DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Estimation of Earthquake Effects Associated with Large Earthquakes in the New Madrid Seismic Zone

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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GLOSSARY

ATTENUATION OF INTENSITY--The fall-off of seismic intensity with distance from the epicenter. In regions where the intensity attenuation is low, such as the central United States, damaging intensities extend to much greater distances from an epicenter than they would, for example, in California, where intensity attenuation is higher.

BODY WAVES--Seismic waves that travel through the earth. There are two kinds of body waves, P waves and S waves. The P wave, sometimes called the "primary wave" because it travels faster and arrives first, is a compression-rarefaction vibrating in the direction of propagation. The S wave, sometimes called the "secondary wave" because it arrives after the P wave, is a shear wave vibrating at right angles to the direction of propagation.

EPICENTER--The location on the earth's surface directly above the focus of an earthquake.

EPICENTRAL AREA--Area surrounding the epicenter, usually the isoseismal of highest intensity.

FAULT--A fracture or fracture zone in the earth. Earthquakes are caused by ruptures along faults. A fault may exist at depth and not break the surface when it ruptures.

FELT AREA--The entire area over which an earthquake is reported felt. See also "isoseismal map".

FOCAL DEPTH--The depth of focus of the earthquake beneath the surface of the earth.

FOCUS--The center, or source, of an earthquake below the surface. Also called the hypocenter.

HYPOCENTER--The focus.

INSTRUMENTAL EARTHQUAKE--An earthquake whose vibrations were recorded by instruments, or seismographs.

INSTRUMENTAL EPICENTER--The epicenter calculated by using the time of the vibration recorded on seismograms. It usually corresponds to the area of highest intensity.

INTENSITY SCALE--An arbitrary ranking of the effects produced by an earthquake on people, structures, and the ground. The intensity value is denoted by a Roman numeral in the Modified Mercalli (M.M.) Intensity Scale (See Appendix 1). The maximum intensity, denoted by I_0, is the most severe of these effects, and occurs, usually, near the instrumental epicenter.

ISOSEISMAL MAP--A map on which assigned intensities for a single earthquake have been plotted and contoured. Examples are figures 2, 4, 5, and 6. The contour lines are called "isoseismals". The innermost contour (highest isoseismal) is the epicentral area, and usually includes the instrumental epicenter. Epicenters for pre-instrumental earthquakes are usually placed at the location of the highest known intensity report. The outermost isoseismal encloses the "felt area" of the earthquake.

LIQUEFACTION--The sudden transformation of soil into a fluid. Repeated earthquake vibrations can cause a loose, water-saturated sand to suddenly loose all of its shear strength or internal friction resistance and collapse. If the released water can find an outlet to the surface, continuing vibrations can then pump water and sand out of the ground. When this water and sand spouts from a single hole it is called a "sand blow"; it may also seep out of the ground along long fractures or cracks. This phenomenon was widespread in the central Mississippi Valley during the 1811-1812 New Madrid earthquakes (figure 3), and the sand deposited at that time may still be seen in aerial photographs (figure 45).

m_b--Body-wave magnitude. See "magnitude".

M_S--Surface-wave magnitude. See "magnitude".

MAGNITUDE--An instrumental measure of the size of an earthquake, or of the total amount of energy released at the source of the earthquake. Several different magnitudes may be calculated from the amplitudes of the seismic vibrations recorded by a seismograph. The two most common ones worldwide are m_b, derived from the body-wave vibrations, and M_S, derived from the surface-wave vibrations. Magnitude is popularly referred to as "Richter magnitude" because the first magnitude scale was developed by Charles F. Richter.

PRE-INSTRUMENTAL EARTHQUAKE--Any historical earthquake that occurred before the development of seismographs. Epicenters for such earthquakes are usually placed at the site of the highest known intensity report, or on the trace of an active fault near that report (when such a fault is known). Magnitudes of pre-instrumental earthquakes are usually estimated from: 1) the maximum intensity, I_o; 2) the felt area; or 3) the attenuation of intensity with distance as determined from an isoseismal map.

SAND BLOW--See "liquefaction".

SEICHE--A wave created on the surface of an enclosed body of water. Seiches caused by seismic waves may occur hundreds of kilometers from the epicenter.

SEISMICITY--The areal distribution of historical earthquakes. Figure 7 shows the geographical distribution of the historical seismicity of the Mississippi Valley. The catalog of these events also gives their distribution in time.

SEISMIC WAVES--The disturbances propagated outward from the focus of an earthquake. They cause the vibrating or rolling or swaying motions observed at sites far from the epicenter. Seismic waves that travel through the earth are called "body waves". Those that travel along the earth's surface are called "surface waves".

SEISMIC ZONE--An area of intense local seismicity. The microseismicity of the New Madrid seismic zone (figure 8) implies the location of the buried fault.

SEISMOGRAM--An instrumental record of earthquake vibrations. Information obtained from seismograms includes arrival times, amplitudes, and periods of seismic waves. These measurements are used to calculate the magnitude of the earthquake and the location of the hypocenter.

SEISMOGRAPH--An instrument to record earthquake vibrations. The record of the vibrations is a "seismogram".

SURFACE WAVES--Seismic waves that travel only along the surface of the earth.

WAVE AMPLITUDE--Height of a wave crest above the base line.

WAVE LENGTH--Distance between succeeding wave crests.

WAVE PERIOD--Time for the passage of one complete wave cycle.

ESTIMATION OF EARTHQUAKE EFFECTS ASSOCIATED WITH LARGE EARTHQUAKES IN THE NEW MADRID SEISMIC ZONE

By Margaret G. Hopper and S. T. Algermissen

ABSTRACT

Estimates have been made of the effects of a great earthquake (M_s = 8.6, I_o = XI), a large earthquake (M_s = 7.6, I_o = X), and a moderate earthquake (M_s = 6.7, I_o = IX) hypothesized to occur anywhere in the New Madrid seismic zone. The estimates are based on the distributions of observed intensities associated with the earthquakes of 1811-12, 1843 and 1895, although the effects of other historical shocks are also considered. The resulting composite type intensity maps for each magnitude are believed to represent the upper levels of shaking likely to occur. A composite intensity map shows a more widespread distribution of effects than would result from a single earthquake of the chosen magnitude, say 8.6, because the distributions of effects were plotted for magnitude-8.6 earthquakes that could occur anywhere from the northern to the southern end of the seismic zone, and the maximum of the resulting intensities was chosen for each point on the map. Specific intensity maps have also been developed for seven cities near the epicentral region taking into account the most likely distribution of site response in each city. Intensities found for the magnitude-8.6 shock are: IX for Carbondale, Ill.; VIII and IX for Evansville, Ind.; VI and VIII for Little Rock, Ark.; IX and X for Memphis, Tenn.; VIII, IX, and X for Paducah, Ky.; VIII and X for Poplar Bluff, Mo.; and VII, VIII, and IX for Saint Louis, Mo. Intensities found for the M_s = 7.6 and 6.7 shocks are one and two intensity units lower, respectively. On a regional scale, intensities are found to attenuate from the New Madrid seismic zone most rapidly on the west and southwest sides of the zone, most slowly on the northwest along the Mississippi River, on the northeast along the Ohio River, and on the southeast toward Georgia and South Carolina. Intensities attenuate toward the north, east, and south in a more normal fashion. Known liquefaction effects are also documented.

INTRODUCTION

by Margaret G. Hopper

The New Madrid seismic zone is the site of some of the largest historical earthquakes in the conterminous United States, the 1811-1812 series. It is also the most seismically active area in the central United States. Since an earthquake with a maximum Modified Mercalli (M.M.) intensity greater than IX has not occurred in the area since 1895 (see Appendix 1 for a description of the Modified Mercalli intensity scale), and not one equivalent to the 1811-1812 sequence since 1812, the people of the region are generally neither expecting nor prepared for a damaging earthquake. There are many older buildings of unreinforced brick that are known from experience in areas of frequent earthquakes to represent a considerable risk. If these structures were located in an area with more frequent large earthquakes, they would have been damaged long ago and perhaps removed. Many people in the Midwest are unaware of the damage potential of a large earthquake. Although the occurrence of the New Madrid earthquakes is widely known, they are regarded only as interesting curiosities.

