in the area although other terms such as Reelfoot Rift, New Madrid Seismic source zone, and Mississippi Valley Graben are used by others. As can be seen in Figure 3b, according to Braile et al. (1982), there are four structural components of the New Madrid Rift Complex: (1) the Reelfoot Rift, (2) the Rough Creek Graben, (3) the Indiana Arm, and (4) the St. Louis Arm. Their presence has been inferred from seismic reflection profiling, aeromagnetics, gravity, and subsurface geology as revealed by deep boreholes. As with many conceptual models, one must realize that it is an early approximation which fits the available data. As more data become available, details of the conceptual model may change. Summarized below are the lines of evidence which led to the formulation of this model which specifically proposes a reactivated rift as the causative structure for the New Madrid earthquakes of 1811-1812.

Specific Research Results

Seismicity Data:

Until the early 1970's, the seismicity data base for the New Madrid area was limited to: (1) that gathered by instruments located far from the epicenters of the 1811-1812 events, and (2) human observations which were recorded in newspaper accounts and journals. Hadley and Devine (1974) collated the available data from 1800-1972 and produced a seismic frequency map (Figure 6). The seismic frequency contours from the Hadley and Devine map show a Y-shaped pattern which matches the New Madrid Rift Complex identified by this research. It follows the Mississippi River to southern Illinois where one branch follows the Mississippi northwestward toward St. Louis. The other branch follows the Ohio and Wabash Rivers northeastward. In part, the Y-shaped pattern may reflect location of observation points since population density was highest along the rivers, or it may reflect amplification of ground motion in the alluvial filled valleys of the Mississippi, Ohio, and Wabash Rivers. However, even with a possible bias due to population distribution, seismicity was indeed considerably higher than in the remainder of the Central Stable Region.

Beginning in the early 1970's the NRC, USGS, NSF and TVA in a coordinated program funded installation of seismographic networks in the New Madrid area. Their purpose was to determine levels of seismicity, recurrence intervals, location of epicenters, and ground motion characteristics of the earthquakes. The results are summarized in Figures 7 and 8, which show epicentral location of detected earthquakes. Their gross pattern is similar to the Hadley and Devine map (Figure 6). In the Reelfoot Rift (see Figure 8b for location) there are two principal northeast-southwest trending zones extending from Cairo, Illinois into northeastern Arkansas. These two zones are offset from one another in the region between New Madrid, Missouri, and Dyersburg, Tennessee, by a zone of northwest-southeast trending seismicity. The seismic zones are thought to represent subsurface faults. Composite focal mechanism studies on the two northeast-southwest zones indicate probable right lateral strike slip movement and the focal plane studies on the northwest-southeast zone suggest reverse faulting (Herrmann and Canas, 1978). There may be another northeasterly trending zone of high seismicity parallel to the postulated western margin of the Reelfoot Rift but outside of the rift zone. However, the pattern is not distinct. Nuttli (1982, p. 15) notes that the three major earthquakes of 1811-1812 occurred in the central portion of the Reelfoot Rift. In the St. Louis Arm (see figure 8b for location) the seismic activity trends northwest from Cairo, Illinois towards St. Louis. Seismicity appears not to extend beyond St. Louis. Seismic activity is low in the Indiana Arm and Rough Creek Graben.

Earthquake focal depths in the Reelfoot Rift are generally 3 to 15 km (Buschbach, 1986, p. 58). This puts them either within a zone of disturbed seismic reflections (Figure 10b shows this disturbed zone) or within the magnetic basement rocks. In the Indiana Arm, several earthquakes had focal depths greater than 16 km. This makes them the deepest earthquakes recorded thus far in the Central Mississippi River Valley. Buschbach (1986) notes that these earthquakes appear to be associated with the eastern edge of the Fairfield Basin, a depression in the Illinois Basin, rather than with the Wabash Valley Fault System which is located 30 km to the east (see Figure 9 for location of the Fairfield Basin and Wabash Valley Fault System).

Aeromagnetic and Gravity Data:

The pattern exhibited by aeromagnetic and gravity surveys of the Central Mississippi River Valley correspond strikingly well with seismic data (see previous section). In particular the data have delineated a northeast striking basement depression about 70 km wide and more than 300 km long (Kane et al., 1981; Hildenbrand et al., 1982). The depression, the Reelfoot Rift portion of the New Madrid Rift Complex, is remarkably linear over its entire length, has nearly parallel sides, and is at least 2 km deeper than the surrounding basement (Kane et al., 1981; Hildenbrand et al., 1982). Both gravity and magnetic anomalies are aligned along the boundaries of the depression. The geophysical signatures along the rift boundaries are characteristic of mafic plutons. Estimated magnetization directions for the postulated plutons indicate a Mesozoic age (Kane et al., 1981).

Similar to the Reelfoot portion of the New Madrid Rift Complex, the St. Louis Arm, Indiana Arm and Rough Creek Graben can be delineated on their aeromagnetic and gravity signatures (Braile et al., 1982). The St. Louis Arm is the broadest of the four arms. The southwest side has the strongest aeromagnetic gradient of any part of the New Madrid Complex. However, its northeast side is not as distinct. Its presence is deduced primarily from interpretations of the patterns exhibited on aeromagnetic and gravity maps. Unlike the other arms of the New Madrid Rift Complex, there is no significant thickening of Paleozoic sediments in the St. Louis Arm (Schwalb, 1982; Buschbach, 1986, p. 26). From stratigraphic evidence alone one would not deduce its presence. Gravity and aeromagnetic data (Braile et al., 1982; Braile et al., 1984; Gori and Hays, 1984) indicate that the Indiana Arm is restricted to the southwestern part of Indiana south of N39.5° latitude (see Figure 7). This is significant because Wollard (1958) using only seismicity called attention to an apparent alignment of the earthquakes of what is now called the Reelfoot Rift with the earthquakes of the St. Lawrence River valley. The Anna, Ohio earthquakes fall within this apparent alignment. Seismicity is low in the Indiana Arm and the most seismically active portions of it appear to be limited to the region south of the Kentucky Fluorspar District.

As to the cause of the Anna, Ohio earthquakes, Braile et al., (1985) have investigated the possible connection of the Indiana Arm and Anna, Ohio. Based on an integration of aeromagnetic, gravity, and subsurface geology, they have not found sufficient evidence to warrant extending the Indiana Arm northeastward to Anna, Ohio. The Anna, Ohio earthquakes appear to be localized in a structurally complex area near the intersection of the northeast trending Grenville Front and a postulated rift complex, the Fort Wayne Rift, which strikes northwest-southeast. The Fort Wayne Rift has an orientation and geophysical signature similar to a Keweenawan Age rift complex found in the Michigan Basin. From the geological/geophysical data available Braile et al. (1985) interpret the Anna, Ohio seismicity as being caused by one or more of the following: (1) lithologic discontinuities associated with the contact between rift type volcanics of the Fort Wayne Rift and low density granitic rocks of the Grenville terrane; (2) reactivation along graben type faults on the northeast flank of a mafic volcanic body within or on the margins of a -60 milligal gravity anomaly which is thought to be a low density granitic body; and (3) basement inhomogeneities within Grenville basement rocks.

Seismic Reflection Data:

Indiana Arm: Seismic reflection data is available for the Indiana Arm and the Reelfoot Rift. Work on the Indiana Arm was done by Purdue University under NRC funding (Hinze et al., 1983; Sexton et al., 1985). The Purdue seismic lines detected faulted layered Paleozoic sediments. More importantly, that data indicated a thickening of pre Mt. Simon layered rocks in the Wabash Valley Area. (Note: the Mt. Simon Sandstone is late Cambrian in age or approximately 500 million years old.) Approximately 2 kilometers of sediment are found in this area but none in the area to the west. This is significant, for the seismic data indicate the presence of a down-dropped fault block in the Wabash Valley Area, which received a thick accumulation of sediment prior to the late Cambrian.

Reelfoot Rift: The seismic reflection data for this area are proprietary information. The USGS purchased over 250 km of multichannel, common-depth-point seismic-reflection profiles (Crone et al., 1985). A more complete presentation of the seismic profiles is found in Howe and Thompson (1984). There are several deep wells (i.e., Dow Chemical No. 1 Wilson and Houston Oil and Minerals No. 1 Singer) which allow tentative correlation of the principal seismic reflectors. The seismic reflection data confirm the existence of a fault bounded down dropped basin, i.e., the Reelfoot Rift. The Reelfoot contains a sedimentary section greater than 30,000 feet thick. This is considerably thicker than the area outside the Reelfoot Rift where sediment thicknesses are around 5,000 feet or less. The thickest part of this sedimentary sequence is found below late Cambrian sediments. Based on sediment thickness patterns, the Reelfoot rift must have formed prior to the late Cambrian.

The seismic profiles in the area show a variety of structural and stratigraphic features which allow a reconstruction of the history of the Reelfoot (see the section on Subsurface Geology which follows on page 9). Noteworthy structural features are the faults bounding the down dropped basin, numerous other high angle faults, and a prominent zone of disturbed seismic reflectors found along the axis in the southern portion of the Reelfoot Rift for a distance of 120 miles from Caruthersville, Missouri, to Marked Tree, Arkansas (see Figures 10a and 10b). This disturbed zone does not show on aeromagnetic or gravity maps. Its presence was revealed by the seismic reflection data. The origin of the disturbed zone is not known. Howe and Thompson (1984) postulate that it originated from late Paleozoic compressional forces which uplifted and reactivated movement on late Precambrian-late Cambrian growth faults. Crone et al. (1985) argue for the disturbed zone being caused by felsic intrusive of post-Paleozoic, pre-Cretaceous age.

