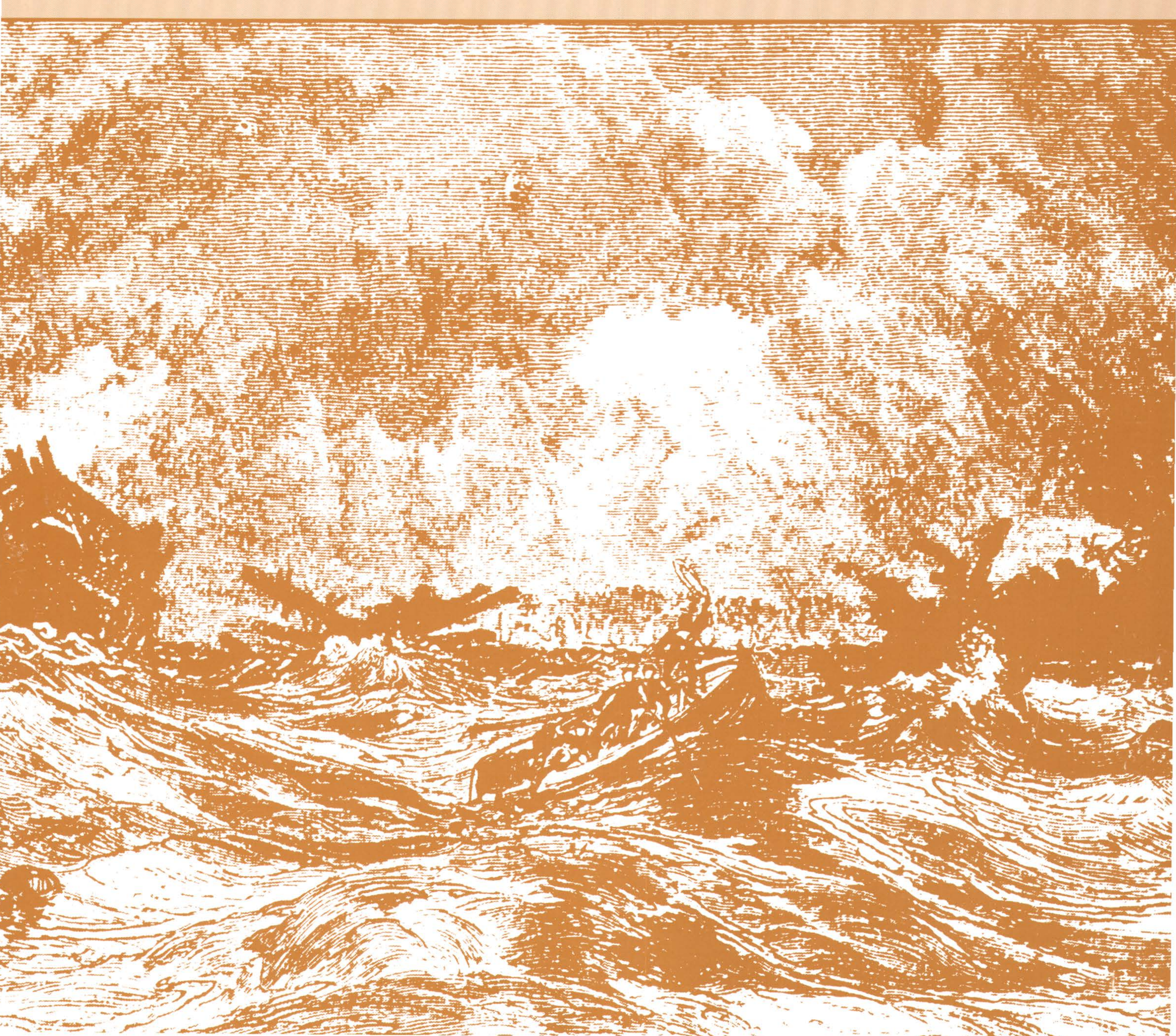
U.S. GEOLOGICAL SURVEY CIRCULAR 1066

Tecumseh's Prophecy: Preparing for the Next New Madrid Earthquake

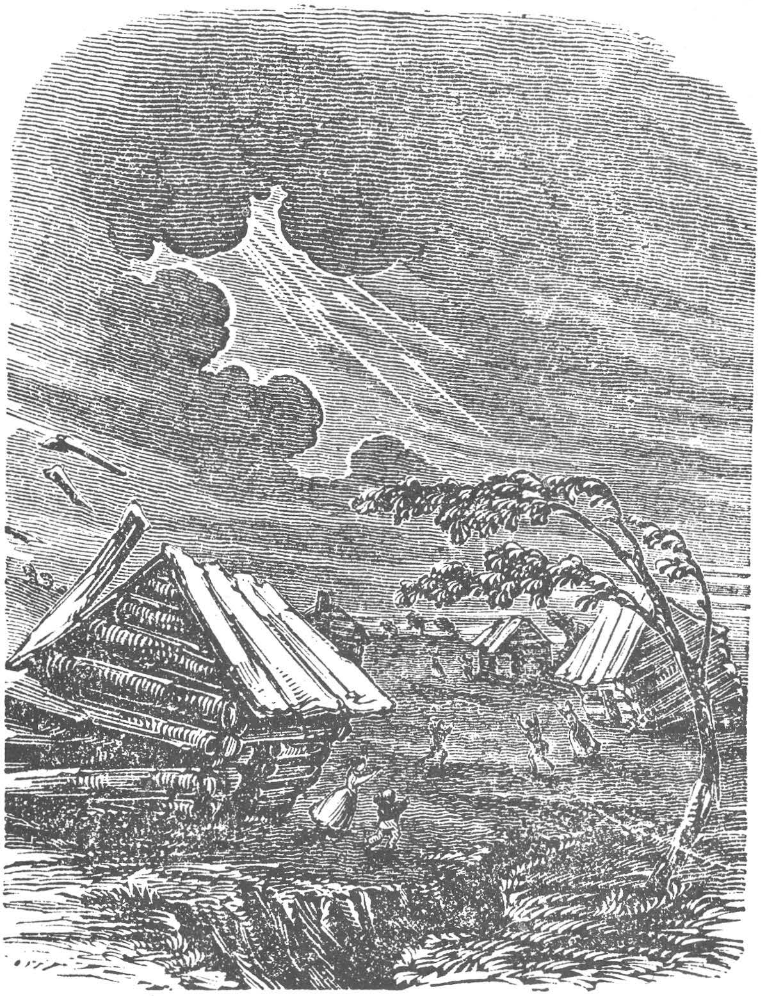


COVER

Woodcut of "Scene of the Great Earthquake in the West" (*Our First Century: One Hundred Great and Memorable Events,* 1877, p. 220). Published with permission of the State Historical Society of Missouri, Columbia, Mo.

ABOUT THE TITLE

According to legend, (Penick, 1981, p. 123), the Shawnee Indian chief Tecumseh traveled south in 1811 from his village of Tippecanoe on the Wabash River in an attempt to recruit supporters. At a town of Creek Indians near the site of Montgomery, Ala., Tecumseh declared that they would know he was sent by the Great Spirit because, upon leaving, he would go to Detroit, stamp his foot on the ground, and shake down all their houses. Tecumseh left. The Creeks counted the days; on the morning they had estimated for his arrival in Detroit, the earth began to shake, and houses fell down. It was the first of the New Madrid, Mo., earthquakes, which were centered about 250 mi away in the Mississippi Valley.



"The Great Earthquake of New Madrid 1811–1812." Published with permission of the State Historical Society of Missouri, Columbia, Mo.

TECUMSEH'S PROPHECY:
PREPARING FOR THE NEXT NEW MADRID EARTHQUAKE

Tecumseh's Prophecy: Preparing for the Next New Madrid Earthquake

A PLAN FOR AN INTENSIFIED STUDY OF THE NEW MADRID SEISMIC ZONE

Edited by ROBERT M. HAMILTON and
ARCH C. JOHNSTON

With contributions by the participants in the New Madrid Seismic Zone Workshop, November 15-16, 1989, Memphis, Tennessee

U.S. GEOLOGICAL SURVEY CIRCULAR 1066

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

First printing 1990
Second printing 1991

UNITED STATES GOVERNMENT PRINTING OFFICE: 1990

Free on application to the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

Library of Congress Cataloging in Publication Data

Tecumseh's prophecy.

(U.S. Geological Survey circular ; 1066)
"With contributions by the participants in the New Madrid Seismic Zone Workshop, November 15-16, 1989, Memphis, Tennessee."
Includes bibliographical references.
Supt. of Docs. No.: I 19.4/2:1066
1. Earthquakes—Missouri—New Madrid Region. 2. Seismology—Missouri—New Madrid Region. I. Hamilton, Robert Morrison, 1936- . II. Johnston, Arch C. III. Series.
QE535.2.U6T43 1990 551.2'2'09778985 90-3151

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Tecumseh's Prophecy: Preparing for the Next New Madrid Earthquake

A Plan for an Intensified Study of the New Madrid Seismic Zone

Edited by Robert M. Hamilton[1] *and* Arch C. Johnston[2]

Summary

Four earthquakes of magnitude near 8 and thousands of aftershocks struck the central Mississippi Valley in the winter of 1811–12. New Madrid, Mo., the largest settlement in the area at the time, and the surrounding land were devastated. The New Madrid region continues to have the highest level of seismicity in the United States east of the Rocky Mountains. Earthquakes of estimated magnitude 6.4 and 6.8 occurred in 1843 and 1895, respectively; statistical analyses indicate that earthquakes of magnitude greater than 6.0 are expected at least once per century.

The potential losses from future earthquakes of magnitude 6 or greater in the New Madrid region are expected to be large because of (1) the high population density (Memphis, St. Louis, and many moderate-sized agricultural and industrial towns), (2) the large number of structures and industrial and transportation facilities, which generally were not designed to withstand earthquakes, (3) the great thickness and extent of poorly consolidated sedimentary rocks, which are weak foundation material and which amplify ground vibrations, and (4) the large area that would be affected by damaging ground motion (about 10 times larger than the area affected by a California earthquake of comparable size). A future great earthquake (magnitude 8.0 or larger) has the potential to cause damages in the tens of billions of dollars and deaths in the thousands unless communities reduce their vulnerability through improved preparedness and increased mitigation measures. A magnitude 6.5 earthquake could cause about $3.6 billion in losses to housing.

Loss of life and damage from earthquakes can be reduced through a variety of measures, all of which could be implemented in the New Madrid region. The most relevant actions include:

- Improving building construction requirements and siting practices through better codes and regulations.
- Reducing building vulnerability by strengthening or demolishing hazardous buildings, particularly unreinforced masonry buildings, and strengthening foundations. This action should begin with schools, hospitals, and emergency centers.
- Increasing awareness and utilization of earthquake mitigation measures through public education and training of those who would implement the measures.
- Improving public response to earthquake disasters through preparedness planning involving realistic scenarios of destructive earthquakes.

Mitigation measures such as these would be implemented by the local, State, and Federal Government agencies that are responsible for emergency preparedness and building regulation and by private and industrial groups. Such measures were in place, to a significant extent, and substantially reduced the losses that might otherwise have occurred as a result of the Loma Prieta earthquake in the San Francisco Bay area on October 17, 1989. Implementing mitigation measures in the New Madrid region has lagged far behind implementation in California, primarily because earthquakes occur less frequently in the New Madrid region, and the public is therefore less aware of the destructive potential. However, the lower frequency of destructive New Madrid earthquakes is offset by the greater area that they affect and by the greater vulnerability of structures and lifeline systems in the region.

Mitigation measures cannot be implemented effectively without reliable information about the likely locations, sizes, frequency, and probable effects of future

[1] U.S. Geological Survey, Reston, VA 22092.

[2] Center for Earthquake Research and Information/Memphis State University, Memphis, TN 38152.

Manuscript approved for publication March 13, 1990.

earthquakes. Because such information is currently incomplete for the New Madrid region, some of the major goals of an intensified study should be to improve the information that would be used as the basis for mitigation.

An intensified study of the New Madrid seismic zone should focus on five goals:

1. Implementing earthquake-hazard mitigation measures.
2. Improving preparedness for earthquakes of magnitude 6 or larger.
3. Establishing a **modern** seismic network in the New Madrid seismic zone to monitor the sizes, locations, and characteristics of the earthquakes and to determine the nature of the ground motions that they generate.
4. Locating faults that could generate destructive earthquakes, determining the recurrence rates of earthquakes, and delineating areas of potential damage.
5. Improving seismic-risk assessments.

Depending on the options selected and the pace of the study, these recommendations could be implemented at a funding level of $5 to $10 million annually for 5 years, at which time progress should be reviewed and a new plan prepared. An intensified study would be conducted under the auspices of the National Earthquake Hazards Reduction Program (NEHRP), which involves the Federal Emergency Management Agency (FEMA), the U.S. Geological Survey (USGS), the National Science Foundation (NSF), and the National Institute of Standards and Technology (NIST). **An intensified study should include the full scope of NEHRP activities.** Generally, mitigation measures are the responsibility of FEMA, NSF, and NIST, and research is the responsibility of USGS and NSF. Coordination of the study would be facilitated by establishing a coordinating committee and by holding an annual workshop to review recent developments and progress and to recommend priorities.

INTRODUCTION

The New Madrid seismic zone in the central Mississippi Valley poses the greatest earthquake danger in the United States east of the Rocky Mountains. Four earthquakes of about magnitude 8 (table 1) occurred in the seismic zone in the winter of 1811–12, and the area continues to experience the highest level of seismicity in the central and eastern parts of the Nation (fig. 1). Concern about the probable effects of future New Madrid earthquakes convinced Congress to direct the U.S. Geological Survey to prepare a plan for an intensified study of the New Madrid seismic zone. The first step in preparing the plan was to convene a workshop of about 70 academic, private, and State and Federal Government experts (appendix) in Memphis, Tenn., on November 15–16, 1989, to prepare recommendations for such an intensified study. This publication summarizes the results of that workshop.

Earthquake studies in the United States are conducted mainly under the auspices of the National Earthquake Hazards Reduction Program (NEHRP), which was authorized by the Earthquake Hazards Reduction Act of 1977 and its subsequent amendments and reauthorizations. The Federal agencies that participate in NEHRP and their areas of responsibility are as follows:

- **Federal Emergency Management Agency (FEMA):** Lead agency of NEHRP; planning, coordination, and program review; annual report to Congress; opportunities for participation by States, localities, private organizations, and individuals; assistance to State and local governments to implement comprehensive earthquake-hazard reduction programs; improved seismic design and construction techniques and standards for application; public education and awareness programs; and coordination of Federal response to catastrophic earthquakes.
- **U.S. Geological Survey (USGS):** Earthquake potential; earthquake prediction; earthquake information and data services; earthquake hazards and risk assessments; strong-ground-motion data and estimates; and technical assistance in fostering implementation of loss-reduction measures.
- **National Science Foundation (NSF):** Earthquake engineering research; earthquake preparedness and emergency response research; social, economic, and political impacts; earthquake research information; and fundamental studies on the sources and mechanisms of earthquakes and on earth structure.
- **National Institute of Standards and Technology (NIST):** Seismic design and construction standards and Federal construction practices.

Representatives from the four NEHRP Federal agencies attended the workshop. The recommendations in this report cover the full scope of responsibilities under NEHRP.