The New Madrid seismic zone has been the focus of a considerable amount of scientific research in recent years. Important publications with particular relevance to this study include a number of papers by Nuttli (1973, 1974, 1979, 1981, and 1982), Street (1981 and 1982), Street and Nuttli (1984), the U.S. Geological Survey Professional Paper on the New Madrid region (McKeown and Pakiser, 1982), the MATCOG (Mississippi-Arkansas-Tennessee Coucil of Governments) study (M & H Engineering and Memphis State University, 1974), and the recent book on earthquake risk for the New Madrid region by Liu (1981). Studies on ground effects during the New Madrid earthquakes include those by Russ (1979) and Obermeier (1984). Considerable research has been done in the city of Memphis, including the MATCOG report mentioned above, a study by Sharma and Kovacs (1980) of Purdue University, and by Nowak and Morrison (1982) of the University of Michigan.

The objectives of the present study are: 1) to estimate the magnitude and location of an 1811-type earthquake (surface-wave magnitude M_s=8.6), a large earthquake (M_s=7.6), and a moderate earthquake (M_s=6.7), 2) to estimate the levels of damaging ground motion (in terms of Modified Mercalli intensities) throughout the Midwest resulting from these simulated earthquakes, 3) to estimate the intensities at each of the seven representative cities studied individually (see figure 1), 4) to assess the potential for liquefaction in the area of intensity IX M.M. and above, 5) to review pertinent aerial photography to find the distribution of sand blows, and 6) to find areas of lower intensities, both regional and in the seven cities, based on damage patterns of previous earthquakes and on local geology.

Similar studies in other areas have been prepared for FEMA and its predecessor agencies. They include reports on San Francisco (Algermissen and others, 1972), Los Angeles (Algermissen and others, 1973), Puget Sound (Hopper and others, 1975), and Salt Lake City (Rogers and others, 1976). While this report is similar in purpose and design to those studies, in method and scope it is necessarily different. The method varies from the previous reports because of the different geologic and seismic setting, particularly the low

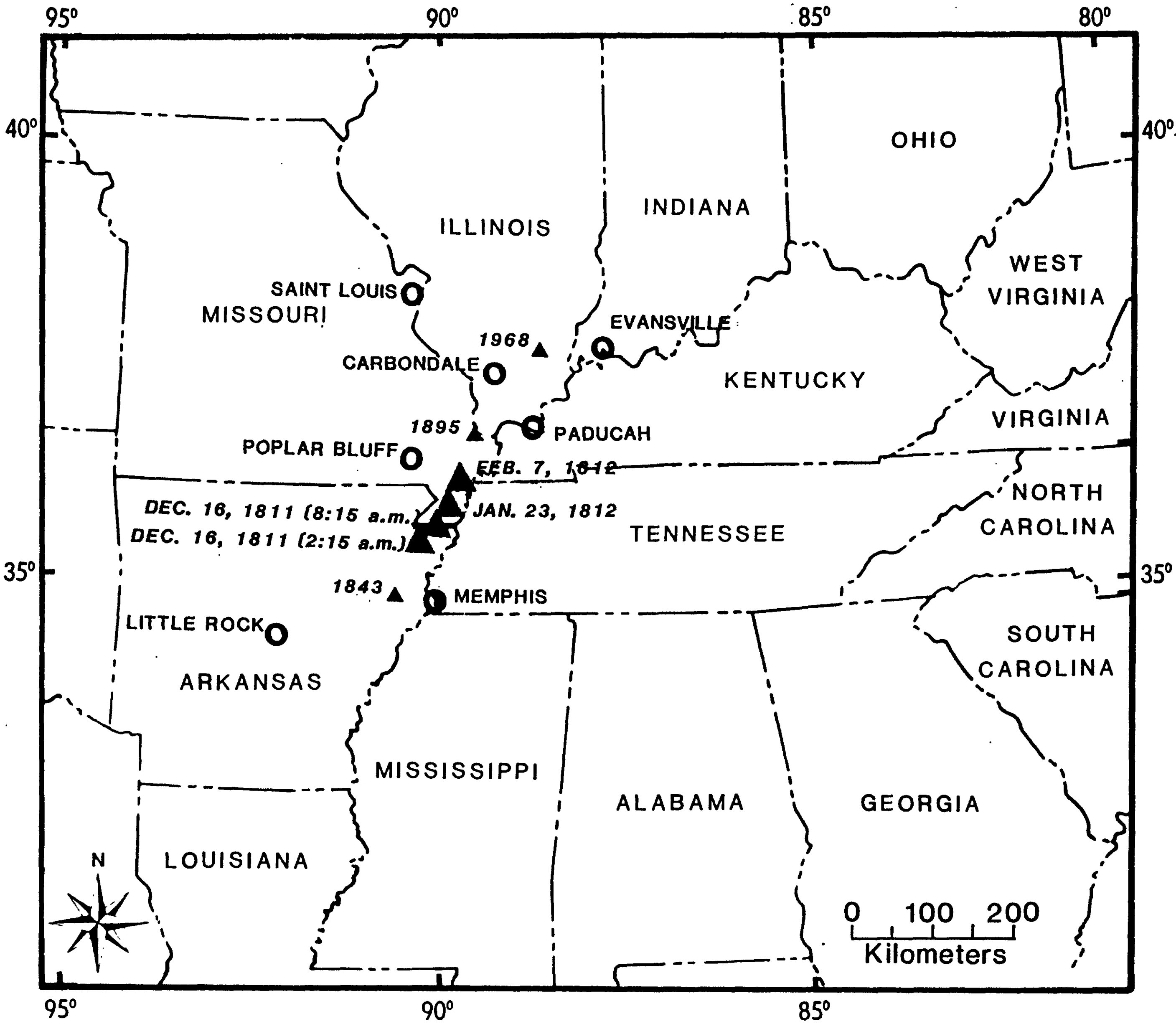


Figure 1.--Map showing the seven cities evaluated in this report. Also shown (triangles) are localities of the epicenters of the large historical earthquakes discussed in this report.

attenuation of seismic energy in the midcontinent, which results in unusually large damage areas. This report does not include specific damage estimates, as did the earlier studies.

A previous interim report prepared for FEMA during this project (Hopper and others, 1983) is superceded by this report.

HISTORICAL SEISMICITY OF THE MISSISSIPPI VALLEY

By Margaret G. Hopper

EARTHQUAKES OF 1811-1812

During the winter of 1811-1812 four great earthquakes occurred in the Mississippi Valley each having body-wave magnitude m_b above 7.0 (see table 1 and figure 2). There have been no other earthquakes larger than these within

TABLE 1.--Relative sizes of the 1811-1812 earthquakes

[Intensity estimates from Nuttli (1981), magnitude estimates from Street and Nuttli (1984), and epicenter estimates from D. P. Russ (oral commun., 1983) and Street (1982). Leaders (---) indicate no data]

Date	Local time	I_o	M_S	m_b	Epicenter	
					Lat N.	Long W.
1811 Dec. 16	2:15 a.m.	XI	8.6	7.2	35.8°	90.3°
1811 Dec. 16	8:15 a.m.	---	---	7.0	36.0°	90.0°
1812 Jan. 23	9:00 a.m.	X-XI	8.4	7.1	36.2°	89.8°
1812 Feb. 7	3:45 a.m.	XI-XII	8.7	7.3	36.5°	89.6°

the conterminous United States during historical times. Their magnitudes are comparable to those of the largest California earthquakes, and, because of the low attenuation of seismic intensities in the eastern and central United States, their felt areas are much larger than similar magnitude California shocks. These earthquakes were felt with intensity greater than or equal to V M.M. (that is, enough to cause alarm; see Appendix 1 for the entire Modified Mercalli scale) over approximately 2,500,000 km^2, which includes the entire eastern United States (Nuttli, 1973). The area of intensity VII (mainly architectural damage) and greater covers parts of Illinois, Indiana, Ohio, Kentucky, Tennessee, Alabama, Mississippi, Louisiana, Arkansas, and Missouri. Because of the low population density in 1811, the effects of these earthquakes west of the Mississippi River are not known, but they can be estimated. From this study and others it is clear that large parts of Kansas, Oklahoma, and Texas were shaken at the intensity-V level.