Regardless of the disturbed zone's origin, the correlation between earthquake hypocenters and it are so pronounced that Crone et al. (1985) conclude that the mapped extent of the disturbed zone defines the source zone for the Reelfoot's axial seismic zone. Note in Figure 10a the close correspondence between earthquake epicenters and the disturbed zone. The dashed line signifying the outer edge of the disturbed zone encloses most of the epicenters. In addition, Crone et al. (1985 p. 549) points out that hypocenters in the axial seismic zone occur within the disturbed zone. As to its extent, Crone et al. can trace the disturbed zone only 25 km southwest of Marked Tree, Arkansas, although geophysical data suggest that the Reelfoot Rift continues a considerable distance farther to the southwest. Thus, the axial seismic source zone does not appear to extend to the southwestern end of the rift.

At the northeastern end of the axial zone near Caruthersville, Missouri, the reflectors do not appear to be upwarped; however, Crone et al., 1985 report that in this area, narrow zones of disrupted reflectors, which they interpret as fault zones, coincide with the seismicity. The northeast end of the source zone probably merges with the Dyersburg, Tennessee-New Madrid seismicity trend. The latter trend is a northwest trending band of seismicity (see Figure 8b for location). Zoback and Hamilton (1980) postulate that the seismicity of this trend is spatially associated with igneous bodies of various ages, presumably emplaced along upper crustal zones of weakness that formed during the initial rifting. The zones of weakness probably formed in a regional extensional stress field rather than the current east-west compressive stress field indicated by fault plane solutions.

Thus, from the seismic profiles coupled with seismic network data, one can define the extent of a major intraplate seismic source zone in the Reelfoot Rift on the basis of geologic structure. The profiles also emphasize the role of preexisting rift related structures on the location of intraplate earthquakes.

Hydrogeologic Data:

Thermal data: Stearns and Reesman (Buschbach, 1984, pp. 145-162 and Buschbach, 1985, pp. 105-128) made ground water temperature measurements in 80 water wells in the Central Mississippi River Valley with the objective of locating zones where there is rapid ground water flux from depth. Such a zone is postulated to signify an unhealed fault. Vanderbilt located two significant anomalous areas. The principal one was in the Missouri bootheel and adjoining Lake

County, Tennessee (see Figure 11). This is in the area where many microearthquakes occur, and also where the Reelfoot Rift and Pascola Arch intersect (see Figure 9 for location of the Pascola Arch and Figure 8b for the location of the microearthquakes). A second area occurs along the Tennessee-Kentucky border, possibly along the east edge of the Reelfoot Rift. There was a remarkable correspondence between the thermal anomalies, some geologic structures in the area, and a zone of numerous microearthquakes. The thermal data can serve as a reconnaissance tool to locate areas worthy of further detailed investigation.

Hydrogeochemical data: Stearns and Reesman also studied the ground water chemistry of the 80 wells in which temperature measurements were made. The objective was to determine if chemical patterns could be linked with seismic activity and geophysical anomalies. Chemical patterns are difficult to draw from the sampled water wells because the data must be segregated by aquifer. However, some interesting relationships were identified. (Details are found in Buschbach, 1985, pp. 106-128.) The chloride level is high in alluvium near the Mississippi River in Missouri in the area of high earthquake activity along the Pascola Arch. Apparently there is vertical leakage along faults, from the McNairy Sandstone aquifer, from a depth of approximately 2000 feet to the land surface. Barium concentrations relate partially to the buried structures which were interpreted as plutons from aeromagnetic and gravity data. Highest concentrations of barium occur on and near the Missouri and Arkansas plutons on the west side of the rift. Lithium concentrations also are higher on the west side of the rift, notably in water above the Bloomfield pluton. Some of that lithium may originate from ground water flow along vertical fractures extending from the Bloomfield pluton to the ground surface. Strontium concentrations are high within the rift. Both lithium and strontium may well relate to the sediments in which the aquifer occurs. In addition to the lithium which may have come from vertical flow of ground water along fractures, igneous minerals containing lithium may have been washed or blown into the depositional area (Eocene volcanic activity). Strontium could be leached from aragonite-rich shells in marine sediment that might concentrate more in the rift if water was deeper there. As was the case with the ground water temperature data, the hydrogeochemical data also proved to be a useful reconnaissance tool. However, the chemical patterns can be complex and they require careful interpretation.

Surface Geology:

Investigation of major fault systems: Under sponsorship of NRC's New Madrid Seismotectonic Research Program, the major fault systems (see Figure 9) within a 200 mile radius of New Madrid were examined in detail to see if there was evidence of geologically recent offset, that is, movement during the Quaternary Period (approximately the last 2 million years). Results of that work is found in Kolata et al., 1981, Nelson and Lumm 1984 and 1985, and Ault, 1985. In the limited number of places where Quaternary materials cover these faults, no evidence of Quaternary reactivation was found.

Trench investigations: The U.S. Geological Survey excavated a trench across the Reelfoot scarp, within the Reelfoot Rift, about 20 miles southeast of New Madrid, Missouri (Russ 1979). The scarp is a prominent linear feature 3 - 9 meters high in an area which has little relief. It strikes in a northerly direction and forms the eastern boundary of the Tiptonville Dome. Deep seismic profiling in the area has shown the presence of a buried fault beneath the Reelfoot scarp which offsets Paleozoic, Mesozoic, and Tertiary strata. The Reelfoot scarp is thought to be an upward continuation of faults identified in the subsurface. The trench revealed a number of small faults and zones where there was ductile deformation of sediment layers similar to what one sees with seismically induced sand boils. Radiocarbon dating of mollusk shells in the trench indicates a maximum age for the sediment exposed in the trench of 2000 years. Field relations of the faults and sand boils indicate three episodes of movement within the last 2000 years. That movement is presumably related to New Madrid type events and it suggests a recurrence interval of about 600 years for earthquakes large enough to produce ground motion great enough to liquefy sand in the alluvium of the New Madrid area. Farther east in the Kentucky River Fault system, about 300 miles from New Madrid but close to the location of the Sharpsburg, Kentucky 1980 earthquake (body wave magnitude 5.1), nine trenches were excavated at four sites under a grant by NRC to the Kentucky Geological Survey (Van Arsdale and Seargeant, 1986) across mapped faults that were partially covered with Pliocene-Pleistocene age sediment. In four of the nine trenches Van Arsdale and Seargeant (1986) identified faulted or folded sediments. In their opinion the faulting an folding of the Pliocene-Pleistocene age sediment is tectonic in origin and that the Kentucky River Fault system has been active within the last 5 million years.

<u>Subsurface geology</u>: There have been 434 deep holes drilled within a 200-mile radius of New Madrid, Missouri. Much of the geologic history of that area can be deduced from lithologic and stratigraphic study of the materials encountered in these holes. Details of the geologic history can be found in Schwalb (1982) and Buschbach (1986, pp. 37-54). See also Figure 5 of this Research Information Letter for a short summary of the geologic history. Thirty-eight of them penetrate the Precambrian crystalline basement. The basement rocks are a mixture of granites, rhyolites and metamorphosed sediments. Age of the crystalline basement varies depending on location and the range is from around 1.0 to 1.5 billion years before present. The time of first rifting within the New Madrid Rift Complex is not known. However, sediments older than the late Cambrian are significantly thicker in the Rough Creek Graben and Reelfoot Rift than on the margins of these structures. That information plus the data provided through gravity, aeromagnetic, and seismic profiling point to the existence of linear troughs bounded by high angle faults dating from before late Cambrian time. Thus the troughs formed over 500 million years ago. For the remainder of the Paleozoic Era, sediments thickened in the Reelfoot and Rough Creek areas indicating topographic depressions but thicknesses were only slightly greater (a few hundreds of feet vs. thousands of feet prior to the late Cambrian) than the surrounding areas. Apparently after an initial episode of rifting a topographic depression was created. Although tectonic activity ceased, this area continued to subside at a slightly greater rate than the surrounding craton. The longevity of the Reelfoot Rift as a topographic depression is indicated by the fact that according to Potter (1978), the lower Mississippi River, i.e., south of the confluence with the Ohio River, has existed in approximately its present position for at least 250 million years and that its course has been structurally controlled, probably by the Reelfoot Rift. This correlation of

large river systems with rift structures is a common geological occurrence according to Potter (1978).

There was a long hiatus between the last Paleozoic sedimentation in the New Madrid area and the first Mesozoic deposits of Cretaceous age. From early Permian to late Cretaceous the sedimentary history of the New Madrid area is unknown because any sediments deposited have been completely removed. This interval is probably represented by uplift and erosion. Drilling in the area indicates that a karst topography developed on the land surface with sink holes later filled with late Cretaceous and younger sediments.

In Early to Mid-Mesozoic time Eastern North America underwent rifting as North America and Africa were split apart by plate tectonics (see Figure 4). The tensional forces which produced the rift basins in Eastern North America (e.g., Newark, Gettysburg, Richmond, Culpeper and Scottsville Basins) were also felt in the New Madrid area. They resulted in reactivation of the rift complex and igneous bodies were intruded along the margins of the ancient rift complex (see Figure 5). Subsurface information on the igneous bodies is derived primarily from geophysical data, principally gravity, aeromagnetics, and seismic profiling. The seismic profiling points to their emplacement before the late Cretaceous (Crone et al., 1985, p. 549). Surface geology supports this interpretation because to the west of the New Madrid area in Central Arkansas at Magnet Cove, and near Little Rock, there are surface outcrops of early Cretaceous syenites which have a similar gravity and aeromagnetic signature to circular features seen in the gravity and aeromagnetic maps of the Mississippi Embayment.

As North America and Africa continued to drift apart for the last 200 million years the regional stress field in Eastern North America has become a compressional one. It is this compressional stress field which is believed to have reactivated some of the old buried faults associated with the New Madrid Rift Complex.