NEHRP not only involves a partnership among four Federal agencies but also encompasses participation by scientists, engineers, and others from universities, State and local government agencies, private groups, and other Federal agencies. University scientists, in particular, have played an important role in NEHRP, a role that developed from their pioneering studies of U.S. earthquakes. Federal Government agencies that are not formally part of NEHRP also have contributed significantly to earthquake studies in the New Madrid region. Most importantly, the U.S. Nuclear Regulatory Commission (NRC) has supported a comprehensive scientific research effort that included expansion of regional seismic network coverage during the late 1970's and early 1980's. Recently, the NRC has been gradually withdrawing financial support for the regional seismic networks; support is scheduled to end in 1992. In

Table 1. Damaging earthquakes in the New Madrid region (data from Nuttli (1983), Coffman and others (1982), and Johnston (1990))

[M is moment magnitude (Hanks and Kanamori, 1979), which is proportional to the logarithm of the product of slip on a fault, the area that slipped, and the rigidity. All magnitudes referred to in the text are moment magnitudes. m_b is body-wave magnitude. MMI_0 is maximum Modified Mercalli intensity]

Date	Lat (°N)	Long (°W)	M	m_b	MMI_0	Locality
1811/12/16	36	90	8.2	7.2	11	New Madrid, Mo.
1811/12/16	36	90	7.8	7.0	11	......do......
1812/01/23	36.3	89.6	8.1	7.1	10–11	......do......
1812/02/07	35.5	89.6	8.3	7.4	11–12	......do......
1838/06/09	38.5	89	5.1	5.0	7–8	Southern Illinois
1843/01/04	35.5	90.5	6.4	6.0	8	Marked Tree, Ark.
1857/10/08	38.7	89.2	5.1	5.4	7	Southern Illinois
1865/08/17	35.5	90.5	5.2	5.3	7	Southeastern Missouri
1891/09/27	38.3	88.5	5.5	5.8	7	Southern Illinois
1895/04/12	37.0	89.4	6.8	6.2	9	Charleston, Mo.
1899/04/29	38.8	87.0	4.3	4.6	7	Vincennes, Ind.
1903/11/04	36.9	89.3	5.0	4.9	7	Southeastern Missouri
1905/08/21	36.8	89.6	4.9	4.8	7	Mississippi Valley
1909/05/26	42.5	89.0	5.2	5.1	7	Illinois
1909/07/19	40.2	90.0	4.3	4.6	7	......do......
1909/09/27	39.5	87.4	4.7	4.8	7	Indiana-Illinois border
1917/04/09	38.1	90.2	4.9	5.0	6–7	Eastern Missouri
1922/11/27	37.5	88.5	4.4	4.5	6–7	Illinois
1923/10/28	35.5	90.4	4.3	4.5	7	Marked Tree, Ark.
1925/04/27	38.3	87.6	4.9	4.8	7	Indiana-Illinois border
1927/05/07	35.7	90.6	4.8	4.8	7	Northeastern Arkansas
1931/12/16	34.1	89.8	4.1	4.7	6–7	Northern Mississippi
1962/02/02	36.6	89.7	4.2	4.2	6	New Madrid, Mo.
1963/03/03	36.7	90.0	4.7	4.7	6	Southern Missouri
1965/10/21	37.8	91.1	4.6	4.9	6	Eastern Missouri
1968/11/09	38.0	88.5	5.4	5.5	7	South-central Illinois
1969/01/01	34.8	92.6	4.3	4.4	6	Central Arkansas
1970/11/17	35.9	89.9	4.1	4.4	6	Blytheville, Ark.
1972/09/15	41.6	89.4	4.1	4.4	6	Northern Illinois
1976/03/25	35.6	90.5	4.6	5.0	6	Northeastern Arkansas
1982/01/21	35.2	92.2	4.4	4.7	6	North-central Arkansas
1987/06/10	38.7	88.0	5.0	4.9	6	Southeastern Illinois

1986, the NRC and the USGS signed an agreement to establish the U.S. National Seismic Network to satisfy NRC's seismologic data needs. The U.S. Army Corps of Engineers has conducted a variety of important studies of the fluvial deposits of the Mississippi Valley and maintains instruments at Corps facilities to record strong ground motion from earthquakes. The Department of Veterans' Affairs has installed instruments to record strong ground motion in some of its hospitals in the region. The NSF established the National Center for Earthquake Engineering Research, which conducts various studies and operates instruments in the the New Madrid seismic zone.

State organizations and universities have taken some very important initiatives in addressing earthquake hazards. Monitoring of the New Madrid seismic zone was begun by seismologists at Saint Louis University when they installed instruments at Cape Girardeau, Mo., and Little Rock, Ark., in 1929. The university continues to monitor seismicity through networks funded by the USGS and the NRC. Faculty members, particularly the late Otto Nuttli, have spent considerable time informing the public of the hazard posed by the New Madrid seismic zone. Professor Nuttli, beginning in the late 1960's, struggled virtually alone for several years to alert State and Federal agencies, as well as the public, to that hazard. The State of Tennessee recognized the earthquake threat in 1977, when it formed the Center for Earthquake Research and Information (CERI) as both a State agency and an independent research unit of Memphis State University. The State has continued its strong support for CERI to the present time and provided resources for major programmatic expansions in 1984 and 1986. The State of Kentucky is one of only a few States in the Nation that provide funding for a State seismic network. Kentucky also adopted building code provisions for seismic loading in 1981 and upgraded them in 1988. The State of Missouri recently established an earthquake-hazard

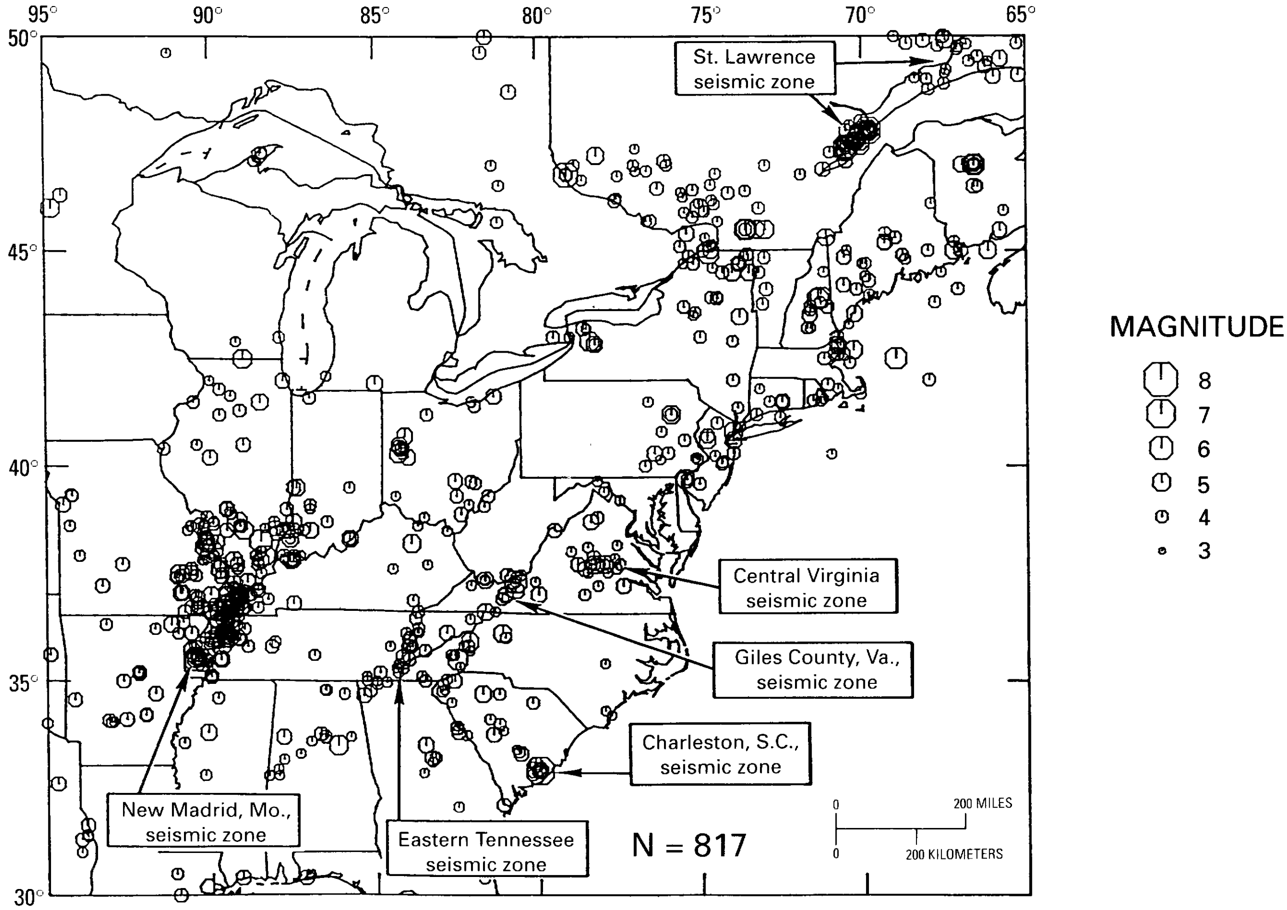

Figure 1. Seismicity of the Central and Eastern United States and adjacent parts of Canada showing earthquakes of magnitude 3 or greater from 1568 to 1987. (Figure prepared by G.A. Bollinger, Virginia Polytechnic Institute and State University, Blacksburg, Va.)

mitigation center at Southeast Missouri State University as a cooperatively funded effort between the State Emergency Management Agency and the university. In conjunction with the agency, the center is taking the lead in implementing an earthquake mitigation and preparedness plan for the State of Missouri. On November 7, 1989, the first meeting of the Illinois "Governor's Earthquake Preparedness Task Force" was held to examine the State's preparedness for a major earthquake. The goals of the task force are to determine the vulnerability of the State to earthquake hazards and to recommend ways to reduce the impact of those hazards. Three public hearings have been held to establish research and development needs. Illinois was instrumental in the development of a computer system for managing the emergency resources of States in the zone. Arkansas has required earthquake preparedness education in the 24 counties most vulnerable to an earthquake in the New Madrid seismic zone.

Congress' request for the New Madrid study plan and the scheduling of the workshop occurred before the Loma Prieta earthquake struck the San Francisco Bay area on October 17, 1989. Clearly, the physical and societal impacts of that earthquake dramatically increased the public's awareness of the New Madrid earthquake danger. The effects of the Loma Prieta earthquake also emphasized some very important lessons that must be considered in planning future studies of the New Madrid seismic zone:

- The most severe damage in the bay area was concentrated in areas of filled land or unconsolidated sediment; some of these areas also sustained heavy damage in the 1906 San Francisco earthquake (areas of engineered fill suffered little damage). Geologic mapping had identified these areas in the bay area and could be used to identify such areas elsewhere. Many cities, towns, and major industrial facilities in the New Madrid region that would be affected by strong ground motion from a major earthquake are located on unconsolidated sediment. Specialized mapping could identify the most vulnerable areas, and land-use policies and engineering practices could be developed to reduce losses.

- High-rise buildings in San Francisco (most of which are located on very firm soil or rock foundation) were not damaged significantly by the earthquake; however, because the ground motion in San Francisco on sites underlain by rock or stiff soil was only about 10 percent of gravity and the duration of strong shaking was only about 10 seconds—generally below the level that the buildings were designed to withstand—the Loma Prieta earthquake did not provide an extreme test of their design. Schools, hospitals, and other critical facilities suffered little damage. In contrast, numerous structures built on filled land experienced ground motion of about 25 to 30 percent of gravity and sustained heavy damage. Earthquake-resistant design and construction practices apparently were effective. Many cities in the New Madrid region have not implemented earthquake-resistant design practices, and most old and new buildings in the region were not designed to withstand earthquakes.
- Government agencies and the general public in northern California responded well to the effects of the Loma Prieta earthquake. Preparedness plans and exercises had helped lay the groundwork. Until recently, little effort had been made to prepare for earthquakes in cities in the Central United States, and the public is largely complacent about the earthquake danger. Regional and local centers—for example, the Central U.S. Earthquake Consortium (CUSEC), CERI of Memphis State University, Saint Louis University, the Governor's Earthquake Hazards and Safety Technical and Advisory Panel of Kentucky, and the Center for Earthquake Studies at Southeast Missouri State University in Cape Girardeau—have developed a good knowledge base for preparedness measures, but the scope of implementation is limited by the meager resources available. The National Center for Earthquake Engineering Research has implemented an active program addressing preparedness and mitigation issues in the Eastern United States in which the New Madrid region has a prominent role.
- The location of the Loma Prieta earthquake had been forecast accurately (U.S. Geological Survey, 1988). It occurred on a section of the San Andreas fault system in the Santa Cruz Mountains that was identified as the fault segment most likely to produce a strong earthquake in the bay area. This successful forecast shows that understanding of the mechanics of the San Andreas fault zone has improved to the point that mitigation actions can be directed to the most hazardous parts of a fault system. In contrast, the little that is known about the relative probabilities of earthquakes occurring along the numerous major fault zones of the New Madrid region emphasizes the need for additional concentrated studies.

The appropriate level of support for New Madrid studies in relation to studies of other U.S. seismic zones, as well as the balance of effort among the various NEHRP Federal agencies, can be determined only through evaluation of the whole NEHRP, a task that is beyond the scope of this report. Also, funding for NEHRP agencies to carry out the recommendations in this plan is, of course, subject to established budget procedures. This plan is intended primarily to provide a basis for budget proposals from each NEHRP agency. It can also be used by other organizations, such as State geological surveys and emergency agencies, to prepare related budget initiatives. Nevertheless, it is necessary to base this plan on an approximate level of funding to indicate the types of products that are needed and the types of projects that are foreseen in the study. The work described here could be carried out with total funding among all four NEHRP agencies of $5 to $10 million annually for 5 years. The exact amount would control the pace of the study and the choice of options. After 5 years, progress should be reviewed and the plan modified.

In recent years, New Madrid research studies have been funded at under $1 million per year. In fiscal year (FY) 1990, $3 million was allocated for New Madrid studies from funds appropriated to the USGS in Public Law 101–130 (FY 1990 Dire Emergency Supplemental to Meet the Needs of Natural Disasters of National Significance). This funding will permit some of the studies described in this plan to be initiated; however, most types of research require several years to complete, and some, such as seismic network operation, are of an ongoing nature and require a stable budget. Thus, the FY 1990 funds will be used mainly for capital expenditures (equipment and data acquisition) and short-term studies that meet urgent needs.