The maximum intensities of the four 1811-1812 earthquakes range from X to XII (see table 1). In the epicentral area of the first shock (December 16, 1811, 2:15 a.m.), the St. Francis River area of northeastern Arkansas, a lake was uplifted and drained, while other places subsided as much as 12 feet (3.7 m) (see figures 2 and 3). Sand and other materials were thrown from fissures or cracks in the swampland. The greatest disturbance occurred along the Mississippi River between Islands 30 and 40 along the Tennessee-Arkansas border north of Memphis (Nuttli, 1973). According to Fuller (1912, p. 10), "Great waves were created, which overwhelmed many boats and washed others high upon the shore, the return current breaking off thousands of trees and carrying them out into the river. High banks caved and were precipitated into the river, sand bars and points of land gave way, and whole islands disappeared." Uplifted areas caused ponding or waterfalls along the Mississippi. Landslides were extensive along the river banks as far up the Ohio River as Indiana, but particularly severe along the Chickasaw Bluffs on

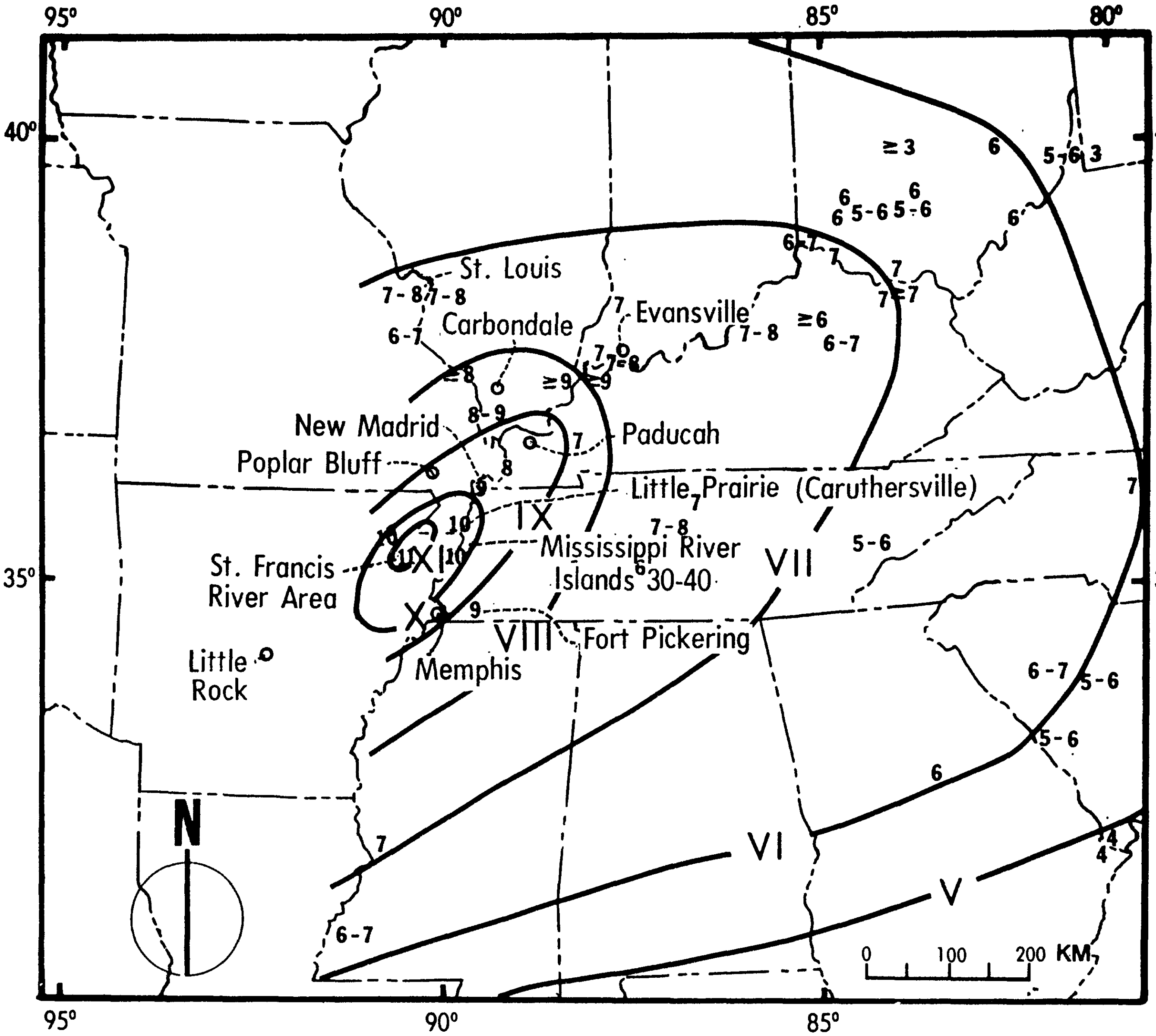


Figure 2.--Isoseismal map of the December 16, 1811, (2:15 a.m.) earthquake, in northeast Arkansas (first major shock of the New Madrid series). After Nuttli (1981). Arabic numbers represent assigned Modified Mercalli intensities for individual locations; Roman numerals, the intensities for the isoseismals. Maximum intensity for this earthquake is XI. No information is available with which to complete the isoseismals on the west side. There are assigned intensities for only two of the seven cities in this study: the IX at Fort Pickering near what is now Memphis and VII-VIII at Saint Louis. Since the isoseismal lines are not very well constrained by the data, they give only an approximation of the intensity at any given place. Within the IX isoseismal lie Memphis, Paducah, and Poplar Bluff; within the VIII, Carbondale and perhaps Little Rock; within the VII, Evansville and St. Louis.