SUMMARY AND CONCLUSIONS

The New Madrid Seismotectonic Research Program was a program of confirmatory research to provide information to support licensing decisions as to the cause of the large damaging earthquakes which have been observed in the Central Mississippi River Valley near New Madrid, Missouri. Prior to the program's inception in 1976, the NRC licensing staff had to rely primarily on surficial geology, a limited number of deep drill holes, and the pattern exhibited by earthquake epicenters. At that time it was not possible to link the earthquakes to known surface faults. To resolve the origin of the New Madrid area earthquakes and the extent of the seismically active area the New Madrid Program drew on many scientific disciplines. It was necessary to integrate surficial geology with subsurface geology through the use of improved earthquake locations, deep drill holes, geophysical exploration methods such as gravity, aeromagnetics, electrical resistivity, and seismic reflection and refraction profiling. These data were then linked with the seismicity and seismic history of the area. Through this integration of many lines of evidence a conceptual model was developed which provides a framework that relates the New Madrid area earthquakes to geologic structure. In this model the earthquakes are associated with an ancient rift complex. The New Madrid area earthquakes are the result of reactivation of structures associated with the formation of the rift complex such as deeply buried faults which extend into the earth's crust, or inhomogeneities associated with a buried zone of disturbed seismic reflectors found along the axis of one part of the rift complex and buried igneous bodies along the margins of the complex. Summarized below are significant points to be noted in licensing actions dealing with the cause and extent of the New Madrid seismicity:

1. The New Madrid area is located within the interior of the North American tectonic plate. (Areas of high seismic activity within crustal plates are rare.)

2. With respect to both size and number of earthquakes, the New Madrid area is currently the most seismically active region of the United States east of the Rocky Mountains (Herrmann, in Gori and Hays, 1984, p. 276; Johnson and Nava, in Gori and Hays, p. 283).

3. The New Madrid earthquakes of 1811-1812 are associated with tectonic structures which are part of the New Madrid Rift Complex. The New Madrid Rift Complex is a major tectonic feature within the North American Continent. It represents a "capable structure" within the meaning of Appendix A to 10 CFR Part 100.

4. Integration of geological/geophysical/seismological data has resulted in a conceptual model which relates historic and contemporary seismicity to geologic structures in the area.

5. The conceptual model consists of a rift complex, called the New Madrid Rift Complex, which has four arms--the Reelfoot Rift, the St. Louis Arm, the Indiana Arm, and the Rough Creek Graben.

6. The rift complex was formed in late Precambrian to Cambrian time (1,500 to 500 million years ago) in a tensional stress regime. There is sufficient geological/geophysical evidence to show that the Reelfoot, Indiana, and Rough Creek portions of the rift complex are down dropped fault blocks bounded by growth faults.

7. In late Paleozoic time (approximately 290 million years ago) the rift complex underwent compression. This resulted in: (a) uplift and subsequent erosion of sediments previously deposited in the rift complex, (b) folding, (c) renewed movement on pre-existing faults, and (d) igneous activity presumably along pre-existing fractures.

8. In late Mesozoic to early Eocene time (approximately 130 to 40 million years ago) there was renewed tectonic activity in the New Madrid Rift Complex as evidenced by renewed igneous activity and faulting of sediments up through the Eocene Epoch.

9. Contemporary stress measurements show that the New Madrid area is now in a compressional stress regime where the principal compressive stress is oriented approximately eastnortheast-westsouthwest.

10. Of the four arms of the New Madrid Rift Complex, the Reelfoot is by far the most active seismically.

11. Based on USGS trenching across the Reelfoot Scarp, the recurrence interval for earthquakes in the Reelfoot Rift large enough to produce ground motion great enough to liquefy sand in the alluvium of the New Madrid area is about 600 years (Russ, 1979).

12. In the southern part of the Reelfoot Rift there is an axial zone extending southwest from Caruthersville, Missouri to Marked Tree, Arkansas which shows as a "disturbed" zone in seismic reflection profiles. More than 90% of contemporary earthquakes in the region coincide with this disturbed zone (McKeown, in Gori and Hays, 1984, p. 11). The disturbed zone also underlies the area containing liquefaction features (sand blows) associated with the New Madrid 1811-1812 earthquakes.

13. The origin of the disturbed zone in the southern portion of the Reelfoot Rift is not known. It appears only in seismic reflection profiles and is absent from aeromagnetic and gravity maps. Crone et al. (1985) postulate that it represents an uplifted, faulted zone associated with felsic igneous bodies. Howe and Thompson (1984) propose that it is an uplifted, faulted zone of former growth faults that were reactivated in a compressional stress regime.

14. Immediately to the north of the disturbed zone, contemporary seismicity strikes approximately 330°, in contrast to the disturbed zone, which strikes 050°. Zoback et al. (1980), using seismic reflection data, related seismicity in the area to small faults and igneous plutons of various ages.

15. Based on geophysical data, the New Madrid research indicates that the Anna, Ohio seismic zone is not an extension of the New Madrid Rift Complex. The Anna seismicity is strongly localized on and around two geophysical anomalies. Whether they are the cause of the seismicity or just control its pattern is not known.

16. The New Madrid Rift Complex can be bounded by geological/geophysical data used in conjunction with historic seismicity. This is significant, for it means that a tectonic structure can be delineated and <u>that seismicity in the area can be linked to that tectonic structure</u>.

RECOMMENDATIONS

1. The New Madrid Rift Complex should be treated as a major tectonic feature within the North American Continental Plate.

2. The New Madrid Rift Complex should be treated as a seismically active area with the potential for earthquakes up to Modified Mercalli Intensity XII.

3. Seismic design criteria should assume a 600-year recurrence interval for earthquakes large enough to liquefy sand in the alluvium of the New Madrid area.

4. The following generalizations should be considered in drawing seismic hazards maps for sites in or near the New Madrid area.

   a. The zone of highest seismicity is located within the New Madrid Rift Complex and on the flanks of mafic plutons situated on its margins.

   b. The Reelfoot Rift is seismically the most active area. Within the last 2000 years it has experienced at least three intensity XI to XII events.

   c. The other three arms of the New Madrid Rift Complex, i.e., the St. Louis, Indiana, and Rough Creek, should be considered seismically active but to a lesser degree than the Reelfoot Rift.

   d. The seismicity of the New Madrid Rift Complex is distinct from that of the Anna, Ohio area. Based on geophysical evidence, the Indiana Arm of the New Madrid Complex appears not to extend north of latitude N39.5°.

Robert B. Minogue

Robert B. Minogue, Director
Office of Nuclear Regulatory Research

Enclosure: List of Selected References

4. The following generalizations should be considered in drawing seismic hazards maps for sites in or near the New Madrid area.

   a. The zone of highest seismicity is located within the New Madrid Rift Complex and on the flanks of mafic plutons situated on its margins.

   b. The Reelfoot Rift is seismically the most active area. Within the last 2000 years it has experienced at least three intensity XI to XII events.

   c. The other three arms of the New Madrid Rift Complex, i.e., the St. Louis, Indiana, and Rough Creek, should be considered seismically active but to a lesser degree than the Reelfoot Rift.

   d. The seismicity of the New Madrid Rift Complex is distinct from that of the Anna, Ohio area. Based on geophysical evidence, the Indiana Arm of the New Madrid Complex appears not to extend north of latitude N39.5°.

Original signed by:
ROBERT B. MINOGUE

Robert B. Minogue, Director
Office of Nuclear Regulatory Research

Enclosure: List of Selected References

Distribution/R-2811:

Circ/Chron	EConti
DCS/PDR	LBeratan
ESB Sbj/Rd	AMurphy
RBMinogue	D/N: Memo Denton/146
DRoss	EO'Donnell
KGoller	

*Note: See Previous Concurrences

OFC:ESB:RES:jk	:ESB:RES	:ESB:RES	:DRPES:DD	:DRPES:D	:RESDD	:RES:D
NAME:EO'Donnell*	AMurphy *	:LBeratan*	:EConti *	:KGoller*	:DRoss *	:RBMinogue
DATE:6/ /86	:6/ /86	:6/ /86	:6/ /86	:6/ /86	:6/ /86	:6/30/86

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   a. The zone of highest seismicity is located within the New Madrid Rift Complex and on the flanks of mafic plutons situated on its margins.

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   d. The seismicity of the New Madrid Rift Complex is distinct from that of the Anna, Ohio area. Based on geophysical evidence, the Indiana Arm of the New Madrid Complex appears not to extend north of latitude N39.5°.