THE DANGER: SEISMIC RISK ASSESSMENT

Introduction

The earthquake dangers in California and Alaska are well known to most Americans. Small but sharply felt earthquakes occur frequently in those States, and destructive shocks are common enough to maintain public awareness. The relative infrequency of destructive earthquakes east of the Rocky Mountains leads to a perception that the earthquake danger there is insignificant in comparison with the dangers from other natural hazards, such as tornadoes and hurricanes. But the low frequency of occurrence of eastern earthquakes is offset by the vast area that they affect (fig. 2). A recurrence of the great New Madrid earthquakes of 1811–12 would be felt from Denver to New York City, topple chimneys in Chicago, Knoxville, Dallas, and Kansas

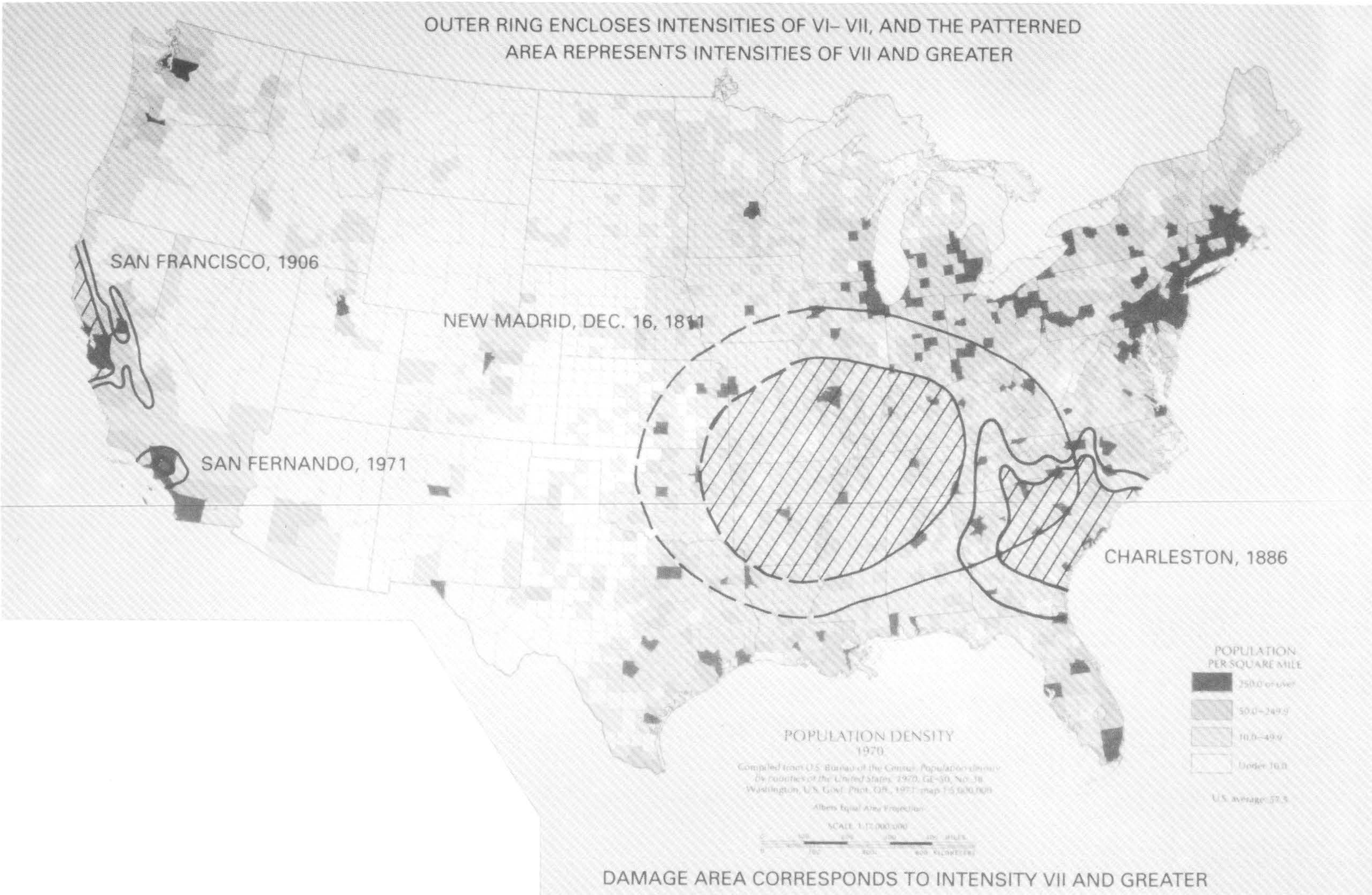

Figure 2. Areas of intensity VI and VII for two great earthquakes of about magnitude 8—New Madrid, Mo., in 1811 and San Francisco, Calif., in 1906—and two major damaging earthquakes—Charleston, S.C., in 1886 and San Fernando, Calif., in 1971 (Rankin, 1977). At intensity VI, minor damage occurs; at intensity VII, principally architectural damage occurs. Areas affected in the East are much larger than those affected in the West owing to lower seismic-wave attenuation in the East.

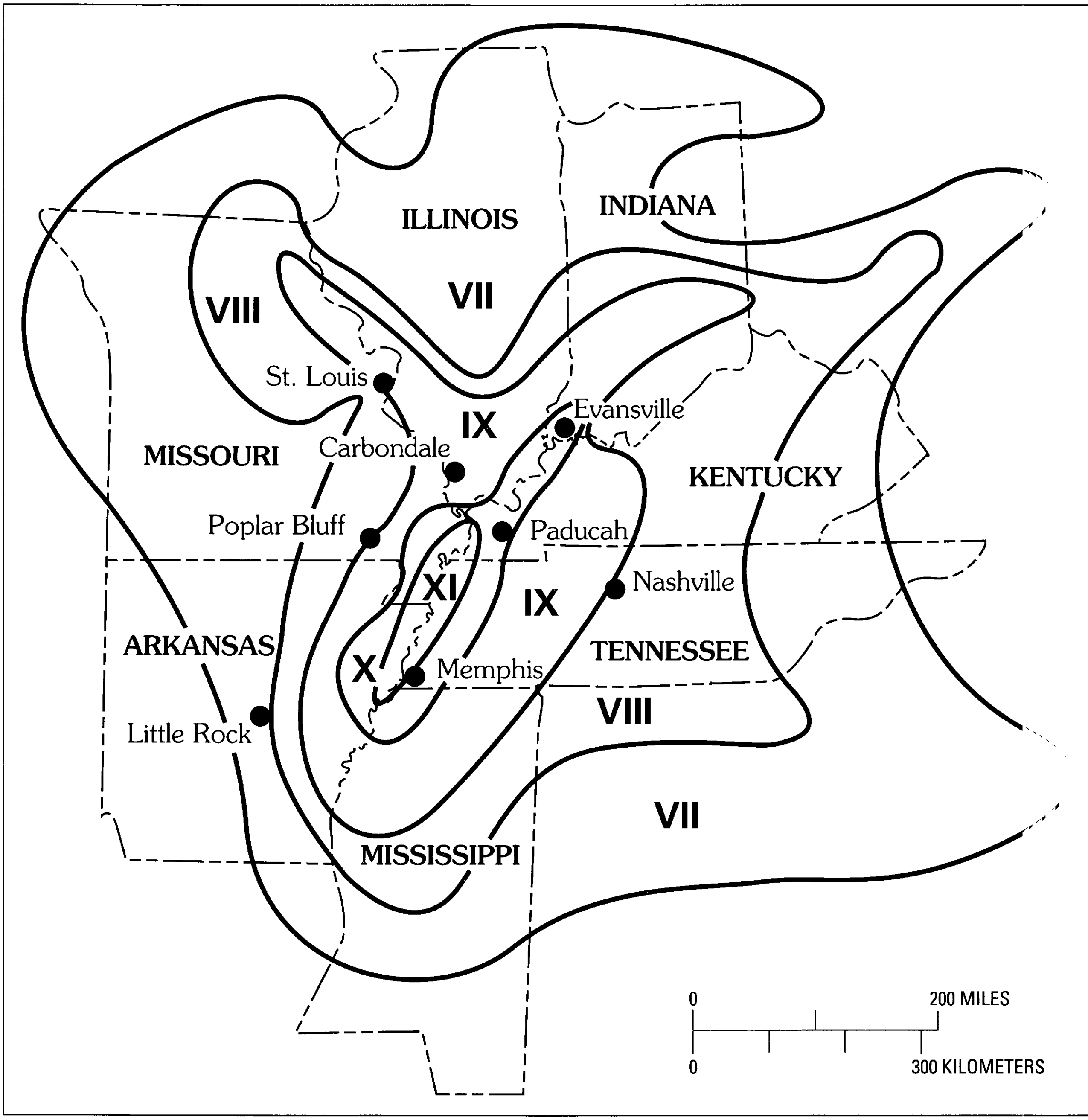

Figure 3. Regional distribution of estimated Modified Mercalli intensities that would result from a recurrence of the 1811–12 earthquake series in the New Madrid seismic zone. Intensity VIII and above indicates that structural damage might occur in a large number of buildings. Intensity VII indicates principally architectural damage. Intensity VI indicates widely felt shaking and items knocked off shelves. This composite intensity map shows a distribution of effects more widespread than what would result from a single earthquake of magnitude 8.6, because the distributions of effects were plotted for magnitude 8.6 earthquakes that could occur anywhere from the northern end of the seismic zone to the southern end. (After Hopper, 1985.)

City, cause architectural damage to tall buildings throughout most of the Central United States, and have devastating physical and societal impacts on the central Mississippi Valley (fig. 3). A magnitude 6 earthquake, which has a significant possibility of occurrence in the next several decades (table 2), would cause severe damage over several counties in several States.

A recurrence of the 1811–12 New Madrid earthquakes undoubtedly would have devastating effects on the region and the Nation, but considerable uncertainty exists

Table 2. Earthquake probability estimates for the New Madrid seismic zone

m_b[1]	M_S[1]	Recurrence time (years)	Probability of recurrence (percent) Next 15 years	Next 50 years
Model I—Time-dependent model[2]				
≥6.0	≥6.3	70(±15)	40–63	86–97
≥6.6	≥7.6	254(±60)	5.4–8.7	19–29
≥7.0	≥8.3	550(±125)	0.3–1.0	2.7–4.0
Model II—Time-independent (Poisson) model[3]				
≥6.0	≥6.3	70(±15)	16–24	45–60
≥6.6	≥7.6	254(±60)	5–7	15–23
≥7.0	≥8.3	550(±125)	2–4	7–11

[1] Uses Nuttli's (1983) m_b-M_S relationship.

[2] Probabilities depend on time elapsed since past earthquakes (Johnston and Nava, 1985). The time-dependent model was developed to describe the recurrence behavior of individual fault segments along plate boundaries.

[3] Probabilities do not depend on time elapsed since past earthquakes (S.P. Nishenko and G.A. Bollinger, unpublished manuscript, 1990). The time-independent, or Poisson, model is a good representation of volumetric processes (that is, the combined behavior of numerous faults). The difference in probabilities between the two models indicates the uncertainties in understanding the tectonic regime of the New Madrid seismic zone and shows the need for further research.

about how often, where, and when such events are likely to occur and about whether other areas in the Eastern United States that have not yet experienced destructive earthquakes of that magnitude might experience one in the future. One goal of earthquake research is to reduce this uncertainty about the locations and frequency of damaging earthquakes in the eastern part of the country. Such information, which is currently inadequate, is essential for deciding where to focus efforts to prepare for and cope with earthquake hazards and for allocating resources accordingly for preparedness and mitigation measures.

Information and knowledge that would enable earthquake-hazards assessment in any area are:

- **Geologic (prehistoric), historical, and instrumental records of past seismicity:** Where, how often, and how regularly have strong earthquakes occurred in the past? When will the next one occur? How big have they been? How big can they be?
- **Geologic setting:** Is the area situated along a boundary between two tectonic plates (like the San Andreas fault) or in the middle of an old, quasi-stable plate (like the New Madrid seismic zone)? What is the location, length, depth, distribution, and direction of movement on the faults that cause the earthquakes? What is their structure? What properties make some faults more susceptible to movement than others?
- **Current rates and past history of land (crustal and surface) deformation:** What is the orientation of stresses that cause earthquakes? What is the cause of the stress? How fast is stress accumulating, and what level does it have to reach before faults slip?
- **Efficiency and nature of seismic-wave propagation:** How large an area would be affected by destructive earthquake shaking? What are the predominant vibration frequencies?
- **Vulnerability of existing structures:** How vulnerable are existing structures of various materials and construction types to a strong earthquake?
- **Effects of strong ground motion on the land surface, buildings, and lifeline systems:** What will be the duration of shaking? Will the ground diminish or amplify the vibrations? How will the structures and lifeline systems respond?
- **Effects of strong ground motion on ground failure:** Where will liquefaction and landslides take place? What properties and physical settings lead to ground failure of unconsolidated sediments?

For the New Madrid region, the data currently available for assessing the earthquake danger are deficient in many respects. This deficiency can be reduced only through further research on the topics described in this report.

Seismicity

The history of earthquake activity in the New Madrid seismic zone (table 1) is dominated by the earthquake sequence that struck the area in the winter of 1811–12 (Fuller, 1912; Nuttli, 1973). The sequence began on December 16, 1811, with a tremendous earthquake, followed by another large shock 6 hours later. Subsequent great earthquakes occurred on January 23 and February 7, 1812. In terms of magnitude, these earthquakes are believed to be the largest shocks known to have occurred in a so-called stable continental interior; in terms of area affected, they may be the strongest historical shocks in the world (Johnston and Kanter, 1990). In contrast to the typical pattern of a single principal shock followed by a series of aftershocks, the 1811–12 sequence consisted of four very large shocks, each of which was followed by aftershocks, many of which were themselves significant earthquakes. Six aftershocks had magnitudes of 6 to 7, and more than 1,800 aftershocks large enough to be recorded as far away as Louisville, Ky., occurred in the first 5 months following the December 16, 1811, event. Aftershocks continued until at least 1817. About as many felt earthquakes occurred in the Mississippi Valley in 5 months as occurred in southern California in the 40-year period from 1932 through 1972. The most intense earthquake activity in the Eastern United States continues to be in the New Madrid seismic zone (fig. 1).

Other strong earthquakes have occurred in the New Madrid region since the 1811–12 sequence (table 1). Of particular note were a magnitude 6.4 earthquake in 1843 near Marked Tree, Ark., and a magnitude 6.8 earthquake in

1895 near Charleston, Mo. These events occurred at the southwestern and northeastern ends, respectively, of the area most affected by the 1811–12 sequence; perhaps the 1811–12 fault movement modified stresses and stimulated fault movement in those areas. The 1843 earthquake cracked walls, felled chimneys, and broke windows in Memphis, Tenn. The 1895 earthquake damaged many buildings in Charleston and caused sand to liquefy and erupt onto the land surface. At Cairo, Ill., buildings swayed, chimneys toppled, and church steeples twisted.

Damaging earthquakes also have occurred in the region surrounding the area of greatest 1811–12 activity, including southern Illinois and Indiana, western Kentucky, and eastern Missouri. The strongest earthquake in the Central United States since 1895 occurred in 1968 in south-central Illinois on the margin of the New Madrid seismic zone. It had a magnitude of 5.4 and was felt over all or portions of 23 States, from Minnesota to Florida and from North Carolina to Kansas. Damage consisted primarily of bricks thrown from chimneys, broken windows, toppled television antennas, and cracked or fallen plaster. A magnitude 5.2 earthquake in 1980 centered in north-central Kentucky was felt over 15 States. Property damage exceeded $1 million at Maysville, Ky., where 37 commercial structures and 269 residences sustained some damage. More recently, in 1987, a magnitude 5.0 earthquake in southeastern Illinois was felt in 21 States and southern Canada and caused one injury and minor damage in southern Illinois and Indiana.

Information on the underlying cause of New Madrid seismicity is derived from earthquake focal mechanisms and other stress indicators, which show that the New Madrid seismic zone is being compressed in an east-northeast–west-southwest direction (Zoback and Zoback, 1981). This orientation is consistent with the direction of drift of the North American plate with respect to the mantle and with the direction of stress caused by pressure on the plate as it moves away from the mid-Atlantic ridge. Although these explanations for the origin of the stresses in the crust of the North American plate are plausible, they do not explain why earthquakes are concentrated in the New Madrid seismic zone.

Regional Tectonic Setting

The New Madrid seismic zone, which geologically is situated in the upper Mississippi embayment (fig. 4), is an area of abundant seismicity that extends generally from near Charleston, Mo., on the northeast to Marked Tree, Ark., on the southwest (fig. 5). The zone of intense seismicity lies within a larger region, including parts of Arkansas, Missouri, Illinois, Indiana, Kentucky, and Tennessee, in which earthquakes are more dispersed and less common. Major structural and tectonic elements in the New Madrid region include the Ozark uplift, the southern part of the Illinois basin, the Cottage Grove–Rough Creek–Shawneetown fault system, the Ste. Genevieve fault, the Wabash Valley fault system, and the Reelfoot rift.