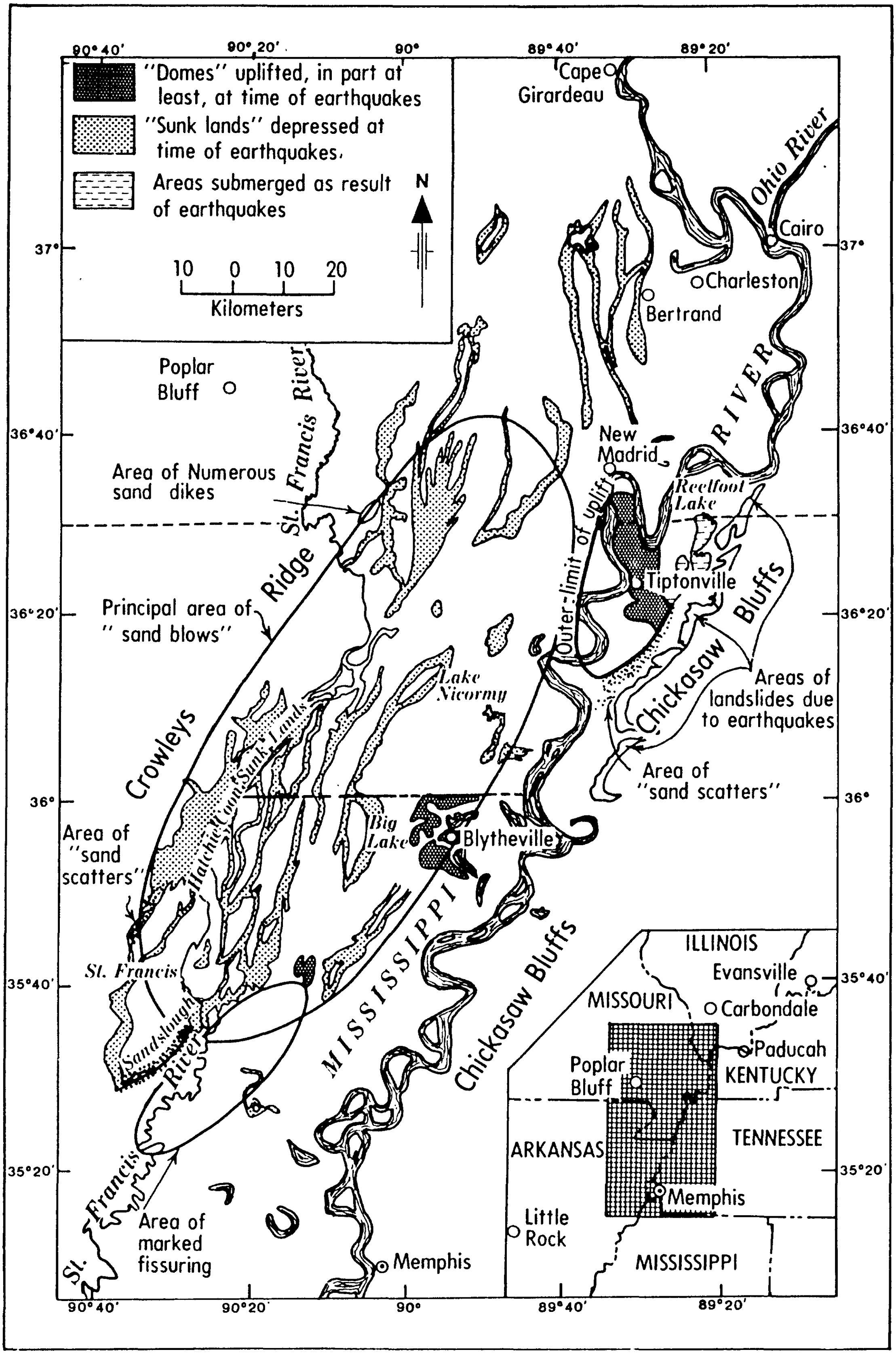


Figure 3.--Map of the ground effects of the New Madrid district. After Fuller (1912).

the Mississippi River north of Memphis. The roads between New Madrid and Arkansas were made impassable by the earthquake. The area of marked earth disturbances extended from Cairo to Memphis and from Crowley's Ridge to Chickasaw Bluffs.

The people in the epicentral area in 1811-1812 were able to survive as well as they did only because of their lifestyle. There were only about 5000 people living in the area of intensity X and greater, and they occupied light, wood-frame structures, the kind least susceptible to earthquake damage. Transportation was by horse, boat, and foot, and most escaped on foot; the small population was able to feed itself after the earthquake by hunting wild geese (Nuttli, 1981).

In addition to the four main shocks, there were numerous aftershocks, fifteen of them quite strong (table 2). All 19 of the above shocks were strong enough to be felt at Washington, D.C., and awaken sleepers at night (Nuttli, 1981). Moreover, Jared Brooks of Louisville, 200 miles (320 km) from the epicentral area, counted 1,874 shocks felt at Louisville from December 16, 1811 until March 15, 1812 (Nuttli, 1973 and Fuller, 1912 p. 33).

TABLE 2.--Aftershocks of the 1811-1812 New Madrid earthquakes

[From Nuttli (1981) and Street and Nuttli (1984)]

I_o	M_S	Number
X-XII	≥ 8	4
IX-X	7-8	5
VIII-IX	6-7	10

There is little available information on the 1811-1812 series for the seven cities in this study. Using Nuttli's (1981) isoseismal map of the 1811 (December 16, 2:15 a.m.) earthquake (see figure 2), Carbondale is in the VIII area; Evansville, the VII area; Little Rock, off the map; Memphis, the IX area; Paducah, the IX area; Poplar Bluff, the IX area; and Saint Louis, the VII area. Nuttli (1973) assigned a IX at Fort Pickering, near what is now Memphis, and a VII-VIII at Saint Louis. Street (1982) assigned VII, VI-VII, and VIII at Saint Louis for the 1811 (December 16, 2:15 a.m.), 1811 (December 16, 8:15 a.m.), and 1812 (February 7) shocks, respectively.

The isoseismals for the 1811 (2:15 a.m.) earthquake, figure 2, are quite smooth and generalized. This is a result of the limited amount of historical data for this earthquake and its distribution over the eastern United States. No information at all is available west of the vicinity of the Mississippi River. Even less is known about the distribution of effects of the other three large shocks in the sequence. Recent work by Street and Nuttli (1984) shows totals of 84, 40, 52, and 45 locations having assigned intensities for the four principal 1811-1812 shocks, respectively. Those intensities are unevenly distributed, being predominately located along the Ohio and Mississippi Rivers and a few other settled areas of the East Coast. Therefore no attempt was made to contour an isoseismal map from them. In order to estimate what the distribution of intensities for such future large shocks might be, another source of intensity information is necessary.

OTHER LARGE EARTHQUAKES IN THE REGION

Significant information is available for three other central U.S. shocks, which are all smaller than the four large shocks of the 1811 series, but have magnitudes (m_b) greater than 5.5 (see table 3). All three were damaging earthquakes. These earthquakes supply more detailed information in areas where there is little or no 1811 data. Their isoseismal maps are shown in figures 4, 5, and 6.

TABLE 3.--Relative sizes of large earthquakes in the area

[Estimates from M. G. Hopper and S. T. Algermissen (1980 and unpub. data, 1980), Coffman and Cloud (1970), and Nuttli (1981)]

Date	I_o	m_b	Epicenter
1843 Jan. 05	VIII	6.0	Near Memphis, Tenn.
1895 Oct. 31	IX	6.2	Charleston, Mo.
1968 Nov. 9	VII	5.5	South-central Illinois.

The two largest of these earthquakes, (1843 and 1895) were chosen as the basis for the simulated earthquakes developed in this study. They occurred near the south (1843) and north (1895) ends of the New Madrid seismic zone. Since it is assumed that the simulated earthquakes in this study might occur anywhere in the New Madrid seismic zone, the locations of these two shocks are ideal for the simulations. Moreover, the greater availability of intensity data for the 1843 and 1895 earthquakes, compared to the 1811-1812 sequence, makes possible the more detailed isoseismals that are necessary for the simulations. Although smaller than the 1843 and 1895 shocks, the 1968 earthquake located north of the New Madrid seismic zone is also discussed here because of its excellent data set, including assigned intensities at all seven of the cities considered in this report.

The information available for each of the seven cities considered in this study for the 1811-1812, 1843, 1895, and 1968 earthquakes is summarized in table 4. The table shows the distances from the epicenters to each city and the assigned intensities in the cities where that information exists. Since there are no records from any of these cities except Saint Louis in 1811-1812 (most of the cities didn't yet exist, except for Saint Louis and Fort Pickering near Memphis), the isoseismal area (from the Nuttli, 1981, isoseismal map for the first 1811 shock) within which a city lies is noted instead of an intensity value assigned on the basis of actual earthquake effects. Intensities near the seven cities are also noted for some of the 1811 locations. Isoseismal areas, rather than assigned intensities, are also given when necessary for the other earthquakes in table 4.

The three large earthquakes for which there is much available information will now be considered in more detail. They are (1) January 5, 1843, near Memphis, Tennessee (figure 4), (2) October 31, 1895, Charleston, Missouri (figure 5), and (3) November 9, 1968, southern Illinois (figure 6). Their effects on the seven cities studied in this report are discussed below. More detailed information can be found in Appendices 2-8 at the end of this report.