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Distribution/R-2811:

Circ/Chron	RMinogue	EConti	D/N: Memo Denton/146
DCS/PDR	DRoss	LBeratan	
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ESB:RES:DF	ESB:RES	ESB:RES	DRPES:DD	DRPES:D	RES:DD	RES:D
EO'Donnell	AMurphy	LBeratan	EConti	KGoller	DRoss	RMinogue
05/27/86	05/27/86	05/27/86	05/ /86	05/27/86	05/29/86	05/ /86

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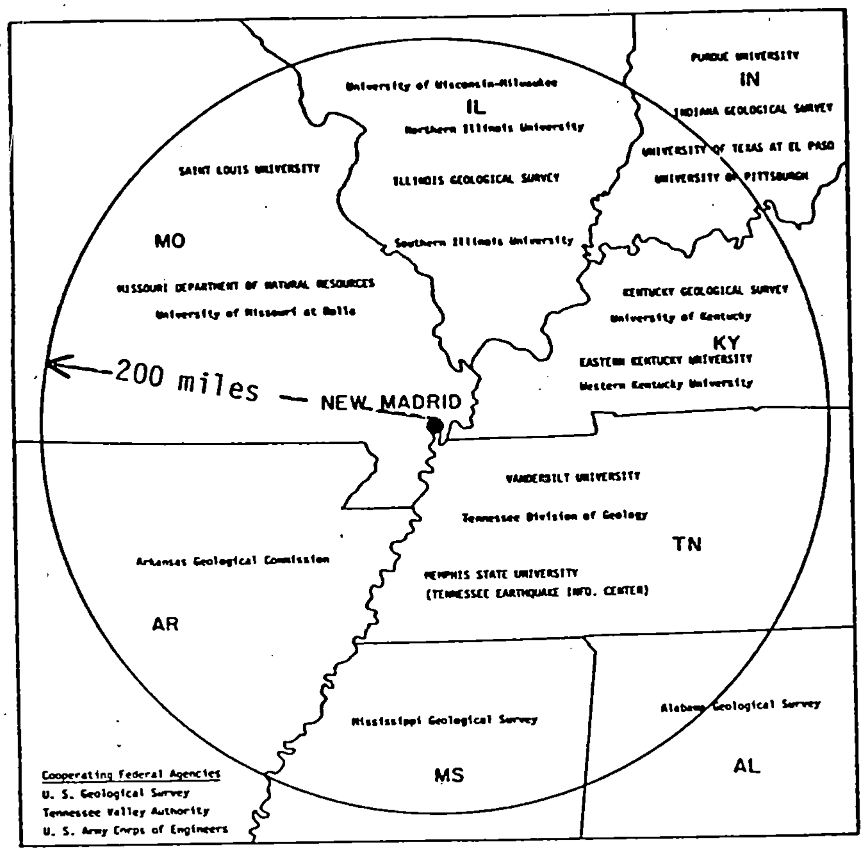


Figure 1. The New Madrid Area, showing State Geological Surveys, Universities, and Federal Agencies cooperating in the New Madrid Seismotectonic Research Program. (NUREG/CR 4226)

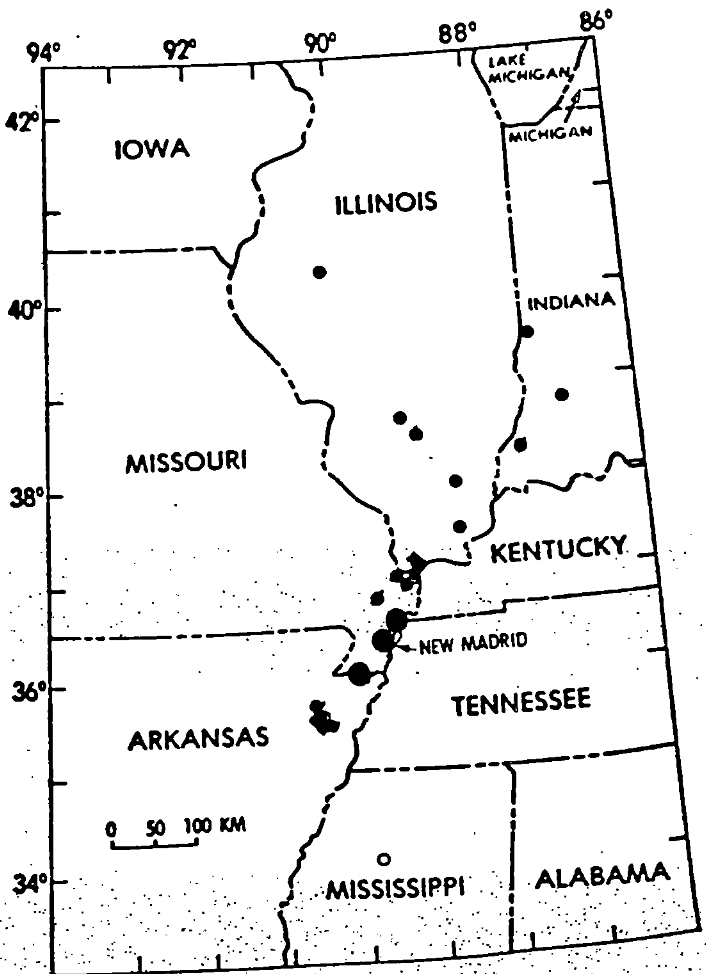
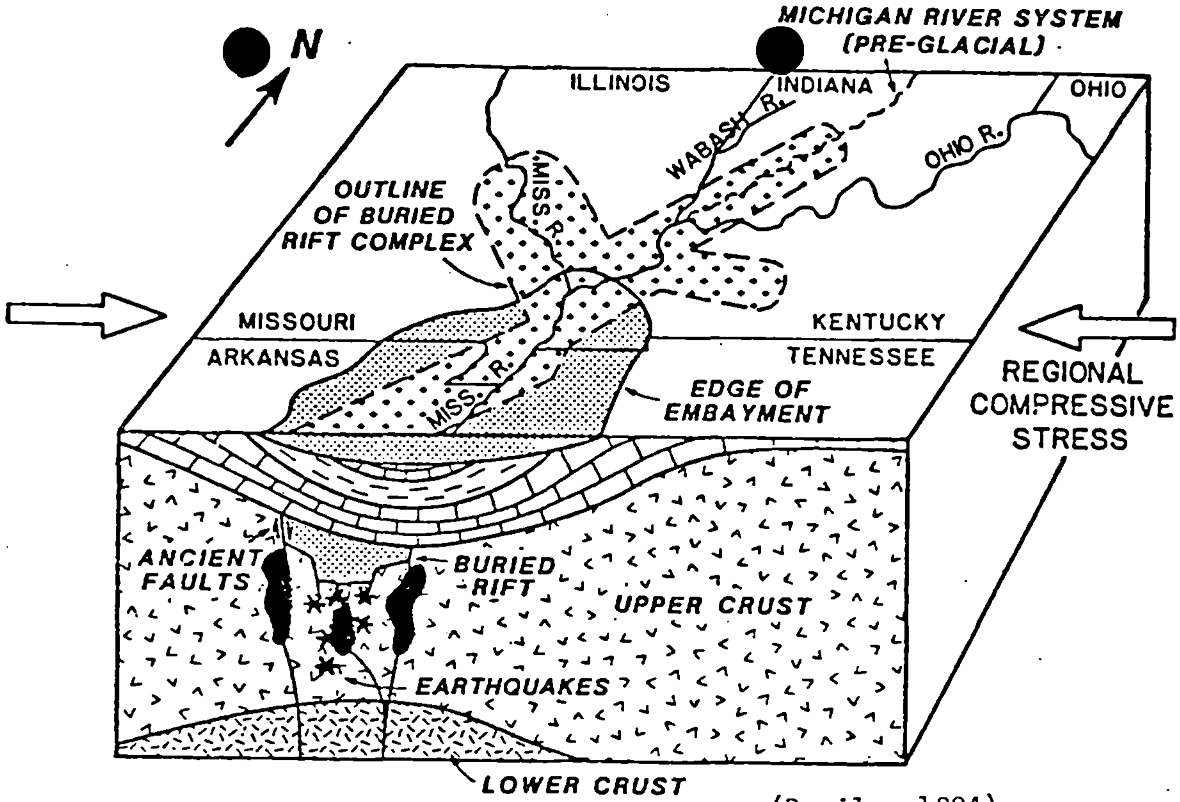


Figure 2. Epicenters of damaging earthquakes in the Central Mississippi River Valley. Large circles are the epicenters of the three major earthquakes of 1811-1812. Epicenters of the 203 damaging aftershocks are not plotted. Small circles are the epicenters of damaging earthquakes which occurred subsequent to 1812. (modified from Nuttli, 1982)



(Braile, 1984)

Figure 3 a. Block diagram illustrating the present configuration of the buried New Madrid Rift Complex. The structurally controlled rivers, Paleozoic rocks in cratonic sedimentary basins, and the Mississippi Embayment, all associated with the buried rift complex, are also shown. Dark areas indicate intrusions near the edge of the buried rift. An uplifted and possibly anomalously dense lower crust is suggested as the cause of the linear positive gravity anomaly associated with the upper Mississippi Embayment.