The most seismically active part of the New Madrid seismic zone lies within the Reelfoot rift (fig. 5), a northeast-striking graben about 40 mi wide and 200 mi long (Hildenbrand, 1985). Limited geologic evidence indicates that the graben formed about 500 million years ago and was filled with thousands of feet of sandstone, shale, limestone, and dolomite. Geophysical surveys, particularly aeromagnetic and seismic-reflection data, show that the top of crystalline basement rocks is generally about 1.2 mi deep outside the rift but is 2.4 to 4.2 mi deep along the axis of the rift. A very thick section of sedimentary rocks originally filled an ancient basin along the rift axis. The basin was subsequently uplifted to form the Blytheville arch (Hamilton and McKeown, 1988). The well-defined, northeast-trending zone of earthquake hypocenters between Marked Tree and Caruthersville, Mo., coincides with the Blytheville arch. Near Caruthersville, the pattern of intense seismicity changes to a northwesterly trend, which coincides with the intersection of the Blytheville arch and the northwest-striking Pascola arch (Grohskopf, 1955). The areal extent of the Pascola arch cannot be mapped adequately from the available subsurface data, but seismic-reflection and sparse drill-hole data show that the Pascola arch also was formerly part of a deep sedimentary basin. Like the Blytheville arch, this deep basin is now a structural high but underwent severe erosion that removed several thousand feet of sedimentary rocks.

Seismic-reflection data show that the boundaries of the Reelfoot rift are marked by fault zones several miles wide that displace basement rocks by as much as 1 mi vertically and, in some places, also displace younger rocks several tens of feet. A few earthquakes are spatially associated with the rift-bounding faults, especially along the southeastern margin (fig. 5). The possibility that the southeastern margin of the rift could produce a strong earthquake is of major concern, because such an event could be within 20 mi of Memphis.

The dispersed seismicity outside the area of intense seismicity in the New Madrid seismic zone has not yet been linked definitely to any major fault zones. In southeastern Missouri, the topographically and structurally highest part of the Ozark uplift—the St. Francois Mountains—is encircled by seismicity. This seismicity and geomorphic evidence suggest that minor uplift may be occurring in the Ozarks.

Similarly, a crude spatial correlation between seismicity and the Ste. Genevieve fault raises the possibility of active deformation on that fault. Reconnaissance studies of the geomorphology of stream terraces across the fault, however, show no evidence of current deformation. Along the Cottage Grove–Rough Creek–Shawneetown fault system, there is no obvious correlation between modern

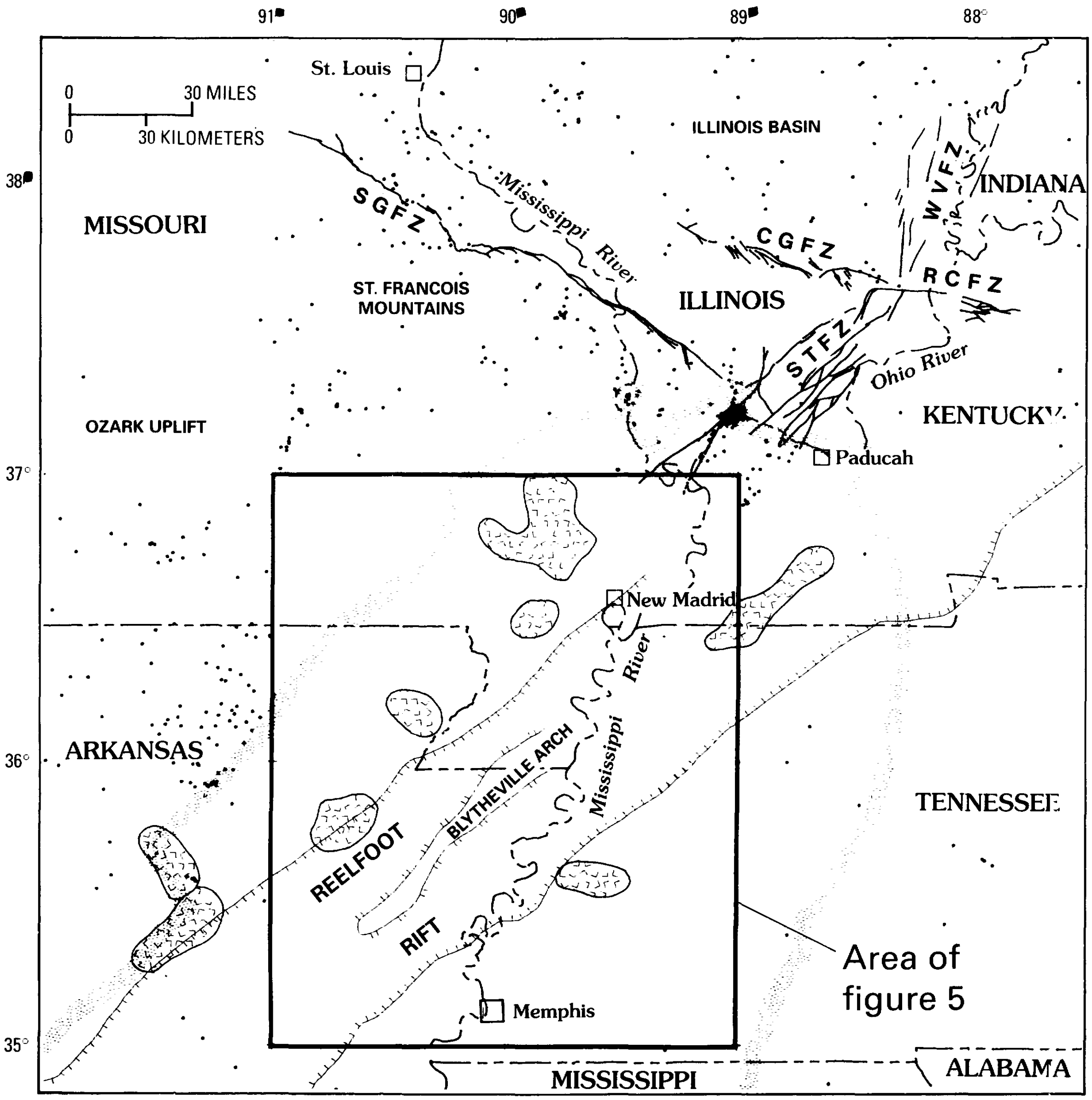

Figure 4. Seismicity and major structural features of the New Madrid seismic zone. Solid circles are epicenters (Saint Louis University). Major fault systems discussed in the text are CGFZ, Cottage Grove fault zone; RCFZ, Rough Creek fault zone; SGFZ, Ste. Genevieve fault zone; STFZ, Shawneetown fault zone; and WVFZ, Wabash Valley fault zone. The boundaries of the Reelfoot rift are shown by the single-hachured lines (hachures on the downthrown side). The boundary of the Blytheville arch is shown by the double-hachured line. Igneous plutons inferred from geophysical data are shown by a v pattern. The stippled line is the margin of the Mississippi embayment. For simplicity, earthquakes within the area shown in figure 5 are not shown (see fig. 5). (Figure prepared by F.A. McKeown, U.S. Geological Survey, Golden, Colo.)

seismicity and the major faults. Along the Wabash Valley fault system, a crude spatial association between the fault system and modern seismicity may be evidence that some of the faults are active. Seismologic data from magnitude 4 to 5 earthquakes in the area show that the style of faulting is predominately strike-slip on northeast- or northwest-trending faults in response to a nearly east-west maximum horizontal stress orientation.

In summary, the tectonic framework in the New Madrid region beyond the New Madrid seismic zone is only poorly known. Modern seismicity cannot be related to specific geologic features except in a general way. Until a cause-and-effect relationship is developed, the earthquake potential of the entire region cannot be reliably assessed. Preparedness and mitigation measures cannot be effected fully until such assessments are made.

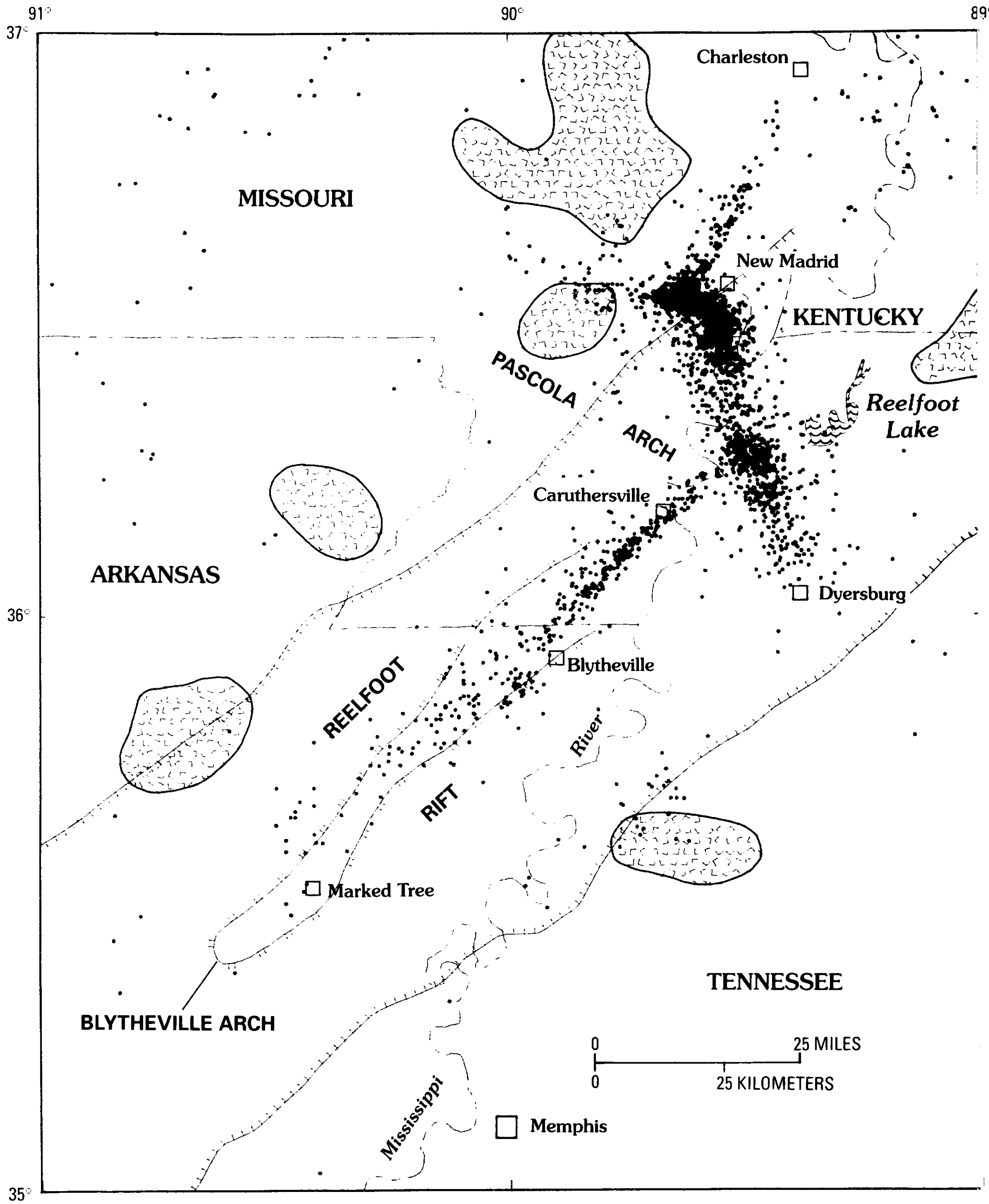

Figure 5. Seismicity (from Central Mississippi Valley Earthquake Bulletin of St. Louis University) and major geologic structures in the most active part of the New Madrid seismic zone. The boundaries of the Reelfoot rift are shown by the single-hachured lines (hachures on the downthrown side). The boundary of the Blytheville arch is shown by the double-hachured line. Igneous plutons inferred from geophysical data are shown by a v pattern. Note the coincidence between the Blytheville arch and the linear trend in seismicity that extends from Marked Tree to Caruthersville. (Figure prepared by F.A. McKeown, U.S. Geological Survey, Golden, Colo.)

Earthquake Effects

The New Madrid earthquakes of 1811–12 severely damaged structures and disrupted the land surface (Fuller, 1912). The area of greatest disruption encompassed approximately 50,000 mi^2. Within this area, uplift and subsidence on the order of a few feet occurred over hundreds of square miles; the most notable area of subsidence was at Reelfoot Lake in northwestern Tennessee. Several islands in the Mississippi River completely disappeared because of flowage of liquefied sediments. Along the bluffs on the eastern side of the valley, landslides were commonplace from near Cairo, Ill., to south of Memphis (fig. 6). Throughout the region, fissures formed at the ground surface, river banks caved hundreds of miles from the epicentral area, and huge quantities of sand and water erupted onto the surface (fig. 7). The eruption of sand and water, which resulted from liquefaction of subsurface sand layers, flooded approximately 4,000 mi^2 with as much as 3 ft of sand and water. More than 250 mi^2 of timber were destroyed by flooding, violent ground shaking, or landsliding. Eyewitness accounts describe the entire land surface as being disrupted and, in many places, uninhabitable.

Accounts of the shaking caused by the 1811–12 earthquakes (Fuller, 1912; Penick, 1981) describe almost unbelievable ground motion. Godfrey Le Sieur, a young boy and resident of Little Prairie (near Caruthersville, Mo.) at the time of the earthquakes, later wrote,

> The earth was observed to roll in waves a few feet high with visible depressions between. By and by these swells burst throwing up large volumes of water, sand, and coal.

James Audubon, the famous naturalist, experienced one of the shocks while riding in Kentucky:

> The ground rose and fell in successive furrows like the ruffled waters of a lake. The earth waved like a field of corn before the breeze.

L. Bringier, who lived with Indians near New Madrid and was later a surveyor in New Orleans, wrote that the water forced its way through the surface deposits,

> ...blowing up the earth with loud explosions. It rushed out in all quarters, bringing with it an enormous quantity of carbonized wood, reduced mostly into dust, which was ejected to the height of from 10 to 15 feet, and fell in a black shower, mixed with the sand, which its rapid motion forced along; at the same time the roaring and whistling produced by the impetuosity of the air escaping from its confinement seemed to increase the horrible disorder.... In the meantime the surface was sinking and a black liquid was rising to the belly of my horse.

The few structures that were present in the area were heavily damaged. Masonry and stone structures were damaged as much as 150 mi away. Chimneys were destroyed in Louisville, Ky., about 250 mi away, and less extensive chimney damage was reported at distances of over 400 mi. The earthquakes were felt southward to the Gulf Coast, southeastward to the Atlantic shore, and northeastward at least to Quebec. No reliable reports to the west are documented.

If estimated isoseismal areas to the west are included, the earthquakes of December 16, 1811, and February 7, 1812, had the greatest potential damage and the largest felt areas known in the earthquake history of the United States and possibly of the world (Johnston and Kanter, 1990) (fig. 2). The area of potential damage (the area shaken at intensity VII or greater) was about 250,000 mi^2. For comparison, a reasonable extrapolation of the area of intensity VII or greater for the 1964 Alaska earthquake covers an area of about 80,000 to 100,000 mi^2. The 1906 San Francisco earthquake affected an area of only about 12,000 mi^2 at intensity VII (or 24,000 mi^2, if isoseismal symmetry to the west in the Pacific Ocean is assumed). Thus, the area of strong shaking associated with the 1811–12 earthquakes is two to three times larger than that associated with the 1964 Alaska earthquake and 10 times larger than that associated with the 1906 San Francisco earthquake.

Potential Losses

Preliminary estimates of potential earthquake losses for dwellings in the Central United States are very large. Analysis of the intensity patterns of the 1811–12 earthquakes and other earthquakes in the Central United States in conjunction with the present-day distribution of dwellings gives an upper-bound loss estimate of about $50 billion to dwellings (in 1980 dollars) for a recurrence of the 1811–12 sequence (Algermissen, 1990). The expected maximum loss to dwellings in a 50-year period (at a 10-percent chance of being exceeded) is about $5.6 billion (1980 dollars), and a magnitude 6 to 7 earthquake would cause approximately $3.6 billion in dwelling losses (S.T. Algermissen, unpublished data, 1990; 1990).