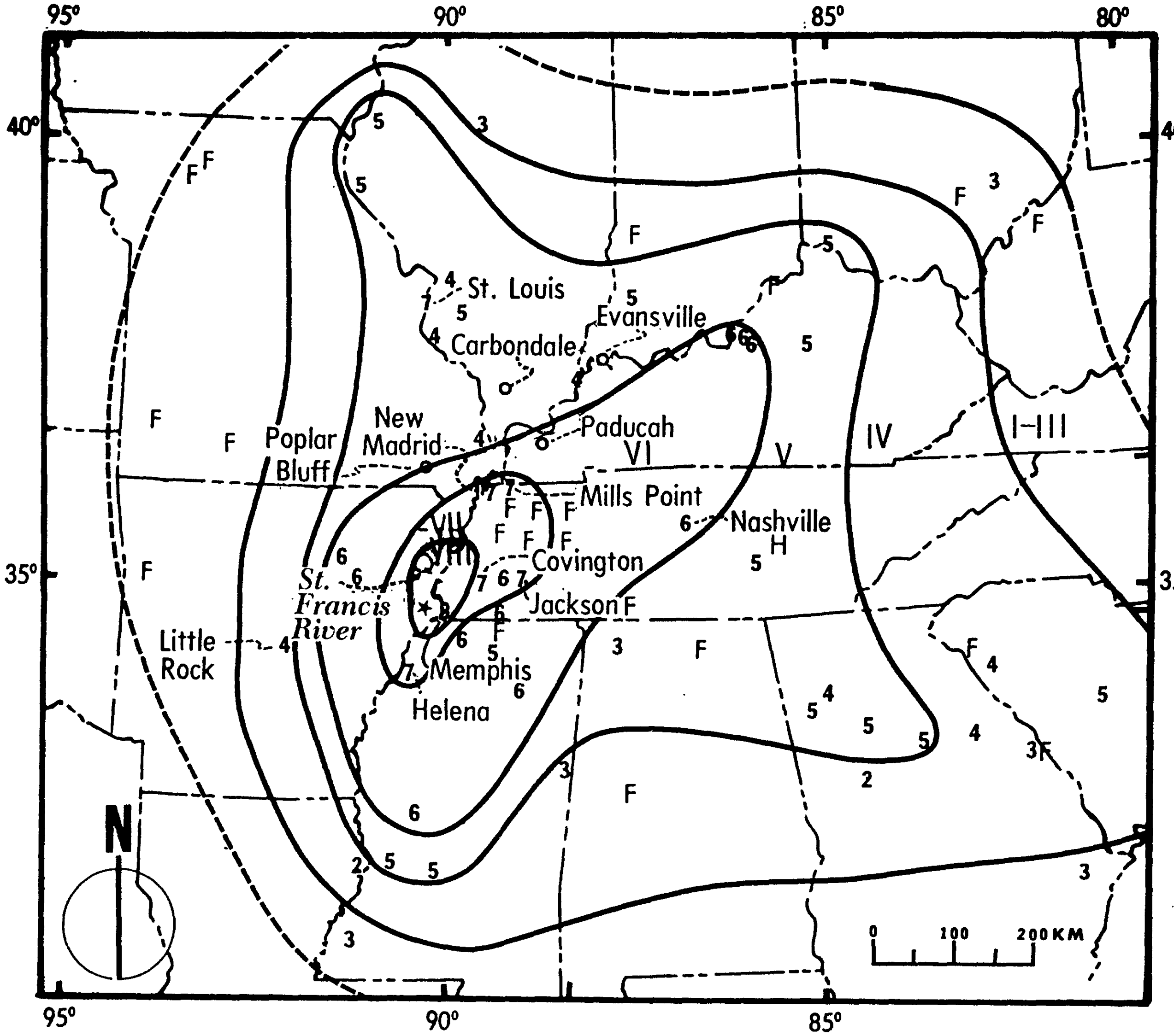


Figure 4.--Isoseismal map of the January 5, 1843, earthquake near Memphis, Tennessee. After Hopper and Algermissen (unpub. data). Arabic numbers represent assigned Modified Mercalli intensities for individual locations; F, H, and Q are used for Felt, Heavy, and Liquefaction, respectively. Star is at the epicenter. Of the seven cities in this study there are assigned intensities for three: IV at Little Rock, VIII at Memphis, and VII at Saint Louis. There are no assigned intensity values for the other four cities, but Carbondale and Evansville lie within the intensity V isoseismal; Paducah and Poplar Bluff, the VI isoseismal.

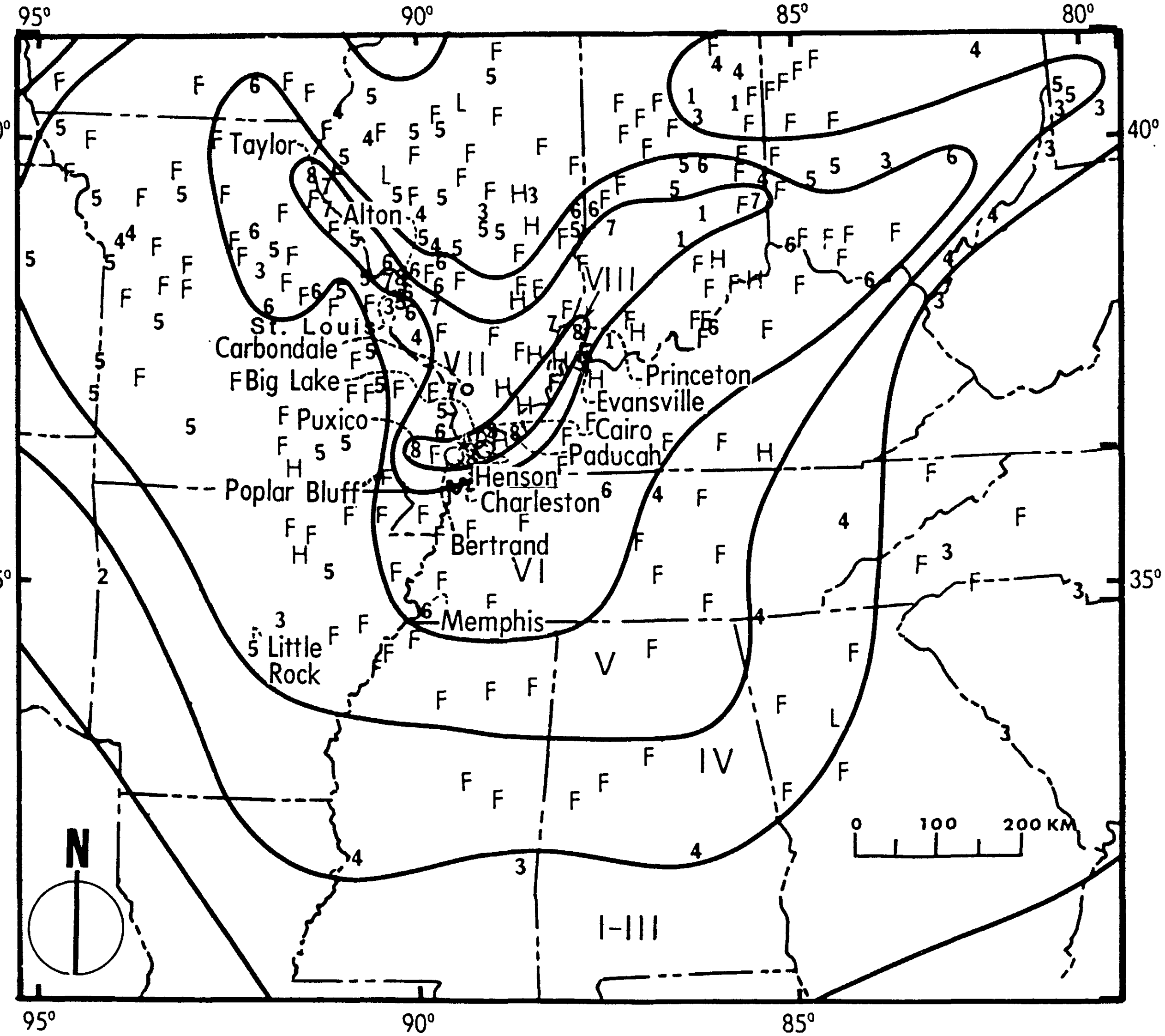


Figure 5.--Isoseismal map of the October 31, 1895, earthquake near Charleston, Missouri. After Hopper and Algermissen (1980). Arabic numbers represent assigned Modified Mercalli intensities for individual locations; F, H, L, and Q are used for Felt, Heavy, Light, and Liquefaction, respectively. Star is at the epicenter. Of the seven cities in this study there are assigned intensities for six: Felt at Evansville, V at Little Rock, VI at Memphis, VIII at Paducah, felt at Poplar Bluff, and VI at Saint Louis. Carbondale has no assigned intensity but lies within the intensity-VII isoseismal.