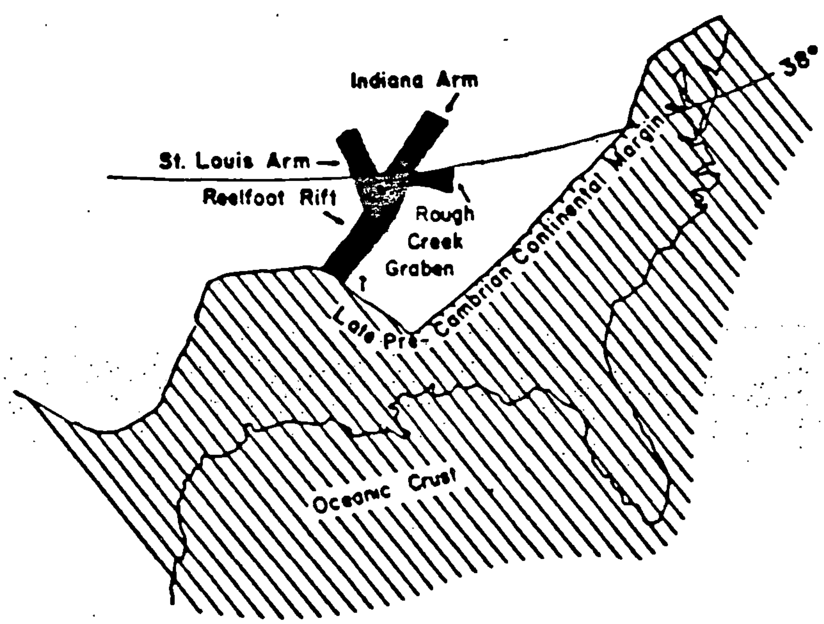


Figure 3 b. The New Madrid Rift Complex is subdivided into four arms

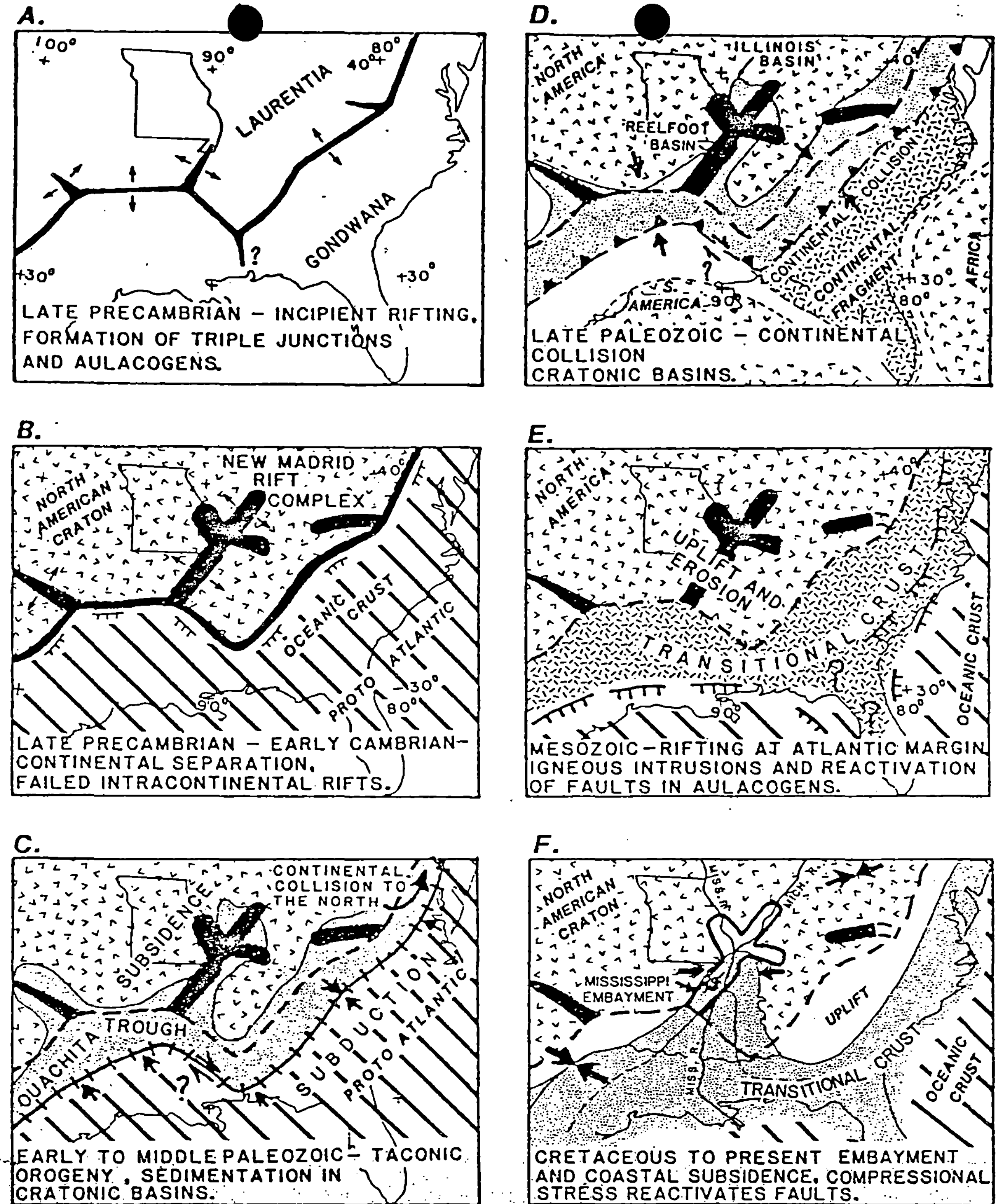
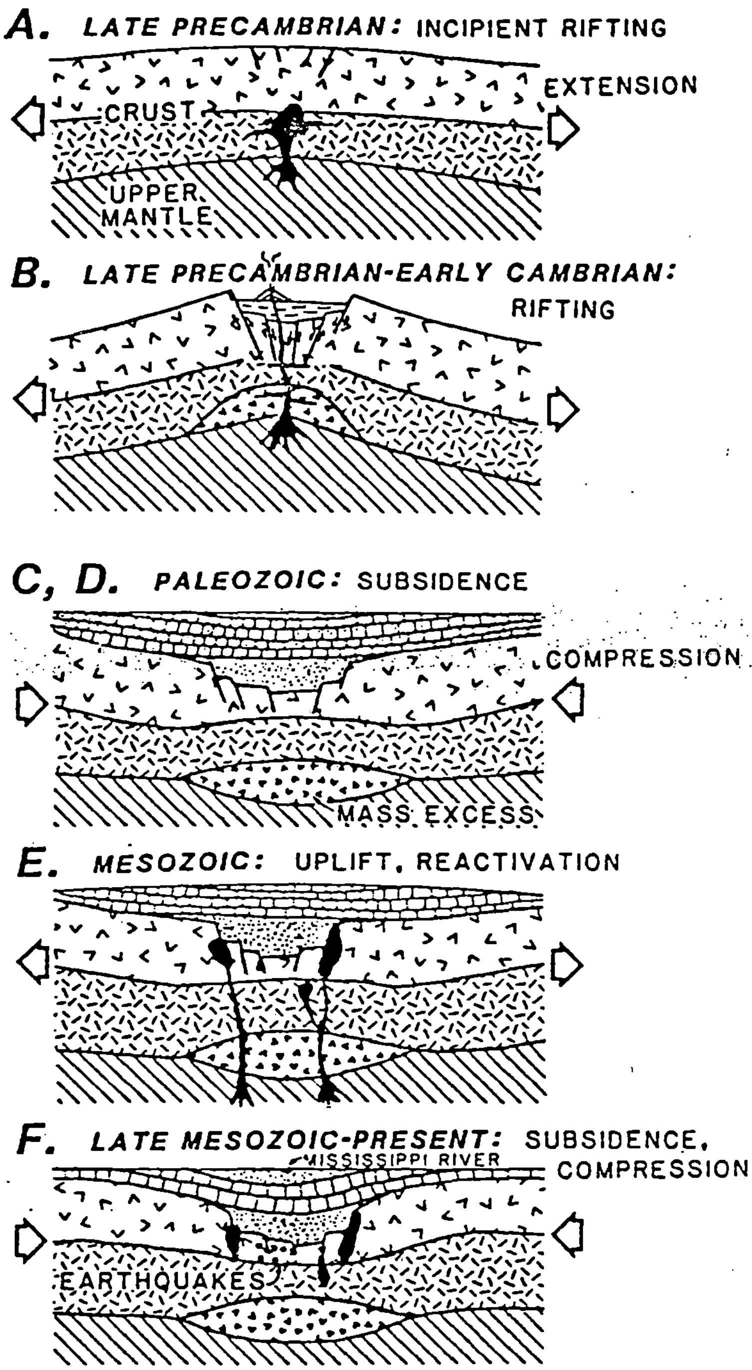


Figure 4. Schematic diagrams illustrating the plate reconstruction of the North American craton and interactions with adjacent plates and geologic activity of the New Madrid Rift Complex since the late Precambrian. The outline of the State of Missouri is shown for location and approximate scale. (Braile, 1984).



(Braile, 1984)

Figure 5. Schematic cross sections for a northwest-southeast profile through the New Madrid Rift Complex illustrating the evolution of the rift complex and associated cratonic basins through time. Stages of development shown in parts A through F are related approximately to the map views illustrated in the corresponding diagrams in Figure 4.