The central Mississippi Valley is a major communication and transportation corridor. Communication facilities, such as radio and microwave towers and telephone trunk lines, are vulnerable. Barge traffic on the river, natural gas and crude oil pipelines, interstate highways, and power lines all provide essential services, the loss of which would have a heavy impact on the entire Central and Eastern United States These transportation and lifeline facilities are highly vulnerable to earthquake damage, particularly because their structural integrity depends, to a great extent, on the stability of the ground. Destruction of pipelines would severely disrupt the delivery of energy fuels to the northern and northeastern parts of the United States.

The Mississippi River would be strongly affected by a large earthquake. After the February 7, 1812, earthquake, two waterfalls or heavy rapids formed in the river and halted traffic for several days. Extensive changes in the course of the river channel made navigation difficult and hazardous. Eliza Bryan, a resident of New Madrid, described the effects of the 1811–12 earthquakes on the river (Fuller, 1912):

Figure 6. Trees tilted by a landslide along the Chickasaw Bluffs near Reelfoot Lake in northeastern Tennessee, photographed in 1904 (Fuller, 1912). The landslide was triggered by the New Madrid earthquakes of 1811–12.

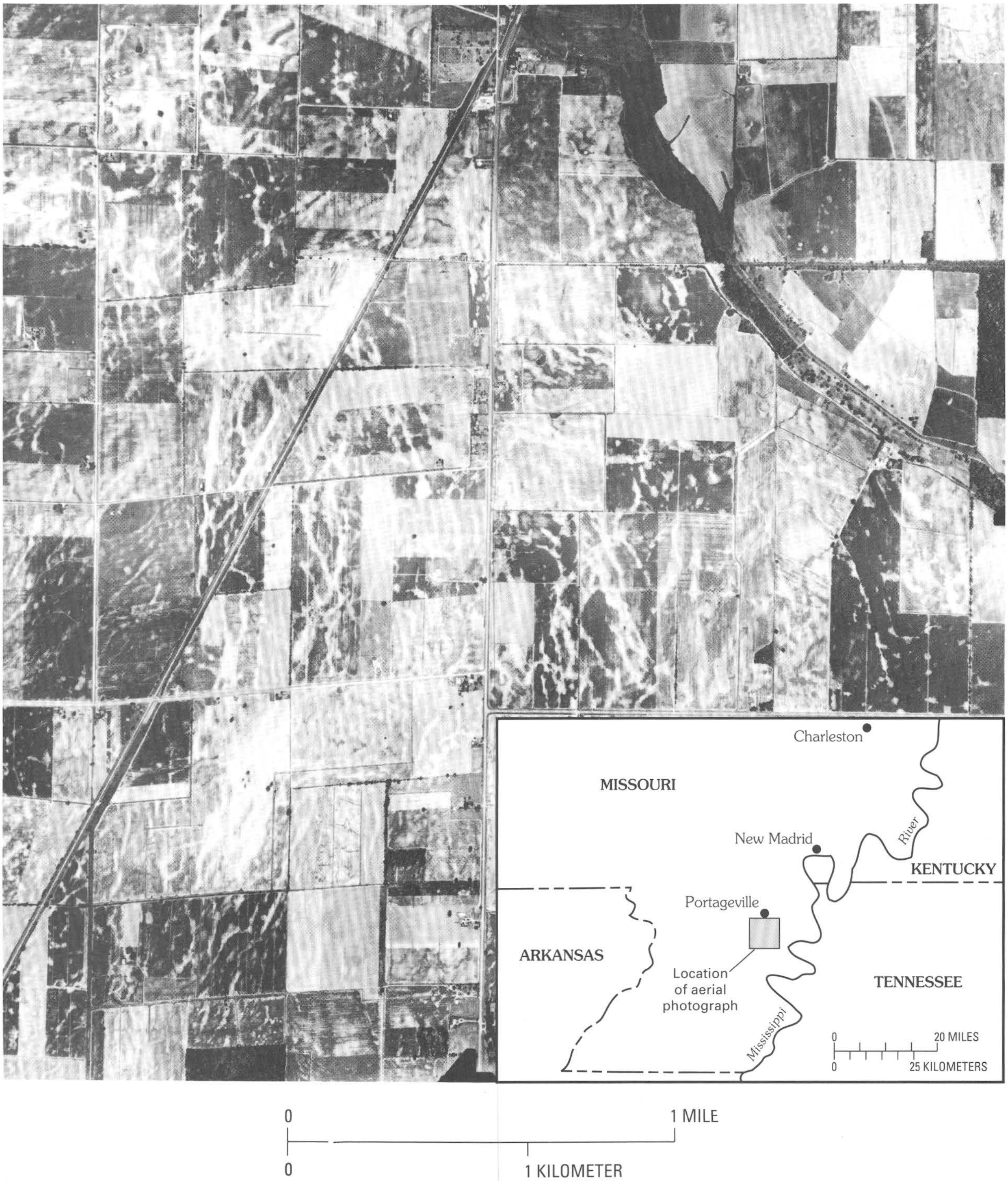

Figure 7. Aerial photograph taken in 1959 near Portageville, Mo. (Obermeier, 1989). White spots and white lineations are from liquefied sand that was vented to the surface over dark clay during the 1811–12 earthquakes. The lineations are caused by ground cracks that are due to lateral spreading; their pattern is controlled by parameters such as the thickness of the clay cap over the liquefied sand and the locations of ancient stream channels.

> At first the Mississippi seemed to recede from its banks, its waters gathered up like mountains, leaving boats high upon the sands. The waters then moved inward with a front wall 15 to 20 feet perpendicular and tore boats from their moorings and carried them up a creek closely packed for a quarter of a mile. The river fell as rapidly as it had risen and receded within its banks with such violence that it took with it a grove of cottonwood trees. A great many fish were left upon the banks. The river was literally covered with wrecks of boats.

Caving of steep banks along rivers and streams was the most widespread type of landsliding triggered by the 1811–12 earthquakes. According to witnesses (Penick, 1981),

> In many places, the banks of the river...sunk hundreds of acres together, leaving the tops of the trees to be seen above the water.
> [Banks] fell in "large columns"; in some places "five, ten, and fifteen acres...sunk down in a body...."

In a future large earthquake, barge traffic would almost certainly be interrupted, perhaps for weeks, if substantial dredging were needed to clear river channels. Foundations of structures and levees could fail in numerous places. Facilities along the river bank, particularly large grain silos and fuel and fertilizer tanks, could collapse and cause fires and spills that would pollute the river. Damage to landfills, wastewater-treatment facilities, pipelines, and chemical storage facilities could cause widespread contamination of ground water and disruption of water-supply systems.

Damage to the interstate and other highway systems would be extensive in a repetition of a great earthquake. The various forms of ground failure (liquefaction, landslides, and so on) would weaken or destroy highway foundations. Ground failure combined with strong ground shaking would severely impact bridges and overpasses, which generally have not been designed with earthquakes in mind. The bridges across the Mississippi River and its numerous tributaries are located on ground that is most susceptible to failure and amplified shaking.

The central Mississippi Valley is one of the most productive agricultural areas in the United States. Not only would farming be disrupted by general earthquake damage, but the extensive canal system that drains water from lowlands also could be damaged both by liquefaction and landslides and by uplift and subsidence of the land surface associated with a great earthquake. Large areas could be inundated by several feet of water, and fields could be covered by liquefied sand vented to the ground surface. Electric power failures could also affect pumping and other equipment systems.

An earthquake in the magnitude 6 to 7 range, such as the one that occurred near Charleston, Mo., in 1895, would also cause severe shaking, but the area affected would be smaller than the area that would be affected by repetition of one of the great shocks of the 1811–12 series. Hundreds of square miles near the epicenter would experience ground motions strong enough to jeopardize many buildings and other facilities; within an additional tens of thousands of square miles, shaking would be strong enough to cause damage to structures located on unfavorable geologic foundation material. An example of the effect of a modern earthquake of similar magnitude in a different geologic setting is provided by the San Fernando, Calif., earthquake of 1971 (magnitude 6.6) (intensity pattern in fig. 2). That shock killed 58 people, caused a near-catastrophic dam failure and collapses of freeway overpasses, and produced $500 million (1971 dollars) in damages. We have not had a modern magnitude 6.8 earthquake in a region similar to the New Madrid seismic zone. The 1895 shock occurred before construction of the numerous facilities that are now present in the area.

A magnitude 6 earthquake beneath a metropolitan center would cause substantial damage. Recent examples of such a shock outside of the New Madrid seismic zone are the Whittier Narrows, Calif., earthquake of 1987 (magnitude 5.7), which killed 8 people and caused property losses of over $300 million (1987 dollars), and the magnitude 5.5 Newcastle, Australia, earthquake of December 27, 1989, which killed 12 people and caused $1 billion in property losses. Unreinforced masonry buildings, of which there are many in the metropolitan areas of the New Madrid seismic zone, were particularly hard hit in the Whittier Narrows shock. The region of intense shaking in a magnitude 6 earthquake is, however, small enough that there are areas of the New Madrid seismic zone in which such an earthquake could occur without strong shaking extending to heavily populated areas.

THE RESPONSE: PREPAREDNESS AND MITIGATION

Although the greatest devastation in the New Madrid region would be caused by the recurrence of a magnitude 8 earthquake, such an event may happen very rarely, perhaps only once in a thousand years or more, on the average. However, extrapolation of earthquake statistics (for example, Johnston and Nava, 1985) indicates that, in that same thousand-year period, roughly 5 (±2) earthquakes in the magnitude 7 to 8 range and about 14 (±6) earthquakes in the magnitude 6 to 7 range would occur. Thus, the type of earthquake on which planning should be based may be one in the magnitude 6 to 7 range. Only time will tell how valid such extrapolations are for the New Madrid seismic zone.

LOSS REDUCTION MEASURES

Figure 8. Goals of community actions in implementing loss reduction measures. (Figure prepared by W.W. Hays, U.S. Geological Survey, Reston, Va.)

Nevertheless, the best available evidence is sufficient to justify a concerted and aggressive mitigation and preparedness effort. By identifying and quantifying earthquake hazards and by adopting and implementing preparedness and mitigation measures, a community can build the capacity to withstand the physical effects of an earthquake (fig. 8). Experience in California convincingly demonstrates that earthquake preparedness and mitigation measures are effective in saving lives and reducing losses.

Preparedness activities must be initiated long before an earthquake to prepare emergency managers for the response and recovery periods. Such activities encompass the following:

- Establishing a process to develop emergency response and recovery plans that are based on the best available earth-science and engineering data.
- Utilizing information gained from scientific and engineering studies and from hazard and risk assessments.
- Developing effective programs to disseminate information and educate the public on the potential vulnerability of the community in such a way as to stimulate real action and accomplish actual changes in structural and nonstructural mitigation as well as actual public preparedness on both an individual and a community basis.

Mitigation activities, like preparedness activities, also are carried out before the event, their goal being the reduction or prevention of damage and societal disruption. They include the following:

- Developing realistic estimates of potential losses and societal impacts for one or more possible events.
- Reducing vulnerability in the community.
- Utilizing seismic zonation; that is, identifying the spatial distribution and nature of specific types of hazards and enacting land-use restrictions in hazardous areas.
- Adopting and implementing codes and standards for the siting, design, and construction of new buildings and lifelines (for example, energy, water, transportation, and communication systems).
- Adopting and implementing criteria for the siting, design, and construction of essential and critical facilities (for example, schools, hospitals, emergency command centers, and conventional and nuclear powerplants) that are vital to the life of the community and must remain functional after an event.

Earth scientists, engineers, and social scientists build the knowledge base that practitioners use in preparedness and mitigation activities. Earth scientists and engineers evaluate the physical nature of the earthquake hazards of ground shaking, earthquake-induced ground failure, surface-fault rupture, regional tectonic deformation, flooding from dam failure, fire following an earthquake, and the aftershock sequence. Their goal is to understand the physical system for each type of earthquake effect, the parameters that control the cause-and-effect relationships of the physical system, the central tendency and variability in space and time of each parameter, and the sensitivity to extrapolation of parameters beyond the limits of the data.

Social scientists study the social components of earthquake hazards. They analyze societal systems and focus their research on the behavior of individuals, households, organizations, and communities. Within this framework of individual and organizational behavior, social scientists analyze how people and institutions respond to, prepare for, and mitigate earthquake and related hazards. Social scientists are, for example, interested in how perception of risk is communicated to vulnerable communities. In addition, some social scientists concentrate on questions of policy development or policy analysis. For example, they might analyze how technical and nontechnical information is transferred from researchers to practitioners or how social, political, and (or) cultural factors constrain or promote the utilization of hazard-reduction information.

Experience has shown that knowledge alone makes no contribution to earthquake preparedness and mitigation measures if the knowledge base is unknown, misunderstood, inappropriate, unintelligible, misdirected, or ignored. Consequently, a vigorous awareness and education program would be needed to support earthquake-hazard mitigation and preparedness activities in the New Madrid region.

THE PLAN: PREPARING FOR THE NEXT NEW MADRID EARTHQUAKE

Introduction

Knowledge of the New Madrid seismic zone lags behind that of most seismic zones in the Western United States, particularly the San Andreas fault zone, for several reasons:

- The seismically active faults in the main part of the New Madrid seismic zone are concealed by as much as 3,000 ft of poorly consolidated sedimentary rocks, whereas most of the San Andreas fault zone is exposed at the surface.
- Earthquakes occur more frequently in California. This frequency thereby yields more data that are critical to understanding their cause, poses a greater danger, and attracts greater scientific and political attention. Consequently, resources devoted to earthquake research are considerably greater in the West than they are in the East.
- The San Andreas fault zone is the boundary between the Pacific and North American plates, a relatively well understood tectonic regime. In contrast, the tectonic framework for "intraplate" earthquakes in the New Madrid region (and worldwide) is poorly understood.

Thus, much research is needed in the New Madrid seismic zone to achieve a level of knowledge comparable to that achieved in California.

Although much remains to be done, significant progress in understanding the New Madrid seismic zone has already been achieved. As recently as the early 1970's, before the formation of NEHRP, the pattern of earthquake epicenters in the region was poorly resolved; it looked like a buckshot pattern from a shotgun blast. No geologic explanation accounted for New Madrid seismicity. Following the installation of the seismic network, the dispersed epicenter pattern was resolved into several well-defined, linear trends that correspond to the locations of buried fault zones, and most of the earthquakes can now be attributed to the reactivation of faults in the Reelfoot rift. Many of the faults in the rift have been identified on seismic-reflection profiles, and the amount of vertical movement has been measured on some of them. Exploratory trenches have been dug in several places where faults extend close to the ground surface and, in one place, have yielded estimates of the rates of fault movement.

Some of the most important questions that cannot yet be satisfactorily answered are:

- How can New Madrid seismicity be explained in terms of global tectonic processes?
- What are the rates and modes of crustal deformation?
- Do the main seismogenic structures extend northeastward into southern Illinois and Indiana, or are the earthquakes in these areas caused by movement on structures unrelated to the Reelfoot rift?
- How far does the New Madrid seismic zone extend southwest into central Arkansas?
- How frequently do great (magnitude 8) and smaller destructive earthquakes occur? Is their occurrence periodic, quasi-periodic, or episodic? Over the long term (centuries or millennia), does seismicity migrate to other intraplate areas?
- On which fault segments of the New Madrid seismic zone and surrounding areas are the next destructive earthquakes likely to occur?
- What will be the effects of future earthquakes on the poorly consolidated ground in the Mississippi Valley?
- What is the potential for amplification of the ground motion and for ground failure?