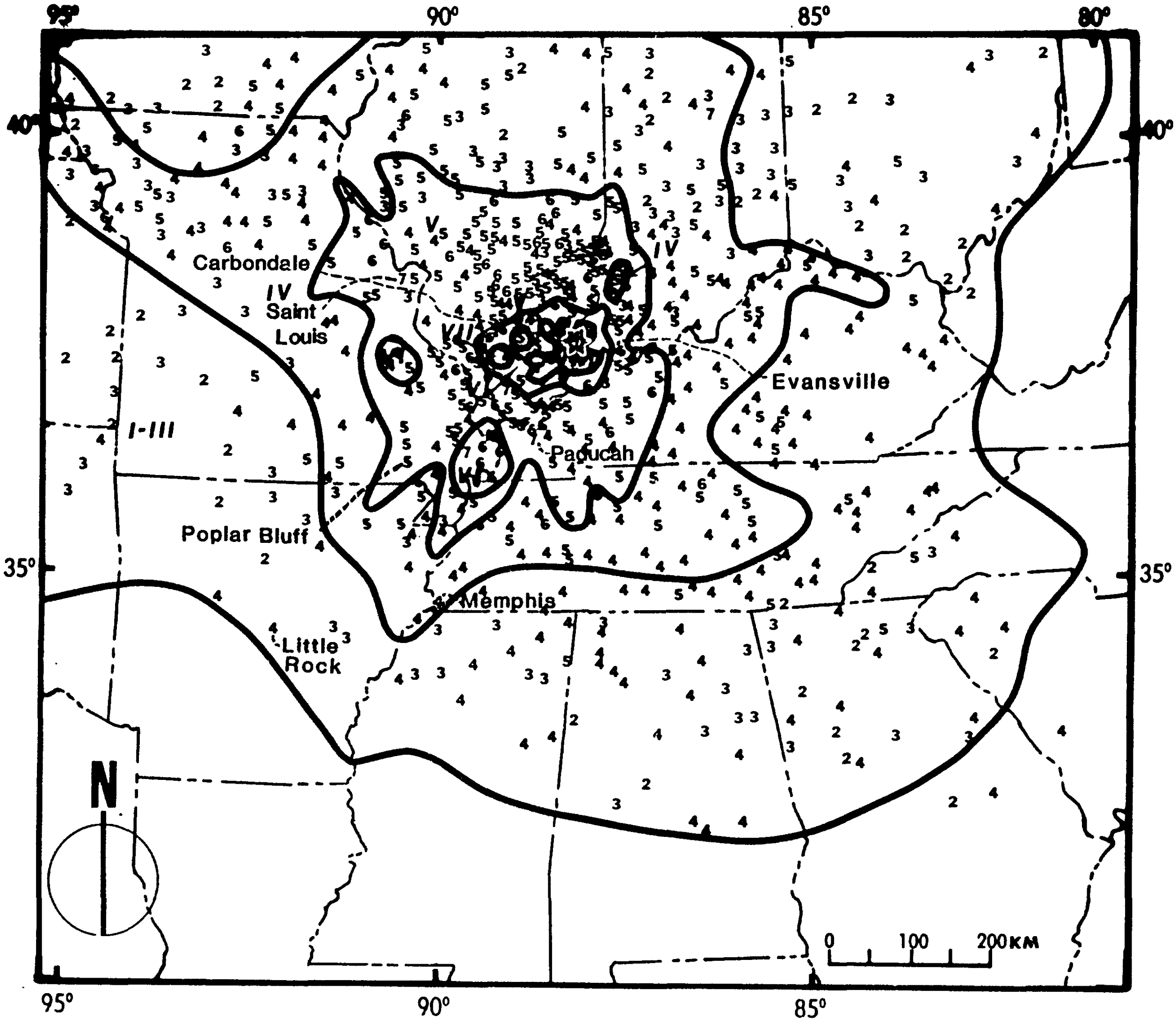


Figure 6.--Isoseismal map of the November 9, 1968, earthquake in south-central Illinois. After Gordon and others (1970). Arabic numbers represent assigned Modified Mercalli intensities for individual locations. Star is at the epicenter. Assigned intensities at the seven cities in this study are: VI at Carbondale, VI at Evansville, I-IV at Little Rock, I-IV at Memphis, VI at Paducah, V at Poplar Bluff, and VII at Saint Louis.

TABLE 4.--Epicenter-city distances and city intensities

[Where there are no assigned city intensities, the isoseismal area in which the city lies is given instead. (See figs. 2 and 4-6.) Intensities at nearby locations are noted where relevant. Latitude and longitude are shown below each city and each earthquake date.]

Date, time, and epicenter	Carbondale, Ill. 37.7° N. 89.2° W.	Evansville, Ind. 38.0° N. 87.6° W.	Little Rock, Ark. 34.7° N. 92.3° W.	Memphis, Tenn. 35.1° N. 90.1° W.	Paducah, Ky. 37.1° N. 88.6° W.	Poplar Bluff, Mo. 36.8° N. 90.4° W.	Saint Louis, Mo. 38.4° N. 90.1° W.
1811 Dec. 16 2:15 a.m. 35.8° N. 90.3° W.	238 km In VIII area.	336 km In VII area.	212 km In VII area? Off map.	80 km IX at Fort Pickering.	205 km In IX area.	104 km In IX area.	317 km VII
1811 Dec. 16* 8:15 a.m. 36.0° N. 90.0° W.	202 km	305 km	247 km	100 km	170 km	90 km	290 km VI-VII
1812 Jan. 23* 36.2° N. 89.8° W.	178 km	280 km	274 km	120 km	145 km	87 km	275 km
1812 Feb. 7* 36.5° N. 89.6° W.	142 km	241 km	311 km	160 km	102 km	82 km	245 km VIII
1843 Jan. 5 35.2° N. 90.5° W.	307 km In V area.	402 km In V area.	170 km IV	32 km VIII	269 km In VI area.	179 km In VI area.	390 km VII
1895 Oct. 31 37.0° N. 89.4° W.	81 km In VII area.	192 km Felt. In VII area.	362 km V	223 km VI	81 km VIII	94 km Felt. In VI area.	198 km VI
1968 Nov. 9 38.0° N. 88.5° W.	69 km VI	81 km VI	498 km I-IV	350 km I-IV	105 km VI	218 km V	162 km VII

*There is insufficient information to contour an isoseismal for this earthquake; the city's isoseismal area is unknown for this shock.

January 5, 1843

The 1843 earthquake (figure 4) is the third largest historical earthquake (or series of earthquakes) in the central Mississippi valley. Only the 1811-1812 and the 1895 earthquakes were larger. Moreover, the 1843 earthquake is the closest of the large Mississippi valley earthquakes to the epicenter of the 1811 earthquake. Slightly more and better distributed intensity data are available for 1843, and therefore its isoseismals show somewhat greater detail than those of the 1811 earthquake.

The maximum intensity for the 1843 shock is VIII M.M. The epicentral area appears to be the area of northeast Arkansas west of Memphis, Tennessee. Nuttli (1974) noted that no reports are available from this area, which was lightly populated in 1843, but the maximum intensity there "probably would have been VIII or slightly greater." He found $m_b = 6.0$ based on intensity attenuation with distance and $m_b = 6.1$ based on the felt area. Total felt area is about 1,500,000 km^2, or about the same as the 1968 southern Illinois earthquake (M. G. Hopper and S. T. Algermissen, unpub. data, 1980). Reports of damage include fallen chimneys and cracked brick walls at Memphis (Heinrich, 1941); damaged chimneys at Covington, Jackson, and Nashville in Tennessee, at Helena in Arkansas, at Mills Point [now Hickman] in Kentucky, and at New Madrid and Saint Louis in Missouri. In the St. Francis River area of northeastern Arkansas a hunter reported that a deep lake had been formed by the earth's sinking on the river. (The Daily National Intelligencer, Washington, D.C., Jan. 30, 1843.)