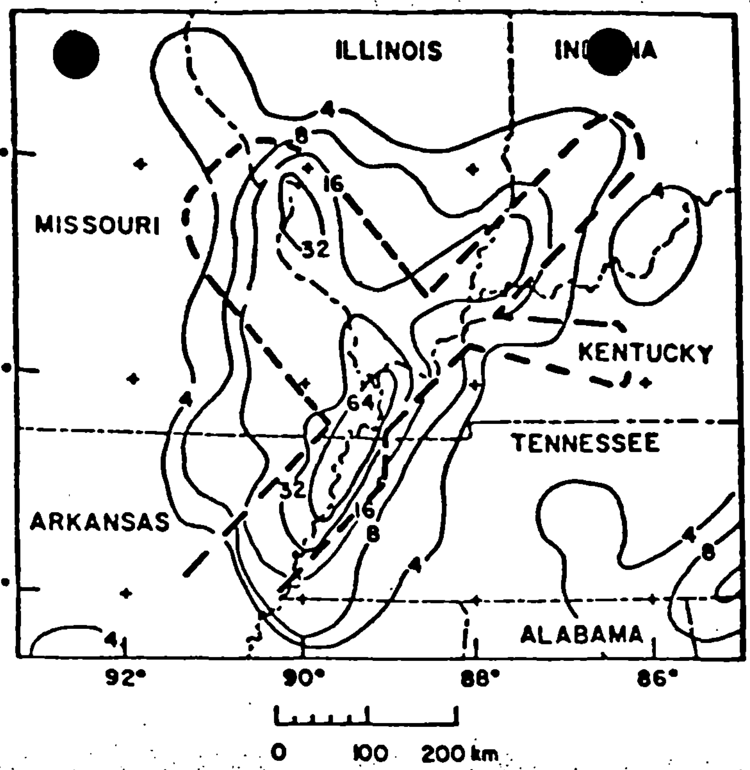
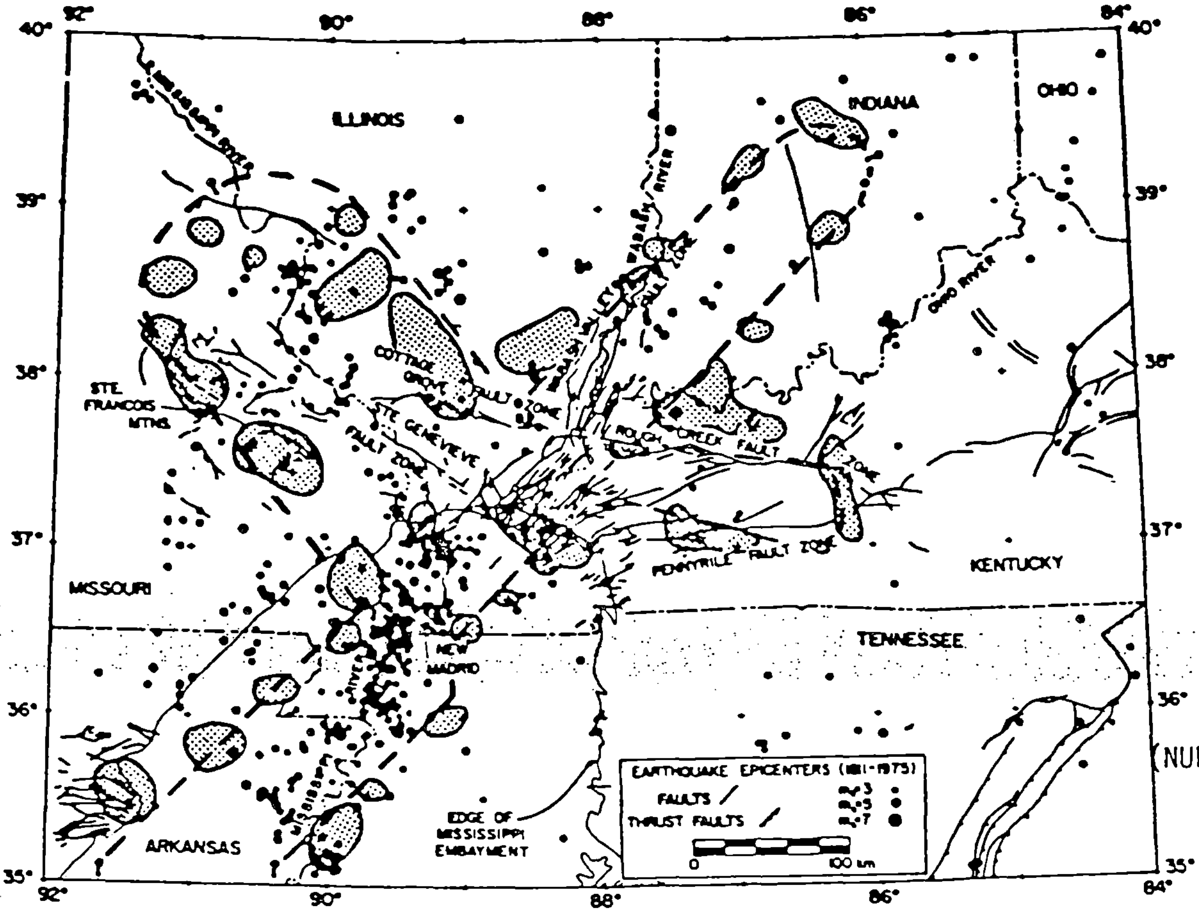


Figure 6. Map showing the contours of the number of earthquake epicenters of modified Mercalli intensity greater than III from 1800 to 1972 per 10^4 km^2 for the New Madrid area (after Hadley and Devine, 1974). Heavy dashed lines are inferred boundaries of the rift complex as shown in Figure 3. (Braile et al., NUREG/CR 2741).



(NUREG/CR 3174)

Figure 7. Earthquake epicenters, tectonic features, and inferred boundaries of the rift complex in the New Madrid area. The shaded regions are areas of positive gravity and magnetic anomalies which have been used to infer the boundaries of the rift complex. (NUREG/CR 3174).

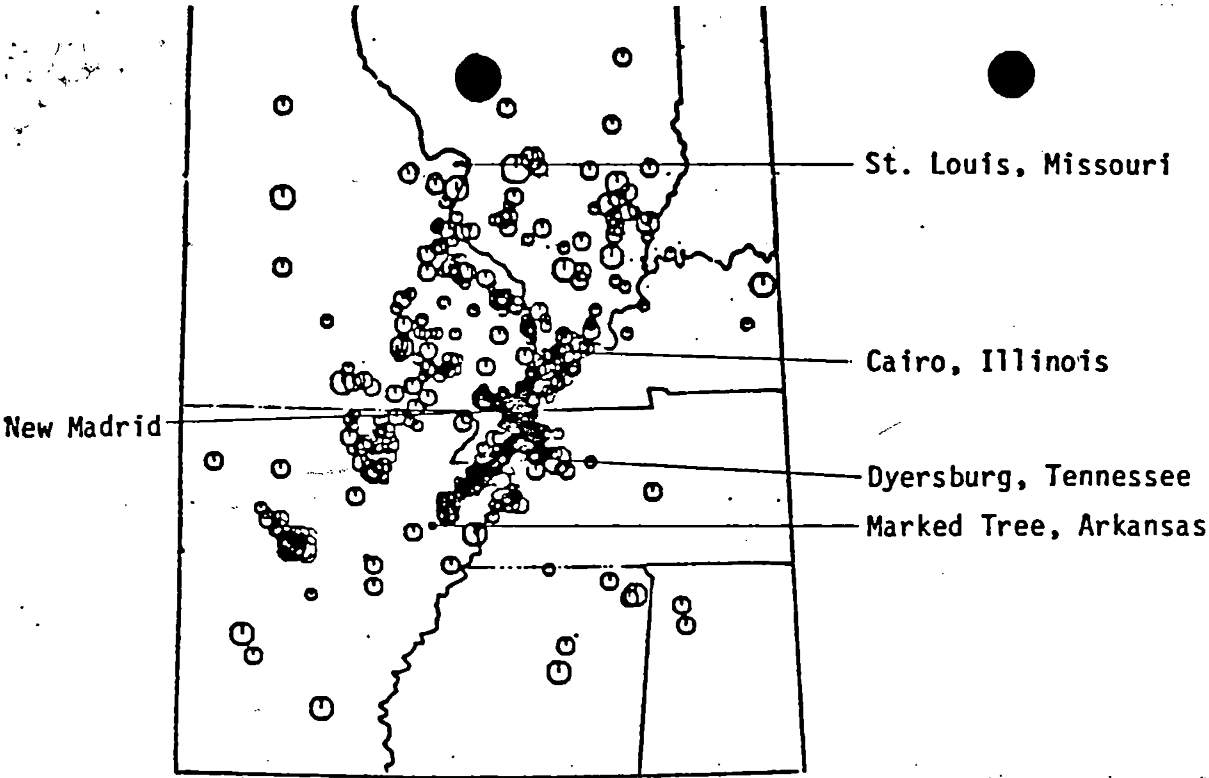


Figure 8 a. Location of earthquakes detected and located using the dense regional network for the reporting period 1976 – 1982.

(Hermann, 1983)