The answers to these questions not only will improve the basis for mitigating earthquake hazards in the New Madrid region but also will provide a better understanding of earthquakes elsewhere in the Central and Eastern United States. Moreover, results from the New Madrid seismic zone will improve the general understanding of intraplate earthquakes and thereby help to reduce casualties and damage from earthquakes in similar environments worldwide.

Purpose

The overall purpose of an intensified study of the New Madrid seismic zone, which is consistent with the general mission of NEHRP, is to reduce casualties and damage from earthquakes through improved estimates of seismic risk and implementation of earthquake-hazard preparedness and mitigation measures.

Goals

Five goals have been identified for an intensified study of the New Madrid seismic zone:

1. **Implementing earthquake-hazard mitigation measures.**
2. **Improving preparedness for earthquakes of magnitude 6 or larger.**
3. **Establishing a modern seismic network in the New Madrid seismic zone to monitor the sizes, locations, and characteristics of the earthquakes and to determine the nature of the ground motions that they generate.**
4. **Locating faults that could cause destructive earthquakes, determining the recurrence rates of earthquakes, and delineating areas of potential damage.**
5. **Improving seismic-risk assessments.**

Activities

The activities that have been identified to achieve the goals of an intensified study of the New Madrid seismic zone are listed below. Activities associated with implementation of mitigation and preparedness and those associated with research should proceed concurrently. Each incremental improvement in implementing earthquake-hazard mitigation and preparedness measures would have a corresponding benefit in terms of loss reduction.

In this discussion of activities, some goals have been subdivided into objectives to show more clearly how certain activities relate to different aspects of a goal.

Goal 1: Implementing earthquake-hazard mitigation measures

ACTIVITIES

a. Facilitate adoption of structural design codes that include appropriate provisions for soil effects and earthquake resistance and of land-use policies that take into account earthquake hazards.
b. Develop effective and economical techniques to facilitate repairing, strengthening, and retrofitting unreinforced masonry and other vulnerable buildings and structures.
c. Increase education and communication concerning earthquake risk and earthquake-hazards preparedness and mitigation measures.

Discussion of Goal 1

Four major research needs have been identified to implement earthquake-hazard mitigation measures in the Central United States (Hanson, 1986): (1) assess the capability of existing buildings to withstand earthquakes, (2) verify the techniques for repairing, strengthening, and retrofitting structures, (3) implement remedial measures, and (4) develop construction methods for enhancing earthquake resistance. Each need requires reevaluation of existing methods and development of new procedures drawing on experience in regions of high seismicity. Because resources for strengthening and repairing existing structures and for constructing new buildings are limited, earthquake mitigation practices in regions of moderate seismicity may vary from those developed for regions of high seismicity.

To meet these needs, research and development work is required in three general areas: (1) behavior of structures in response to earthquake shaking, (2) nondestructive testing of structures, and (3) building codes. Substantial work needs to be done in evaluating the earthquake response of structures that may have little earthquake resistance. A feasible, cost-effective solution for these structures in the New Madrid seismic zone entails more than simply modifying building codes that have been calibrated primarily for highly seismic regions. New procedures for nondestructive testing and new design and evaluation methods are required, and they must be communicated to a professional community that has not dealt extensively with earthquake risk. For the Central United States, assessment of the earthquake hazard is a very critical issue. An overly conservative estimate of the hazard could result in an overestimation of the cost of solving the problem, which in turn could result in nothing being done to reduce the risk.

Goal 2: Improving preparedness for earthquakes of magnitude 6 or larger

ACTIVITIES

a. Identify, assess, and retrofit, if necessary, those structures and facilities having special importance to survival and recovery in the event of an earthquake.
b. Prepare loss estimates for large cities.
c. Prepare earthquake response and recovery plans.
d. Provide training tailored to the needs of those who respond to emergencies.

Discussion of Goal 2

Although earthquake preparedness in the New Madrid seismic zone lags behind that in some of the western earthquake zones, some important progress has been made. The Central U.S. Earthquake Preparedness Project (CUSEPP) was initiated by FEMA in 1982. CUSEPP's short-term goals were to (1) prepare maps showing the intensity of effects for selected earthquakes in the New Madrid seismic zone, (2) inventory structures, lifelines, and critical facilities in selected cities in the Central United States, and (3) assess the risk in those cities. Little Rock, Ark., Carbondale, Ill., Evansville, Ind., Paducah, Ky., Poplar Bluff, Mo., and Memphis, Tenn., were selected for these assessments (Federal Emergency Management Agency, 1985). The long-term goals of the project are to (1) increase the awareness of public officials and the private sector of earthquake hazards, (2) develop options for engineering solutions based on the balance of risk and cost, (3) accelerate the implementation of earthquake-hazard mitigation and preparedness strategies, and (4) improve earthquake response plans.

To facilitate its earthquake preparedness efforts, FEMA formed the Central U.S. Earthquake Consortium (CUSEC) in 1983. CUSEC consists of representatives of the seven States that are most vulnerable to damage from earthquakes in the New Madrid seismic zone: Arkansas, Illinois, Indiana, Kentucky, Mississippi, Missouri, and Tennessee. The goal of CUSEC is to ensure a coordinated program for achieving earthquake preparedness and mitigation goals common to all seven States. CUSEC developed and encouraged the adoption of a multistate-interstate compact, which allows neighboring States to share resources during an earthquake emergency in fields such as medicine, engineering, law enforcement, and fire fighting. The compact addressed liability protection for emergency personnel who render services in States where they are not licensed, registered, certified, or insured.

Goal 3: Establishing a modern seismic network in the New Madrid seismic zone to monitor the sizes, locations, and characteristics of earthquakes and to determine the nature of the ground motions that they generate

Objective 3.1: Install and maintain a modern seismic network to monitor earthquakes in the New Madrid seismic zone

ACTIVITIES

a. Upgrade the present regional seismic network (fig. 9) with modern three-component, broadband, high-dynamic-range instruments. The network would cover approximately the area of intensity VII shaking shown in figure 2.

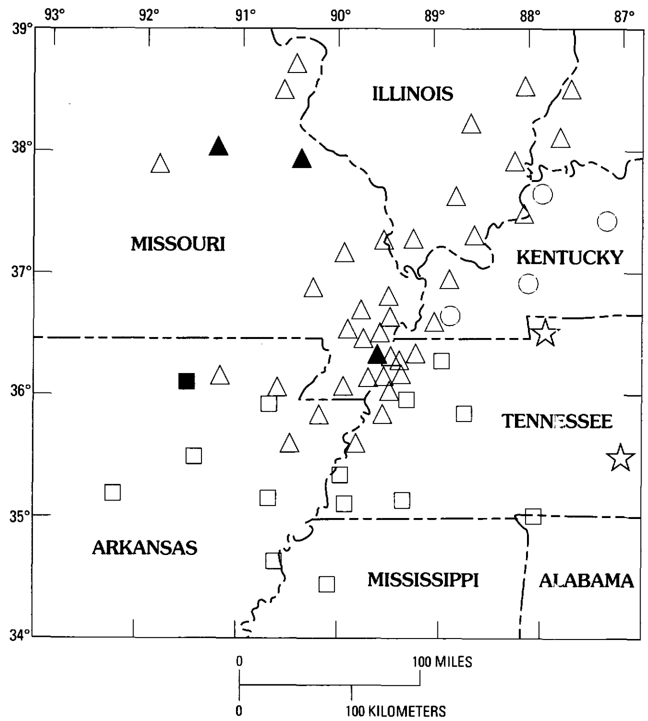

Figure 9. Current regional seismic network in the New Madrid seismic zone. Symbols denote network operators: triangles, Saint Louis University; circles, University of Kentucky; squares, Center for Earthquake Research and Information/Memphis State University; and stars, Tennessee Valley Authority. Solid symbols are three-component stations; open symbols are vertical component only. Strong-ground-motion instruments (fig. 11) are not shown. (Figure prepared by A.C. Johnston, Center for Earthquake Research and Information/Memphis State University, Memphis, Tenn.)

b. Integrate the regional earthquake monitoring network with the U.S. National Seismic Network (fig. 10) and establish a common data transmission system.
c. Upgrade and extend the spatial extent of the seismic coverage on the periphery of the New Madrid seismic zone.

Objective 3.2: Obtain records of strong ground motion and data on seismic-wave attenuation

ACTIVITIES

a. Improve the current regional network of strong-ground-motion stations (fig. 11).
b. Establish two field laboratories in areas of intense seismicity in the New Madrid seismic zone to acquire data on earthquake characteristics near the source and seismic-wave propagation, including strong ground motion. (Each array would consist

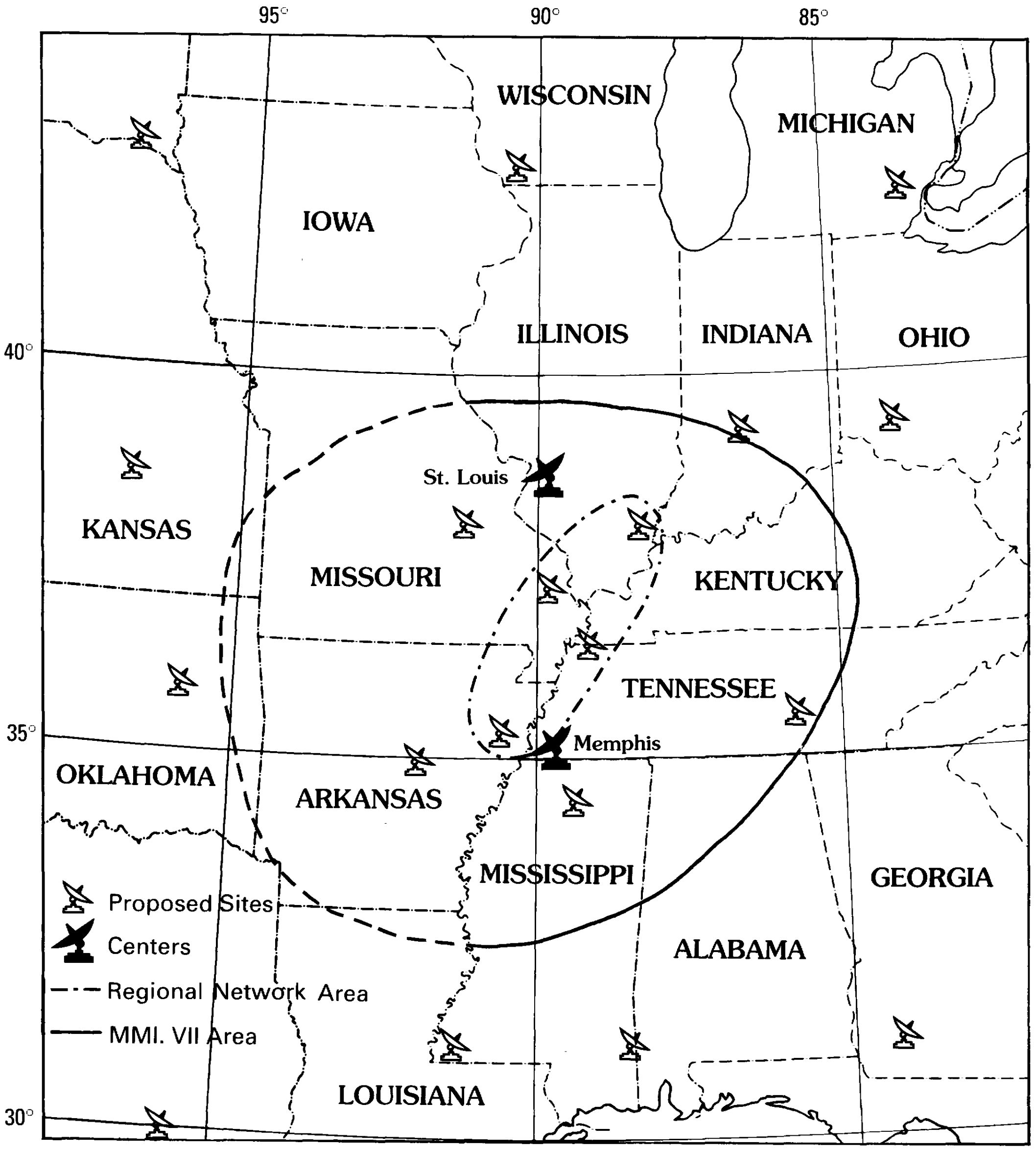

Figure 10. U.S. National Seismic Network (USNSN) stations in the Central United States. The area affected by shaking of intensity VII or greater during the 1811–12 New Madrid earthquakes is shown by the solid line (dashed where there are no data). The area covered by the regional seismic network is indicated by the dash-dot line. The regional stations would be linked to satellite communication nodes of the USNSN by radio or telephone. Data would be relayed to research centers through the USNSN master station in Golden, Colo., by means of satellite antennas; this concept is illustrated by antenna symbols at Memphis, Tenn., and Saint Louis, Mo., where the largest regional network operators are located. (Figure prepared by R.E. Needham, U.S. Geological Survey, Golden, Colo.)

of eight three-component high-frequency instruments deployed at the surface, together with one array of instruments in a deep drill hole.)

c. Install a strong-ground-motion instrument array of high dynamic range within or near a large metropolitan area (for example, Memphis) to obtain records of moderate-sized earthquakes that can be used to predict the ground motion from a future large earthquake. (This installation would consist primarily of a vertical array of ground-motion and soil-dynamics sensors in a borehole.)

d. Integrate the maintenance of strong-ground-motion instruments into the national strong-ground- motion program. (USGS personnel could

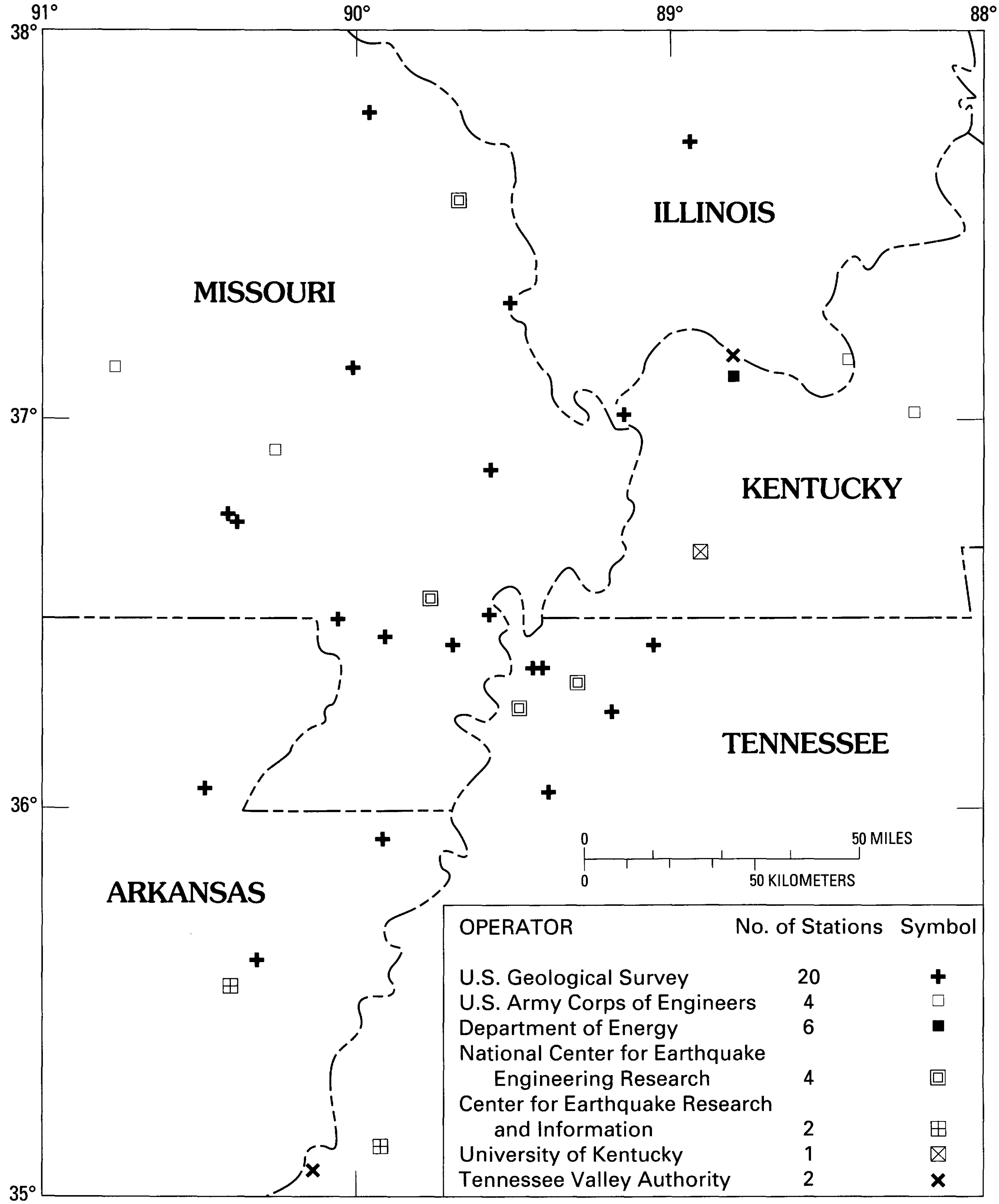

Figure 11. Current strong-ground-motion stations in the New Madrid seismic zone (Figure prepared by K.H. Jacobs, National Center for Earthquake Engineering Research, Lamont-Doherty Geological Observatory, Palisades, N.Y.)

be stationed in the New Madrid seismic zone to implement this recommendation.)

e. Develop a small, portable seismic network and provide for its rapid deployment to monitor aftershocks. (This network would consist of eightthree-component seismometers connected to a regional seismic-network satellite processor and would be used to define site-specific ground-motion characteristics.)
f. Deploy semiportable seismographs to study seismic-wave propagation to larger distances. (Selected studies could be conducted at St. Louis and Louisville, for example.)