The following is the available information, taken from M. G. Hopper and S. T. Algermissen (unpub. data, 1980), for the 1843 earthquake for each of the seven cities in this study:

Carbondale, Illinois:

No report is available from Carbondale for the 1843 earthquake, but the city is within the intensity-V isoseismal. No reports exist within a 50-km radius of Carbondale. The closest available intensity data are three IV's at distances of 75, 95, and 120 kilometers from Carbondale, and one V at 115 kilometers.

Evansville, Indiana:

No report is available from Evansville for the 1843 earthquake. The city is within the intensity-V isoseismal but no reports are located within a 50-kilometer radius of Evansville. The nearest report is a IV from a location about 60 km downstream along the Ohio River.

Little Rock, Arkansas:

The Little Rock State Gazette describes "the rattling of windows, glasses, and cupboards, and the creaking of our wooden houses....The shaking of the earth...seemed to indicate a vibratory motion from N.E. to S.W., and continued for about the space of one minute." This report is assigned intensity IV.

Memphis, Tennessee:

Several newspapers give accounts of the earthquake at Memphis. The American Eagle of January 6, 1843, says, "We were in our office..., in the second story of a new block of brick buildings. The commencement of the jarring we conceived to proceed from the violent undertaking of some person to shake open a door beneath us. But in a moment afterwards, the agitation seized the brick walls surrounding us, shaking and reeling them, to such an extent, as to knock down particles of brick and plaster, jarring the roof and whole buildings so as to impress us with the fear of the buildings's falling....We hastily fled into the street for safety....In the street there was still a violent rocking of the earth, and a rattling and rumbling noise. People fled into the streets.

The shock lasted about two minutes, and reached its most agitation period at the end of the first half minute, when it gradually died away in a dismal rumbling sound, apparently moving to the south-east, and proceeded from the north-west.

The tops of several chimneys were shaken down, the bricks falling inside....A great many brick walls are seriously cracked and sunk, windows broken, and a cotton shed, naturally crazy, fell down shortly after the shock."

Memphis is assigned an intensity of VIII. It is the only intensity VIII assigned for the shock. The epicenter is assumed to be about 30 km west of Memphis.

Paducah, Kentucky:

No report is available from Paducah in 1843. The city is within the intensity-VI isoseismal with no reports within a 50-km radius. The closest reports are a IV at 85 km from Paducah and two VII's at 75 and 100 km from Paducah. The two VII's are about 90 km closer to the epicenter than Paducah.

Poplar Bluff, Missouri:

No report is available for Poplar Bluff for 1843. The city is on the line between the intensity-V and VI areas. No other reports are located within a 50-km radius of Poplar Bluff, and the closest report is the intensity-VII at New Madrid, about 80 km away from Poplar Bluff.

Saint Louis, Missouri:

There are several reports of the earthquake's effects at Saint Louis (see Appendix 8 for complete accounts). W. C. Love wrote in a letter, "I have heard of no damage, in town, except to Mauro's chimney and the chimney of the Session-House of Ballard's church."

Saint Louis is assigned intensity VII.

October 31, 1895

The 1895 earthquake (figure 5) is the largest historical earthquake in southeast Missouri, except for the 1811-1812 sequence. It is therefore of particular interest to this study because its effects were much better observed than those of 1811 and 1812. The numbers of people and structures in the area by 1895 provided more numerous and better distributed reports than were available in 1811. This allows much better defined isoseismals, which can be used to estimate the shaking west of the Mississippi River that must have occurred as a result of the 1811 earthquake.

The maximum M.M. intensity is at least VIII, and probably IX; VIII is assigned at seven places by Hopper and Algermissen (1980). Heinrich (1941) notes that at Charleston "every building in the commercial block was damaged...and many walls were cracked." At Cairo "the number of chimneys shaken down in the city probably runs into the hundreds" (Marvin, 1895). Sandblows, or spouts of water and sand, were reported near Bertrand, Big Lake, and Charleston, Missouri, and a new lake was formed south of Henson Lake, Missouri; these places are all within the VIII contour, but this evidence of liquefaction is not used to assign intensities in figure 5. Rather, the liquefaction locations (for example, Bertrand, Missouri) are denoted on figure 5 by "Q", when no other information is available on which to assign a Modified Mercalli intensity. (Note that, similarly, brief, non-definitive reports are denoted on figure 5 by "F" (felt), "H" (heavy), and "L" (light).) Nuttli (1974) assigned a maximum intensity of IX to the Bertrand report and VIII-IX at Charleston. He derived m_b = 6.2 based on the intensity fall-off with distance. The epicenter is placed near Charleston at 37.0°N, 89.4°W by both Nuttli and other researchers. It is marked on figure 5 with a star. The felt area is estimated to be about 2,500,000 km^2 (Hopper and Algermissen, 1980).

The following is the available information, taken from Hopper and Algermissen (1980), for the 1895 earthquake for each of the seven cities in this study:

Carbondale, Illinois:

No report is available from Carbondale in 1895. The city is within the intensity-VII isoseismal, and there are intensity-VII reports from two other locations within a 50-km radius of Carbondale.

Evansville, Indiana:

Marvin (1895) reports the 1895 earthquake felt at Evansville. The city is within the intensity-VII isoseismal, and there are assigned intensities of VIII and VII, plus two others simply denoted as "heavy", within a 50-km radius of Evansville.

Little Rock, Arkansas:

At Little Rock, Marvin (1895) says, "Distinct earthquake, the vibrations being east and west and lasting about one minute." Little Rock is assigned intensity V and is within the intensity-V isoseismal.

Memphis, Tennessee:

Marvin (1895) notes that in Memphis "there was no damage done...except to two chimneys in the suburbs, which were shaken down." Memphis is assigned an intensity of VI for 1895 and is inside the intensity-VI isoseismal. The closest other reports are all "felt's."

Paducah, Kentucky:

Paducah is assigned an intensity of VIII (Hopper and Algermissen, 1980) and is within the VIII isoseismal. The Saint Louis Post-Dispatch says, "Houses swayed to and fro, a number of chimneys fell and several walls were cracked." Within 50 km of Paducah are another VIII and two "heavy" locations.

Poplar Bluff, Missouri:

Of Poplar Bluff Heinrich (1941) said, "The movement was described as rocking and seemed to be east-west. A noise 'like a cyclone' preceded the shock." Poplar Bluff is inside the intensity-VI isoseismal and within 50 km of locations assigned VIII, V, and "felt." Poplar Bluff is assigned "felt" rather than a specific intensity.

Saint Louis, Missouri:

There are several reports of the effects of the 1895 earthquake at Saint Louis (see Appendix 8 for the complete accounts). The Saint Louis Post Dispatch of October 31, 1895, says: "...Houses Rocked, Windows Rattled and Brick Chimneys Tumbled to the Ground...The damage to property consisted of the destruction of a few chimneys and the demolition of a few tottering walls. The German Lutheran Church... got about the worst treatment. It will probably have to be torn down, as the walls are badly cracked....A chimney at its northeast corner was thrown down, and the cornice work... was crumbled and cracked in a number of places. The massive front section... seems to be wholly detached at the top from the body of the building...[which was] put up in 1834...."

Saint Louis was assigned intensity VI by Hopper and Algermissen (1980).

November 9, 1968

The November 9, 1968 earthquake (figure 6) is the largest earthquake to occur in the central United States since 1895. Stauder and Nuttli (1970) located it at 37.95°N, and 88.48°W with a depth of 25 km. They found a body-wave magnitude of $m_b = 5.54 \pm 0.44$ using stations at teleseismic distance (beyond 25°) or $m_b = 5.44 \pm 0.29$ using Evernden's (1967) formula. Stauder and Nuttli (1970) suggested that the earthquake is probably closely related to the Wabash Valley fault system in southern Illinois. Gordon (1983) relocated the epicenter of this shock at 37.911°N, 88.373°W, in the Eldorado subzone of the Wabash seismic source zone. Gordon and others (1970) found that the strongest shaking, VII M.M., took place in the Wabash and Ohio River Valleys and adjacent lowlands of south-central Illinois. They observed that damage consisted primarily of bricks thrown from chimneys, broken windows, toppled TV antennas, and cracked plaster. In the epicentral area they found cracks in foundations, chimneys thrown down, and scattered instances of collapsed parapets and overturned tombstones. Their survey showed 15 percent of the chimneys within 25 miles (40 km) of the epicenter had sustained damage. The felt area included 580,000 mi^2 (1,500,000 km^2) of the central United States including all or portions of 23 states.