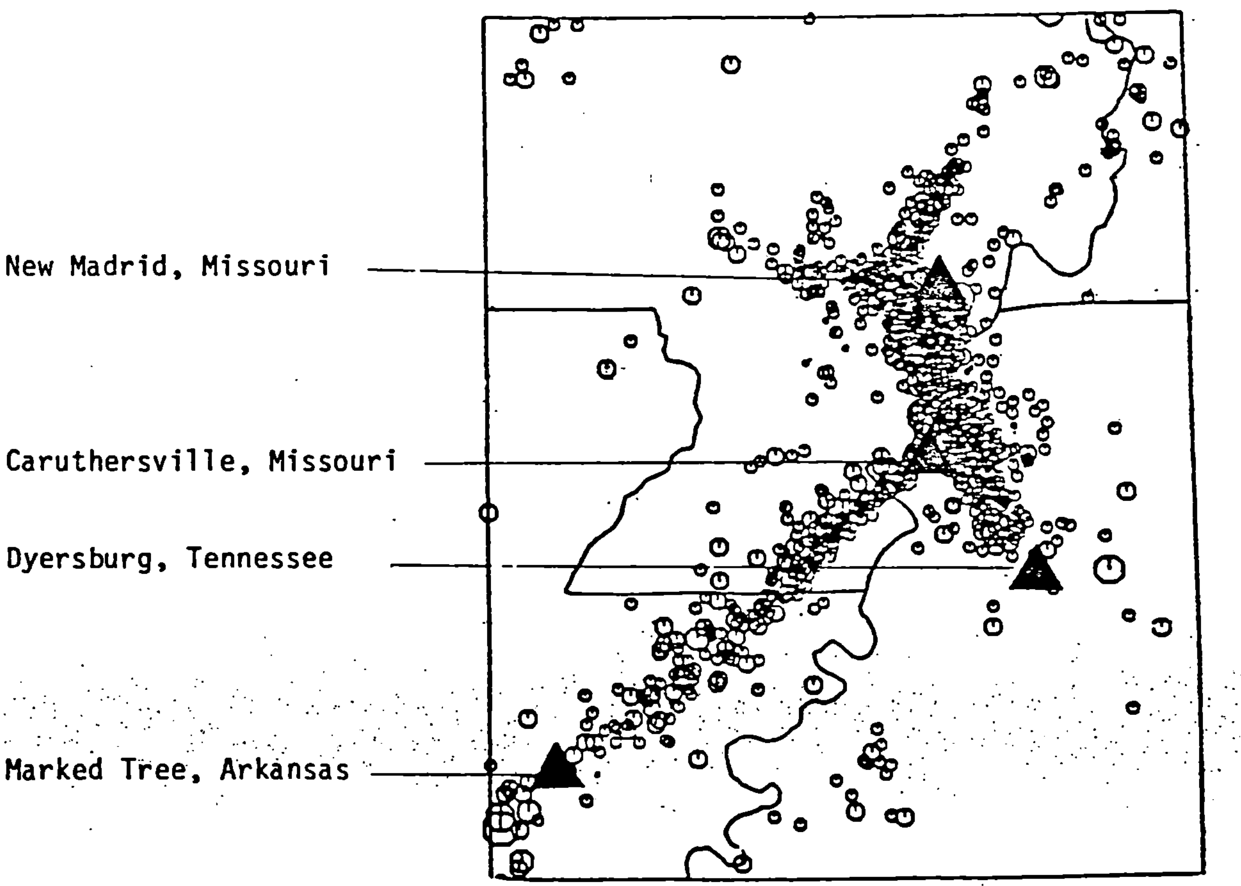
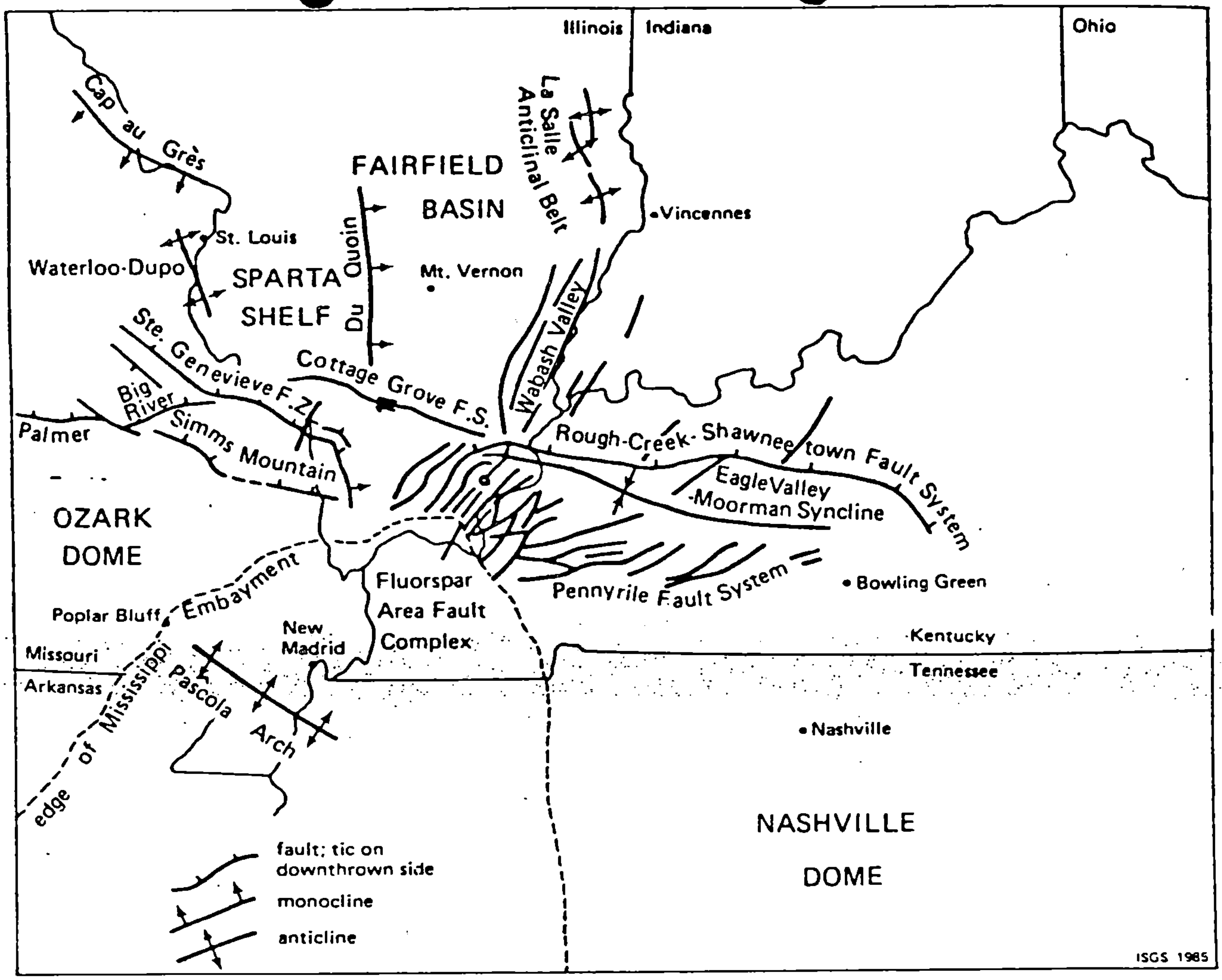


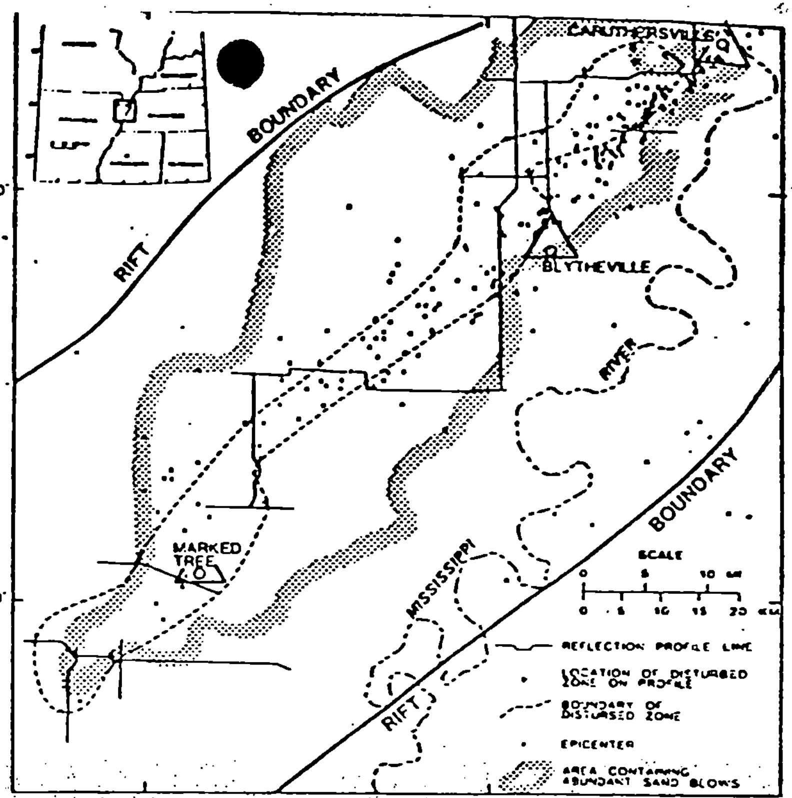
Figure 8 b. Location of earthquakes detected and located using the dense regional network for the reporting period 1976 – 1982 in the immediate vicinity of New Madrid, Missouri.

(Hermann, 1983)



(From Nelson and Lumm, 1985, NUREG/CR 4333)

Figure 9. Principal tectonic features in the New Madrid area.



(Crone et al., 1985)

Figure 10 a. Preliminary map showing relationship of seismicity to disturbed zone mapped at the depth of magnetic basement in the southern part of the New Madrid seismic zone. Epicenters are for the period June 29, 1974, through March 28, 1981, from R. B. Herrmann (written commun., 1981).

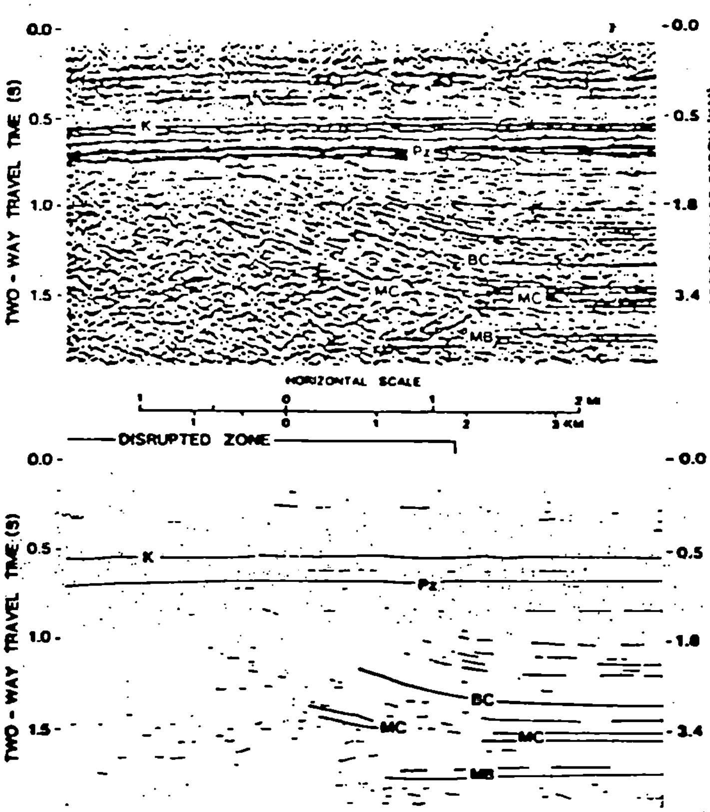


Figure 10b. Seismic reflection profile and interpretive line drawing showing details of one edge of the disturbed zone shown in Figure 10a. Note the structural divergence between the magnetic basement (MB) and the slightly warped top of the Paleozoic (PZ). Specific location of these data cannot be identified because they are proprietary.

legend: K = Cretaceous
PZ= Top of Paleozoic sediments
BC= Base of marine carbonates
MB= Magnetic basement

(Crone et al., 1985)