Objective 3.3: Improve capabilities to process and analyze data from earthquake-monitoring systems

ACTIVITIES

a. Establish research centers to conduct and monitor seismic network and other instrument operations, locate earthquakes, and archive waveform and other earthquake data for future use. (These data centers, which would have separate functional responsibilities, would provide basic data to all research scientists for earthquake-hazard studies and would maintain the earthquake-monitoring networks.)
b. Upgrade USGS capabilities to support earthquake monitoring systems and to utilize the data in earthquake-hazard assessment projects (National Academy of Sciences, 1990). (The USGS projects would include support services to link the regional seismic network and the USNSN, acquisition of data for common use, and interpretation.)

Discussion of Goal 3

Although the present seismic network is crucial to improving our knowledge of earthquakes in the New Madrid region, it now lacks a funding base and has major technical limitations that must be corrected to yield further advances. The current network was designed 15 to 20 years ago, when its goals were only to locate and determine the magnitudes of small earthquakes and to obtain a focal mechanism for a few larger ones. Today, more information must be obtained from the earthquake recordings to answer the complex questions related to earthquake hazards. The majority of seismometers in the network (fig. 9) do not sense the horizontal component of ground shaking, have limited frequency response and limited dynamic range, and are not installed in boreholes, where sensitivity would increase owing to the reduction of surface noise.

Horizontal-component seismometers would provide data to determine earthquake locations more accurately and would, for the first time, provide data on the transverse waves that are the main cause of earthquake damage. Without better locations, including accurate depth estimates, the geologic structures causing the earthquakes cannot be reliably identified. In addition, these data would be used for research on the shear modulus of crustal and surficial materials, a property that characterizes the mineral composition and fluid content of rocks and can be used to understand the rupture process of earthquakes. The data would also permit studies of material anisotropy (for example, seismic waves traveling at different velocities in different directions) that could be used not only to map fault zones but also to monitor the stress buildup for future large earthquakes. Finally, the horizontal data provide better estimates of the attenuation of ground shaking with distance and are necessary for accurate determination of earthquake focal depths.

A major deficiency of the current seismic instruments is that they record earthquakes of about magnitude 3 and smaller on scale, but larger earthquakes cause them to go off scale. The current instruments are set this way to sense the numerous small earthquakes that are used to delineate active faults. The tradeoff, however, sacrifices recording the complete waveform for the few larger (magnitude 4+) earthquakes. Thus, no usable near-source record of ground motion exists for larger earthquakes in the New Madrid seismic zone that can be used to define the expected shaking in metropolitan areas during major earthquakes. This deficiency can be resolved by using modern instruments having wide-dynamic-range digital telemetry and recording.

Several metropolitan areas and many critical facilities are located on poorly consolidated sediments in the New Madrid seismic zone. The prediction of ground motion at the surface is calculated from ground motion incident at the base of these sediments. Thus, for reliable estimates of ground motion at the surface, it is necessary to install seismometers at the base of the poorly consolidated sediments and also at the surface. The thickness of poorly consolidated sedimentary rocks in the most densely populated parts of the New Madrid region is as great as that in any earthquake zone in the country (as much as 3,000 ft). Ground-motion prediction methods developed for California need to be calibrated for this kind of geologic setting.

Goal 4: Locating faults that could cause destructive earthquakes, determining the recurrence rates of earthquakes, and delineating areas of potential damage

Objective 4.1: Define the boundaries and characteristics of seismic source zones in the New Madrid seismic zone and surrounding areas

ACTIVITIES

a. Expand geologic and geophysical studies; trace the areal extent of geophysical features at depth.

b. Conduct geologic mapping, including shallow drilling to determine the physical properties of subsurface materials.
c. Acquire additional high-resolution and reconnaissance geophysical data (gravity, magnetic, seismic reflection) to fill critical gaps in existing data sets.
d. Identify deep faults that extend to the surface by means of seismic-reflection and other geophysical data.
e. Drill one or more research holes to determine the physical properties of geologic materials under realistic conditions, to calibrate geophysical data, and to permit borehole monitoring of seismogenic processes.

Discussion of Objective 4.1

Accurately defining and characterizing seismic source zones require a clear understanding of the relationship between earthquakes and major geologic structures at the depths where earthquakes are generated. Subsurface geologic and geophysical studies conducted during the past 15 years in the New Madrid seismic zone have shown a strong correlation between seismicity and specific fault zones associated with the Reelfoot rift.

Geologic investigations of earthquakes in the New Madrid seismic zone have focused primarily on establishing the relationship between seismicity and specific structures within the Reelfoot rift. Subsurface geologic and geophysical data have been invaluable in identifying and characterizing the major seismic source zone along the axis of the rift, although a comprehensive, regional earthquake-hazard assessment must include information on the earthquake potential of other major faults both inside the rift and outside it, knowledge of which is now completely lacking. For example, in the past 100 years, five earthquakes of magnitude 4.5 to 5.5 have occurred in the Wabash Valley seismic zone of southern Illinois and southwestern Indiana. A magnitude 5.0 earthquake in southern Illinois in June 1987 was felt in 21 States and southern Canada. The historical record of the Central United States also shows a relatively high level of seismicity along the eastern and southeastern margins of the Ozark uplift. Thus, regional seismicity shows that the scope of deep structural studies should be expanded beyond the bounds of the Reelfoot rift to encompass important structural features such as the Wabash Valley fault zone, the Cottage Grove–Rough Creek fault zone, the Ste. Genevieve fault zone, and the Ozark uplift (fig. 3). Studies are needed to establish a geologic and geophysical basis for defining seismic source zones throughout the region and to determine the potential for damaging earthquakes in each zone.

Expanded regional studies will require that critical gaps in existing aeromagnetic and gravity data be filled. Aeromagnetic and gravity data acquisition was originally designed to identify broad-scale structural features such as major tectonic blocks, shallow igneous intrusions, and anomalous zones of the crust in the northern Mississippi embayment. High-resolution aeromagnetic and gravity data sets that uniformly cover the rift and the surrounding region are now needed. These data are vital to correctly interpret the structural relationships of features at seismogenic depths and to resolve details about the structures in the upper crust in the area north of the Reelfoot rift. In addition, selected areas within the rift need specialized geophysical investigations. For example, magnetotelluric surveys in the Reelfoot rift could provide detailed information about structural relationships in the middle and lower crust in the rift and help determine the physical properties of a low-velocity, high-attenuation zone along the center of the rift where earthquakes are concentrated. Similarly, detailed aeromagnetic and gravity profiles could refine geophysical models and clarify the interrelationships among plutons, deep basins, fault zones, rift boundaries, and seismicity concentrations.

Geologic mapping is a fundamental source of structural and stratigraphic information. The status of geologic mapping should be evaluated throughout the region and places identified where specialized geologic mapping, supplemented by shallow drilling, could contribute to understanding the seismotectonics of the region. A high priority should be to compile and plot the pertinent current geologic, seismologic, and geophysical data on a topographic base map, similar to the now-outdated map of Heyl and McKeown (1978). Such a compilation would show spatial relationships among geologic, geophysical, and seismicity patterns that are likely to be important but that may not be recognized on separate maps. Within the Mississippi embayment, poorly consolidated, generally undeformed sedimentary rocks conceal structural relationships and faults in the bedrock. However, outside the Mississippi embayment, bedrock mapping may complement and corroborate some structural interpretations that are based on geophysical data.

Detailed investigations of deep structure in the rift should continue as the new studies outside the Reelfoot rift begin. Faults associated with the rift probably constitute the greatest seismic threat to the region. Therefore, detailed studies of structures that are apparently associated with seismicity, such as the Blytheville and Pascola arches, are imperative. Such studies would utilize a variety of geophysical techniques to define the extent and understand the origin of major structures in the rift that are associated with seismicity. Mapping these structures would require the acquisition of additional seismic-reflection data. An extensive petroleum-exploration program in the Reelfoot rift in the early 1980's included the collection of almost 4,000 mi of seismic-reflection profiles. These data cover many of the most active parts of the New Madrid seismic zone and are available for purchase, but new data would have to be acquired over the Pascola arch and some other parts of the zone to improve understanding of the relationship between structure and seismicity.

Recent work in the New Madrid seismic zone has suggested that the crust in the most active part of the region is characterized by low seismic-wave velocities and high seismic-wave attenuation (Al-Shukri and Mitchell, 1987, 1988; Hamilton and Mooney, 1990). These properties may provide a criterion for evaluating whether a fault zone is capable of producing large earthquakes.

To date, very little effort has been made to evaluate the seismogenic potential of the major faults along the margins of the Reelfoot rift. If the rift-bounding faults are seismogenic, then Memphis would be only a few tens of miles from the epicenter of a potential large earthquake. Densely populated Shelby County, Tennessee, would lie even closer, and West Memphis, Ark., a community of 30,000, actually straddles the southeastern rift margin. Seismic-reflection data and detailed geophysical data are essential in evaluating the earthquake potential of major faults related to the rift margins.

To assess the seismogenic potential of deep faults that appear to extend close to the surface on seismic-reflection profiles, detailed studies using high-resolution seismic-reflection profiling and exploratory trenching, if appropriate, should be made. These studies would determine whether the faults deform young sediments near the surface where the resolution of conventional reflection data diminishes and thus constrain the likelihood of damaging earthquakes in specific source zones.

Because much of the New Madrid seismic zone is covered with soft sedimentary rocks, deep scientific drilling offers the only means of directly sampling and measuring the physical properties of the bedrock to depths that approach hypocentral depths. Better information on the properties of these rocks will contribute to improved interpretations of aeromagnetic, gravity, and seismic data. This information also will help determine the factors that affect the way seismic energy is attenuated as it propagates through these rocks in the uppermost crust. A deep drill hole would permit direct measurement of the orientation and possibly the magnitude of the modern stress field in the New Madrid region, which is the driving force for the seismicity. Much of the data and information derived from a deep drill hole are unique and cannot be obtained in any other way.

Objective 4.2: Determine the spatial and temporal characteristics of damaging earthquakes in the New Madrid region

ACTIVITIES

a. Continue and expand efforts to identify and determine the age of prehistoric earthquakes by studies of paleoliquefaction, surface faulting, landslides, seismically induced disruption of lacustrine deposits, archeology, and dendrochronology.
b. Document land deformation produced by the 1811–1812 and earlier earthquakes.
c. Identify deep faults that potentially extend to the surface by means of seismic-reflection and other geophysical data; target these faults for shallow, high-resolution, seismic-reflection studies, ground-penetrating radar, and (or) trenching.
d. Determine the age of young sedimentary rocks on various alluvial terraces in the Mississippi Valley to improve understanding of rates of deformation.
e. Evaluate the status of geologic mapping and determine if more or specialized mapping is needed.
f. Conduct a comprehensive study of the fluvial geomorphology of the Mississippi Valley.

Discussion of Objective 4.2

The accounts of the New Madrid earthquakes provide a fairly complete picture of the sequence of events in 1811–12 (Fuller, 1912), but the historical record offers no clues about the occurrence of strong earthquakes before 1811. Fuller (1912) briefly discussed five pre-1811 earthquakes, but his information is too sparse to determine even if they were Mississippi Valley events.

The historical record of earthquakes in most parts of the world, including the United States, is too short to document the long-term behavior of seismogenic faults. Yet information on the locations and frequency of strong earthquakes in a region is vital to reliably assessing earthquake hazards. Because of the short historical record, geologic and archeological studies of prehistoric earthquake phenomena (paleoseismology) have played an increasingly important role in improving earthquake-hazard analyses and probabilistic hazard assessments. Thus, geologic studies on the locations, timing, and sizes of prehistoric earthquakes have successfully extended the historical seismicity record in many parts of the world.

Unlike many earthquake-prone places in the Western United States, the surface expression of young faults in the New Madrid seismic zone is very subtle to nonexistent. Geologic studies to determine the recurrence of major earthquakes and the locations and nature of surface deformation in the region can contribute a great deal to hazard assessments, but these studies are difficult to conduct because of the subdued and concealed expression of tectonism.

The only fully reported geologic data on the recurrence of large earthquakes in the New Madrid region are Russ's (1979) study of shallow faulting associated with the Reelfoot scarp, a 7-mi-long escarpment along the western margin of Reelfoot Lake in northwestern Tennessee. The 10- to 30-ft-high scarp is a prominent physiographic feature in the Mississippi Valley, where the topographic relief is otherwise very low. An exploratory trench across the scarp exposed numerous, small-displacement faults that are coincident with the scarp and revealed evidence of two strong earthquakes that predate the 1811–12 events (Russ, 1979). Stratigraphic relationships in the trench and radiocarbon dating show that both of the ancient earthquakes are less than 2,000 years old. Thus, the three strong earthquakes (1811–12 and the two older events) that have occurred at this site in the past 2,000 years imply an average recurrence interval of about 600 to 900 years for strong earthquakes but not necessarily for earthquakes of the size that occurred in 1811–12.

The geologic recurrence estimate of 600 to 900 years is in the range of estimates based on statistical analysis of historical and modern seismicity; these calculations yield recurrence estimates for maximum-magnitude events that range from about 200 years to more than 2,500 years but cluster around 600 to 1,200 years (Johnston and Nava, 1985, table 1). The wide range in the estimates from seismologic data and the paucity of constraints from geologic data demonstrate the need for greater efforts to determine the age of prehistoric earthquakes in the New Madrid seismic zone.