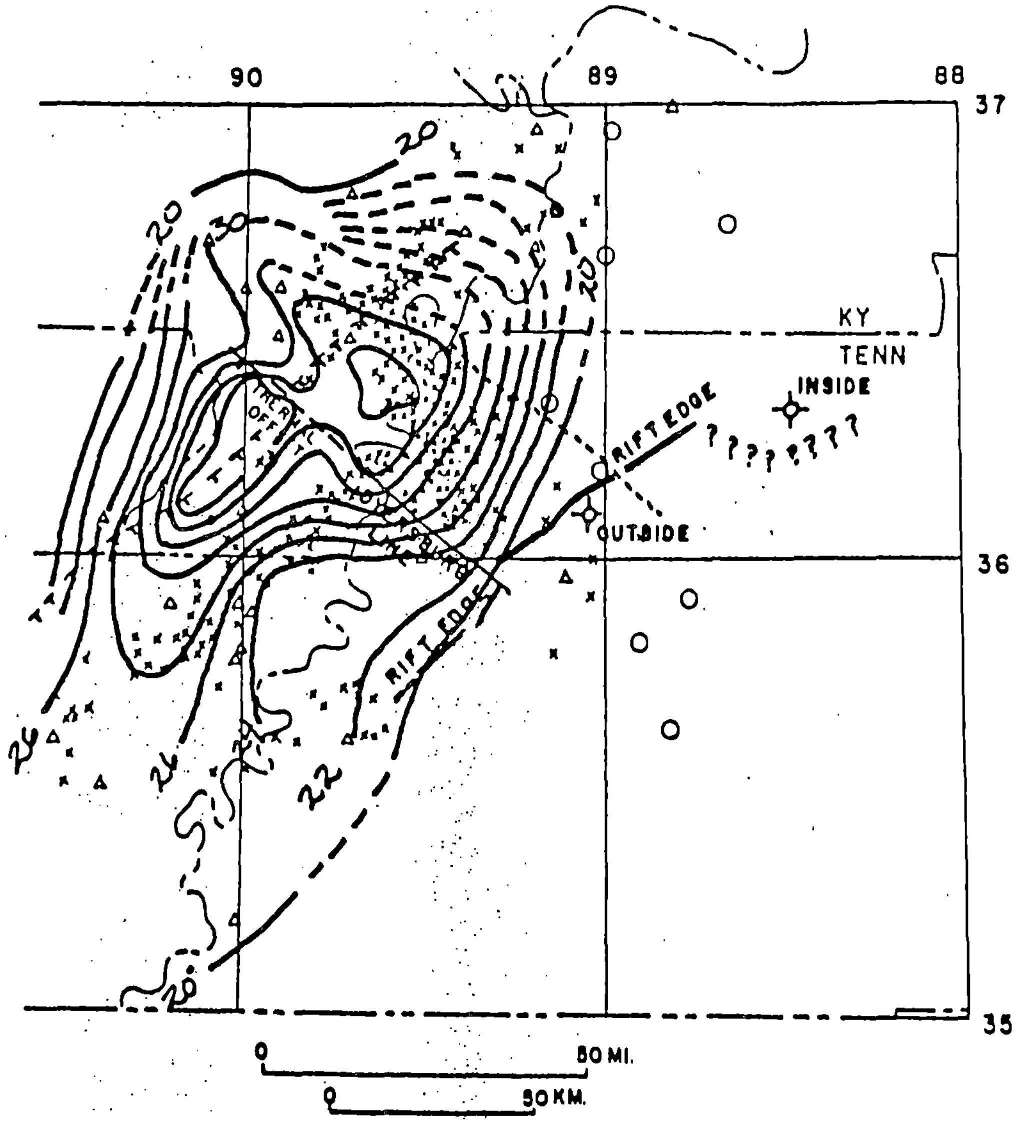


Figure 11. Temperature gradients in relation to the edge of the Reelfoot Rift and location of earthquakes. Contours are in degrees c/km. Note the correspondance of contours with the Dyersburg Line and earthquakes. (Modified from NUREG/CR 4226)

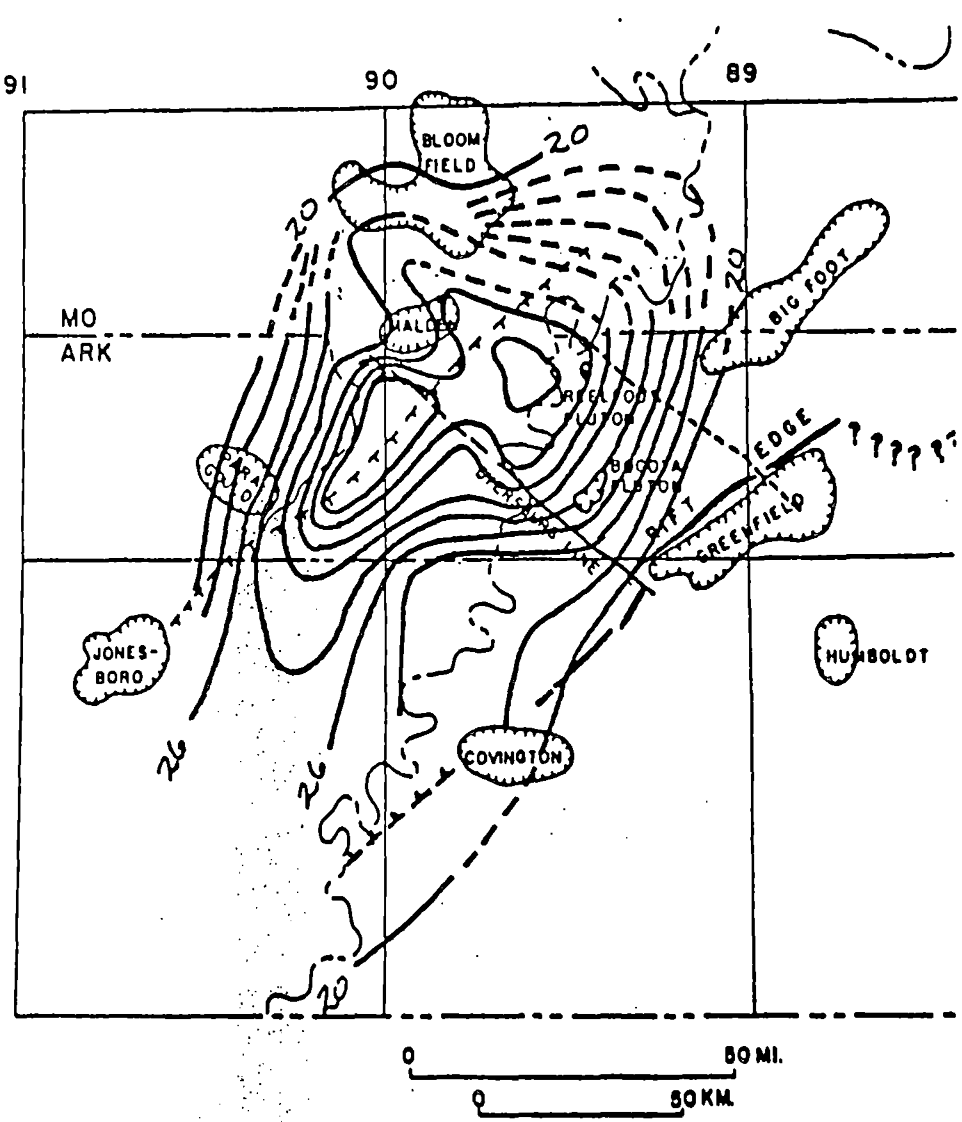


Figure 12. Temperature gradients in relation to the edge of the Reelfoot Rift and buried plutons. (Modified from NUREG/CR 4226).

MAJOR GEOCHRONOLOGIC AND CHRONOSTRATIGRAPHIC UNITS

Subdivisions in use by the U. S. Geological Survey (and their map symbols)					Age estimates[1] of boundaries in million years (m.y.)	
Phanerozoic Eon or Eonothem	Cenozoic Era or Erathem (Cz)	Quaternary Period or System (Q)		Holocene Epoch or Series	0.010	
				Pleistocene Epoch or Series	2	(1.7-2.2)
		Tertiary Period or System (T)	Neogene Subperiod or Subsystem (N)	Pliocene Epoch or Series	5	(4.9-5.3)
				Miocene Epoch or Series	24	(23-26)
			Paleogene Subperiod or Subsystem (Pe)	Oligocene Epoch or Series	38	(34-38)
				Eocene Epoch or Series	55	(54-56)
				Paleocene Epoch or Series	63	(63-66)
	Mesozoic Era or Erathem (Mz)	Cretaceous Period or System (K)		Late Cretaceous Epoch or Upper Cretaceous Series	96	(95-97)
				Early Cretaceous Epoch or Lower Cretaceous Series	138	(135-141)
		Jurassic Period or System (J)			205	(200-215)
		Triassic Period or System (TR)			~240	
	Paleozoic Era or Erathem (Pz)	Permian Period or System (P)			290	(290-305)
		Carboniferous Periods or Systems (C)	Pennsylvanian Period or System (IP)		~330	
			Mississippian Period or System (M)		360	(360-365)
		Devonian Period or System (D)			410	(405-415)
		Silurian Period or System (S)			435	(435-440)
		Ordovician Period or System (O)			500	(495-510)
		Cambrian Period or System (Є)			~570[2]	
Proterozoic Eon or Eonothem (P)	Proterozoic Z (Z)[3]				800	
	Proterozoic Y (Y)[3]				1,600	
	Proterozoic X (X)[3]				2,500	
Archean Eon or Eonothem (A)				Oldest known rocks in U. S.	3,600	

[1] Ranges reflect uncertainties of isotopic and biostratigraphic age assignments. Age of boundaries not closely bracketed by existing data shown by ~. Decay constants and isotope ratios employed are cited in Steiger and Jager (1977).

[2] Rocks older than 570 m.y. also called Precambrian (pЄ), a time term without specific rank.

[3] Time terms without specific rank.

Geologic Names Committee, 1980 edition

Figure 13. Geologic Time Scale. (U. S. Geological Survey)