Geologic data on the timing of prehistoric earthquakes throughout the entire New Madrid region are needed not only to estimate the likelihood of future major earthquakes but also to understand the rate and processes of strain accumulation and release in the region. The most direct recurrence information is derived from studies of faults that have repeatedly ruptured the ground surface during successive events. However, other than the study of the Reelfoot scarp, efforts to identify tectonically significant surface faulting have been unsuccessful, in part, because it is difficult for displacements in competent bedrock to propagate to the surface through thousands of feet of soft sediment.

It is fortunate that geologic estimates of recurrence intervals need not rely solely on finding evidence of surface faulting. The 1811–12 events show that the strong ground motion and deformation from major earthquakes in the New Madrid region caused a variety of secondary geologic effects, including extensive liquefaction, earthquake-induced landslides, and uplift and subsidence. Ancient earthquakes surely produced similar effects that would be preserved in the geologic record. Identifying and dating these ancient effects would provide crucial information about the recurrence of strong ground motion—and thus large earthquakes—in the New Madrid seismic zone. Recurrence information is of such great importance that novel methods of dating prehistoric earthquakes need to be fully explored. For example, Reelfoot and Big Lakes are in the epicentral area of the seismic zone. Strong ground motion during the 1811–12 events may have disturbed the well-stratified sediments in these lakes, both of which probably were enlarged or even formed by the 1811–12 sequence. If sediment cores from these lakes show disruption from the 1811–12 events, deeper cores may reveal similar features caused by older earthquakes that could be dated.

Dendrochronology, the study of annual growth rings of trees, might also be useful in dating prehistoric earthquakes in the region. The strong ground shaking during earthquakes probably broke large branches, disturbed root systems, tipped trees, and caused temporary changes in the water table, all of which stressed the trees. If this earthquake-induced stress were severe enough, it would have been recorded in tree growth rings, which could be dated. Very little old-growth forest remains; what is left should be systematically inventoried to determine the feasibility of dendrochronologic paleoseismic research.

Successfully obtaining recurrence information in the New Madrid seismic zone requires a strategy for locating the areas where evidence of prehistoric earthquakes is likely to be found. The areas that experienced substantial deformation in 1811–12 presumably suffered similar deformation during earlier events. Drainage patterns and the morphology of stream channels can be very sensitive indicators of tectonic deformation. Therefore, a first step in this strategy would be to analyze the fluvial geomorphology in the seismic zone to identify areas of significant deformation during 1811–12 and then to use this analysis as a basis for selecting sites for intensive investigations using techniques such as high-resolution seismic-reflection studies or exploratory trenching. An important related aspect of this geomorphic analysis would be to obtain better data on the age of alluvial and fluvial deposits in the Mississippi Valley to help determine the rates of deformation.

Objective 4.3: Determine the rates and causes of active crustal deformation and improve understanding of the stress regime and tectonic setting

ACTIVITIES

a. Identify areas of strain accumulation and quantify accumulated strain by using geodetic data.
b. Acquire information on the modern stress field that is independent of seismicity data (by using existing wells).
c. Drill one or more research drill holes.

Discussion of Objective 4.3

Modern geodetic methods for determining rates of active crustal strain provide critical data about the occurrence of large intraplate earthquakes. The rate at which elastic strain energy is accumulating should be measured; the relationship between such changes and earthquakes may provide a means for discriminating among regions where large intraplate earthquakes are likely to occur (and reoccur) and those where they are not.

The opportunity to conduct this kind of research in intraplate seismic areas is facilitated by the presence of a comprehensive network of bench marks that have been accurately surveyed by triangulation techniques for many decades (in some cases, these networks extend back to the 19th century) and by the recent development of accurate, relatively inexpensive surveying methods using the Global Positioning System (GPS). By using GPS, it is now possible to measure crustal strain efficiently by resurveying old triangulation networks as well as by establishing new baseline data for future surveys.

One hypothesis frequently cited to account for intraplate earthquakes is that they occur in zones of extreme crustal weakness. To test this hypothesis, it is necessary to accurately map the orientation of the stresses in the Earth's crust. Although the ability to map the crustal stress field has improved markedly in the past decade, data coverage in areas such as the New Madrid seismic zone is quite sparse and completely inadequate to examine this hypothesis. It is now possible to obtain data on the orientation of the crustal stress field by making straightforward geophysical measurements in boreholes (for example, wellbore breakouts). These measurements could be made either in holes drilled for other purposes or in shallow holes drilled specifically for stress measurements. Such measurements would provide a greatly improved knowledge of the physical mechanisms responsible for intraplate seismicity. The advantage of wellbore breakout data is that they are independent of seismicity; the disadvantage is that they are confined to shallow crustal depths and generally do not sample the depths of principal seismogenic strain release.

Goal 5: Improving seismic risk assessments

ACTIVITIES

a. Delineate seismic source zones.
b. Identify areas expected to experience strong ground shaking.
c. Identify areas having soil deposits that can amplify ground motion.
d. Identify areas subject to ground failure.
e. Identify areas vulnerable to flooding from levee or dam failure and eruption of water associated with liquefaction.
f. Inventory high-occupancy hazardous buildings.
g. Conduct analytical and experimental studies on the earthquake response of engineered facilities.
h. Identify procedures to reduce vulnerability through structural and nonstructural means.
i. Evaluate the 1988 editions of the seismic design provisions of the principal model building codes (that is, Standard Building Code, Uniform Building Code, National Building Code, and the NEHRP Recommended Seismic Design Provisions) and recommend adoption of the code that is most relevant.
j. Provide a data base for seismic zonation.

Discussion of Goal 5

Assessment of seismic risk requires three elements: an earthquake-hazards model, an exposure model (inventory), and a vulnerability model. A generic earthquake-hazards model requires knowledge of ground shaking and its probability of nonexceedance, surface-fault rupture, earthquake-induced ground failure, and regional tectonic deformation. The exposure model, or inventory, involves the spatial distribution of population and various structures, including buildings, utility and transportation structures, hydraulic structures (dams, reservoirs, levees, and so on), and others. The vulnerability model is a means for predicting losses among the inventoried items. One element commonly used in a vulnerability model is a fragility curve, which shows the probability of damage versus the level of ground motion for a specific type of structure. Predicting damage is very difficult for a variety of reasons: nonuniform design and construction, variability in material properties, changing design strength of aging structures, uncertainty in the level of ground shaking, uncertainty in structural response, and uncertainty in the response of sediments that are susceptible to liquefaction, to name a few.

Improved techniques are needed for estimating seismic risk in the Central and Eastern United States because development of the current methodology was based primarily on experience in high-seismicity regions of the Western United States. More attention should be devoted to structural materials and systems that are no longer used in locations such as coastal California because of their perceived inherent low resistance to earthquake shaking but that are still widely used in the central and eastern areas of the country. The response of these materials and systems to both strong and moderate levels of ground motion will greatly influence the pattern of losses in a future, strong New Madrid earthquake. Nondestructive testing would be necessary in evaluating the response of such structures.

Methods have been developed and applied in the Western United States to predict the probability and geographic extent of landsliding that would be triggered by earthquakes of given magnitudes and locations. Such methods could be applied to the New Madrid seismic zone but only after detailed investigation to (1) determine the distribution of susceptible slopes, (2) model the ground shaking that those slopes would experience, and (3) develop computer models to simulate how the slope materials would respond to the strong shaking. A predictive map of earthquake-induced landslide susceptibility developed in this way could be combined with an exposure model to obtain a landslide risk model for future New Madrid seismic zone earthquakes.

MANAGEMENT AND COORDINATION

An intensified study of the New Madrid seismic zone would be conducted under NEHRP, and standard NEHRP procedures would be followed in managing the study. Thus, the study would be incorporated in the overall plans of NEHRP, and the interagency coordinating groups would provide an overview of activities in the New Madrid region.

Much of the work in the intensified study would be conducted by scientists in universities, State geological surveys, and private groups. The award of research grants and contracts would be based on peer review of research proposals. Thus, detailed allocation of funds among the various activities identified in this plan would depend on the peer-review process.

In addition to the usual NEHRP procedures for managing regional studies, there is a need for stronger coordination of studies in the New Madrid region because of the large number of participating organizations. At least seven States (Arkansas, Illinois, Indiana, Kentucky, Mississippi, Missouri, and Tennessee) are involved. Participating agencies from each State could include both their emergency planning groups and their geological surveys. At present, CUSEC coordinates some of the State activities. Research groups from several universities and the USGS also are involved; these groups need to jointly plan instrument and data-processing systems and to share data from these systems. Coordination among these groups could be facilitated in three ways:

1. Establish a New Madrid seismic zone coordinating committee comprised of representatives of each group that has a substantial responsibility for conducting part of the intensified study.
2. Hold an annual workshop to present results of activities and to plan future work.
3. Encourage presentation of results at scientific meetings and publication of results in appropriate scientific journals and other documents.

Although additional means may be needed, these steps would certainly provide effective—probably essential—ways of coordinating the study.

CONCLUSIONS

Earthquakes in the New Madrid seismic zone pose a relatively high and generally unappreciated danger to the Central United States in comparison with that of other natural hazards. A recurrence of the magnitude 8 earthquakes that struck the area in 1811–12 would cause thousands of casualties, and damage could run as high as $50 billion, unless communities reduce their vulnerability through improved preparedness and mitigation measures. Such an event could devastate the region in minutes; rebuilding and recovery would take years.

The probability of a magnitude 8 earthquake in the New Madrid region, although difficult to evaluate with currently available data, appears to be low—in the range of 2.7 to 11 percent in a 50-year period. An earthquake in the magnitude 6 to 6.5 range, which could cause heavy damage, has a 16- to 63-percent probability of occurring in a 15-year period; that probability increases to a 45- to 97-percent probability in a 50-year period (table 2). Refining these probability estimates and reducing the uncertainty of the potential damage estimates are objectives of studies in the New Madrid seismic zone.

The level of earthquake preparedness in the New Madrid region is low, primarily because earthquakes are not perceived to be of great concern in comparison with other demands on resources. Consequently, although some exercises have been conducted to prepare for earthquake disasters, few land-use or structural design provisions have been implemented to guide new construction, and virtually no efforts have been made to deal with the numerous existing structures that are vulnerable to earthquakes (for example, unreinforced masonry buildings).

One of the reasons for inaction in dealing with the earthquake threat is the uncertainty about the locations and frequency of damaging earthquakes. Current data have been used to make general estimates of the seismic risk, but those estimates contain relatively arbitrary assumptions and large uncertainties. The lack of strong-ground-motion data for events exceeding magnitude 5 and the lack of a chronology of strong earthquakes that exceeds estimated recurrence intervals are the two data limitations that present the greatest uncertainties.

An intensified research program would greatly improve the basic data needed to assess seismic risk in the Central United States; these data also would provide better estimates of where and how often future earthquakes are likely to occur and what types of physical effects to expect. This foundation of scientific information would provide a basis for government agencies and the private sector to improve building codes, to retrofit or remove dangerous structures, to start earthquake awareness and education programs, and to improve preparedness planning.

The intensified study of the New Madrid seismic zone should have five goals:

1. Implementing earthquake-hazard mitigation measures.
2. Improving preparedness for earthquakes of magnitude 6 or larger.
3. Establishing a modern seismic network in the New Madrid seismic zone to monitor the sizes, loca-

tions, and characteristics of earthquakes and to determine the nature of the ground motions that they generate.
4. Locating faults that could cause destructive earthquakes, determining the recurrence rates of earthquakes, and delineating areas of potential damage.
5. Improving seismic-risk assessments.

Implementation of this five-point program would provide the information necessary to improve the reliability of seismic-risk assessments for the New Madrid region. The scope of activities envisioned under this program could be undertaken at a funding level of $5 to $10 million a year, for 5 years, after which time the status of earthquake-hazard information for the New Madrid region would be reexamined and the plan modified to reflect the improved status of each element. Coordination would be facilitated by establishing a New Madrid seismic zone coordinating committee, holding an annual workshop, and presenting results in publications and meetings.

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APPENDIX: NEW MADRID SEISMIC ZONE WORKSHOP PARTICIPANTS

Algermissen, S.T. (U.S. Geological Survey)
Beavers, James (Martin Marietta Corporation)
Bologna, Antonio (Memphis/Shelby County Building Code Enforcement Board)
Braile, Lawrence (Purdue University)
Branton, Fiona (U.S. Senate Committee on Commerce, Science, and Transportation)

Chang, T.S. (Memphis State University)
Chiu, Jer-Ming (Memphis State University)
Chung, Wai-Ying (Memphis State University)
Clarke, Timothy (Memphis State University)
Crone, Anthony J. (U.S. Geological Survey)

Dorman, James (Memphis State University)
Fanning, Harold (Reaves & Sweeney, Inc.)
Guccione, Margaret T. (University of Arkansas)
Hall, William (University of Illinois)
Hamburger, Michael (Indiana University)

Hamilton, Robert M. (U.S. Geological Survey)
Hanson, Robert (National Science Foundation)
Hatcher, Robert D., Jr. (University of Tennessee)
Hays, Walter W. (U.S. Geological Survey)
Herrmann, Robert B. (St. Louis University)

Hester, Norman C. (Indiana Geological Survey)
Heigold, Paul (Illinois State Geological Survey)
Hildenbrand, Thomas G. (U.S. Geological Survey)
Hill, William T. (Tennessee Department of Conservation)
Howe, Warner (Gardner & Howe Structural Engineers)

Hughes, Terry (Memphis/Shelby Co. Code Enforcement)
Hwang, Howard (Memphis State University)
Jacob, Klaus H. (Lamont-Doherty Geological Observatory, Columbia University)
Jibson, Randall W. (U.S. Geological Survey)
Johnson, Gary D. (Federal Emergency Management Agency)

Johnston, Arch C. (Memphis State University)
Kanter, Lisa R. (Memphis State University)
Kernell, Michael (Tennessee State Representative)
Kiefer, John (Kentucky Geological Survey)
Krinitsky, Ellis (U.S. Waterways Experiment Station)

Lanelle, Kathleen
Lew, H.S. (National Institute of Standards and Technology)

Masse, Robert P. (U.S. Geological Survey)
McCrary, Tom (Memphis State University)
McFarland, John David (Arkansas Geological Commission)

McKeown, Frank A. (U.S. Geological Survey)
McMullen, Richard (U.S. Nuclear Regulatory Commission)
Mitchell, Brian J. (St. Louis University)
Murphy, Andrew J. (U.S. Nuclear Regulatory Commission)
Murphy, Loyal (P.E.)

Newton, Danny (Tennessee Emergency Management Agency)
Nishenko, Stuart P. (U.S. Geological Survey)
Obermeier, Stephen F. (U.S. Geological Survey)
Padovani, Elaine R. (U.S. Geological Survey)
Palmer, James (Missouri Geological Survey)

Paul, James (U.S. House Committee on Science, Space, and Technology)
Reiter, Leon (U.S. Nuclear Regulatory Commission)
Russ, David P. (U.S. Geological Survey)
Ryland, Harvey (Central U.S. Earthquake Consortium)
Schweig, Eugene S. (Memphis State University)

Sexton, John L. (Southern Illinois University)
Sharrocks, Fred (Federal Emergency Management Agency)
Shedlock, Kaye M. (U.S. Geological Survey)
Stauder, William, S.J. (St. Louis University)
Stevens, Jill (Memphis State University)

Stewart, David (Southeast Missouri State University)
Street, Ron (University of Kentucky)
Suiter, Lacy (Tennessee Emergency Management Agency)
Sutter, John (U.S. Geological Survey)
Van Arsdale, Roy B. (University of Arkansas)

Vaughn, James (Missouri Geological Survey)
Wesnousky, Stephen G. (University of Nevada, Reno)
Wesson, Robert L. (U.S. Geological Survey)
Whitcomb, James (National Science Foundation)
Zoback, Mark (Stanford University)

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