The following are the reports from the seven cities included in this study:

Carbondale, Illinois:

In United States Earthquakes, 1968 (Coffman and Cloud, 1970) intensity VI is assigned at Carbondale, where there were reports of a crack in the putty on a window, a cracked sidewalk, and overturned oil tanks. Carbondale is within the intensity-VI isoseismal.

Evansville, Indiana:

In United States Earthquakes, 1968 (Coffman and Cloud, 1970) intensity VI is assigned at Evansville, where there were reports that plaster fell throughout the city, a chimney on an old house fell, and bricks were loosened on an old church so that the wall threatened to collapse. Evansville is within the VI isoseismal.

Little Rock, Arkansas:

In United States Earthquakes, 1968 (Coffman and Cloud, 1970) intensity I-IV is assigned at Little Rock. Little Rock is in their I-III area.

Memphis, Tennessee:

In United States Earthquakes, 1968 (Coffman and Cloud, 1970) intensity I-IV is assigned at Memphis. Memphis is within their IV isoseismal.

Paducah, Kentucky:

In United States Earthquakes, 1968 (Coffman and Cloud, 1970) intensity VI is assigned at Paducah, where a few bricks fell from chimneys. Paducah is within the VI isoseismal.

Poplar Bluff, Missouri:

In United States Earthquakes, 1968 (Coffman and Cloud, 1970) intensity V is assigned at Poplar Bluff. Poplar Bluff is within the intensity-V area. There is a VI nearby on the east and V's to the north.

Saint Louis, Missouri:

Coffman and Cloud (1970) report: "Several injured by falling debris. Walls cracked, chimneys fell, and windows broke. A... section of... wall at Mid-American Metal Company collapsed. Civil War Museum at Jefferson Barracks closed due to a large crack opening in museum wall, causing bricks and plaster to fall."

Intensity VII is assigned by Coffman and Cloud (1970).

SEISMICITY OF THE NEW MADRID SEISMIC ZONE

Large earthquakes of the New Madrid seismic zone are shown in figure 7. It includes the four principal 1811-1812 earthquakes, the 1843 and 1895 earthquakes with maximum intensities (Io) of VIII and IX respectively, and all other shocks with Io $\geq$ VI-VII. Intensities $\leq$VI are indicated by small dots.

There are numerous smaller earthquakes in the study region in addition to the four large earthquakes of 1811-1812 discussed above. The New Madrid seismic zone (figure 8) is the most active seismic area in the central and eastern United States (Zoback and others, 1980). The zone has recently been well defined as a result of the data gathered by a regional seismic network, which was established in 1974 (Stauder, 1982) and through seismic reflection profiling (Zoback and others, 1980). Seismic reflection profiling is a method for determining the locations and attitude of strata beneath the surface by recording artifically induced vibrations.

Epicenters determined using the recordings obtained by the seismic network from 1974 to 1981 are shown in figure 8. They are plotted from a computer tape of epicenter locations made available by Robert B. Herrmann of Saint Louis University. These instrumentally recorded microearthquakes, for the most part not felt, give sharp definition to the location of the New Madrid seismic zone. Precise definition of the zone prior to the installation of the seismographic network in 1974 was impossible because of the scatter in the historical epicenters (figure 7), which are for the most part located by intensity data, rather than by instrumental data.

Note that, while the recent seismicity defines the zone, it does so only for the interval 1974-1981. Activity may have occurred elsewhere in the zone prior to 1974. The epicenters of the 1843 and 1895 shocks, although poorly located themselves, appear to be somewhat south and north, respectively, of the clustered epicenters shown in figure 8.

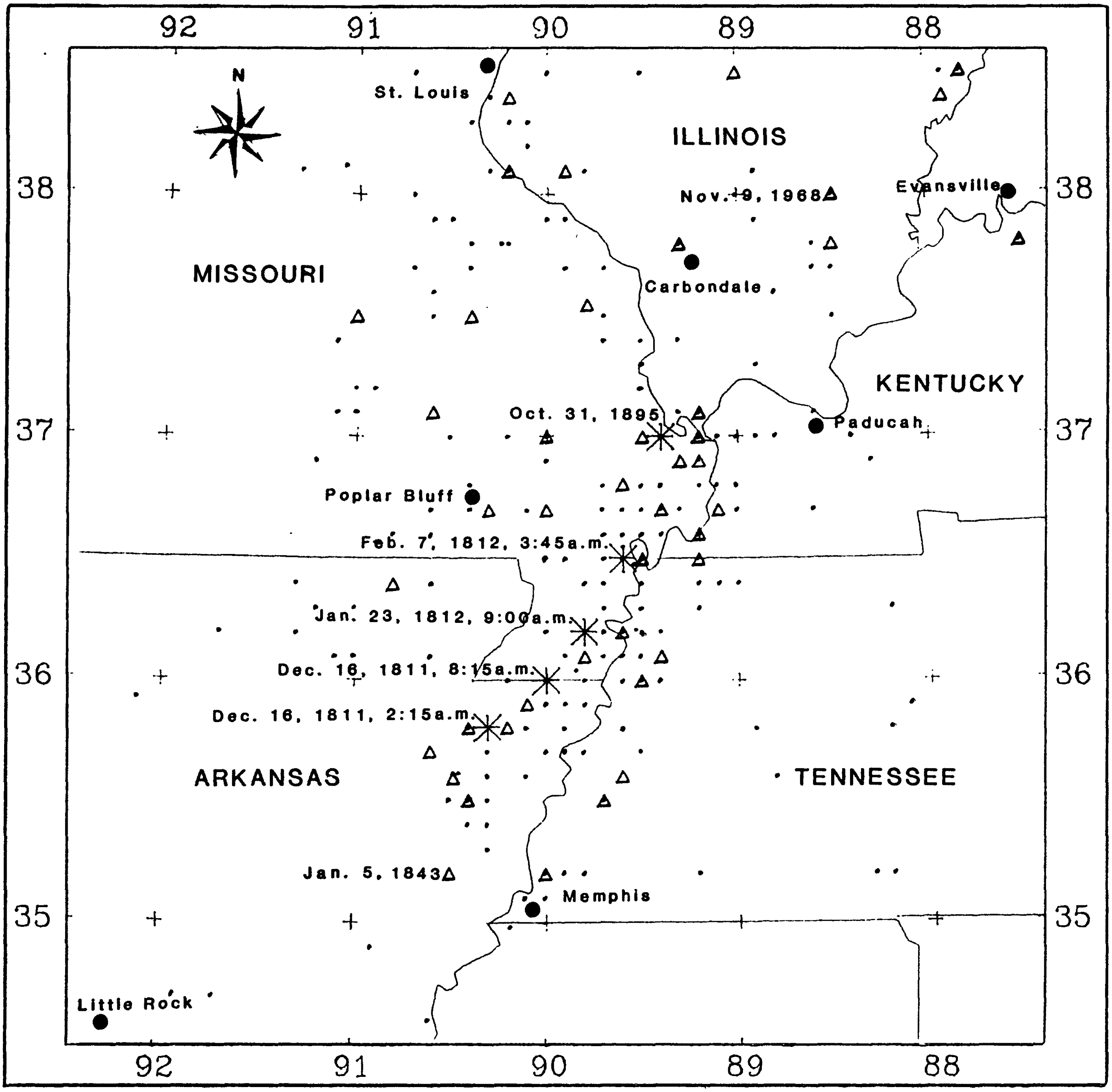


Figure 7.--Historical seismicity of the New Madrid seismic zone and surrounding areas, 1800-1982. Plotted from Algermissen and Askew, unpublished listings. Epicenters for intensities IX and above are indicated by astericks; VI-VII, VII, and VIII by triangles; and VI and below by small dots. Epicenters for the first, third, and fourth 1811-1812 shocks are from David P. Russ (oral communication, 1982). Epicenter for the second 1811 shock is from Street (1982).

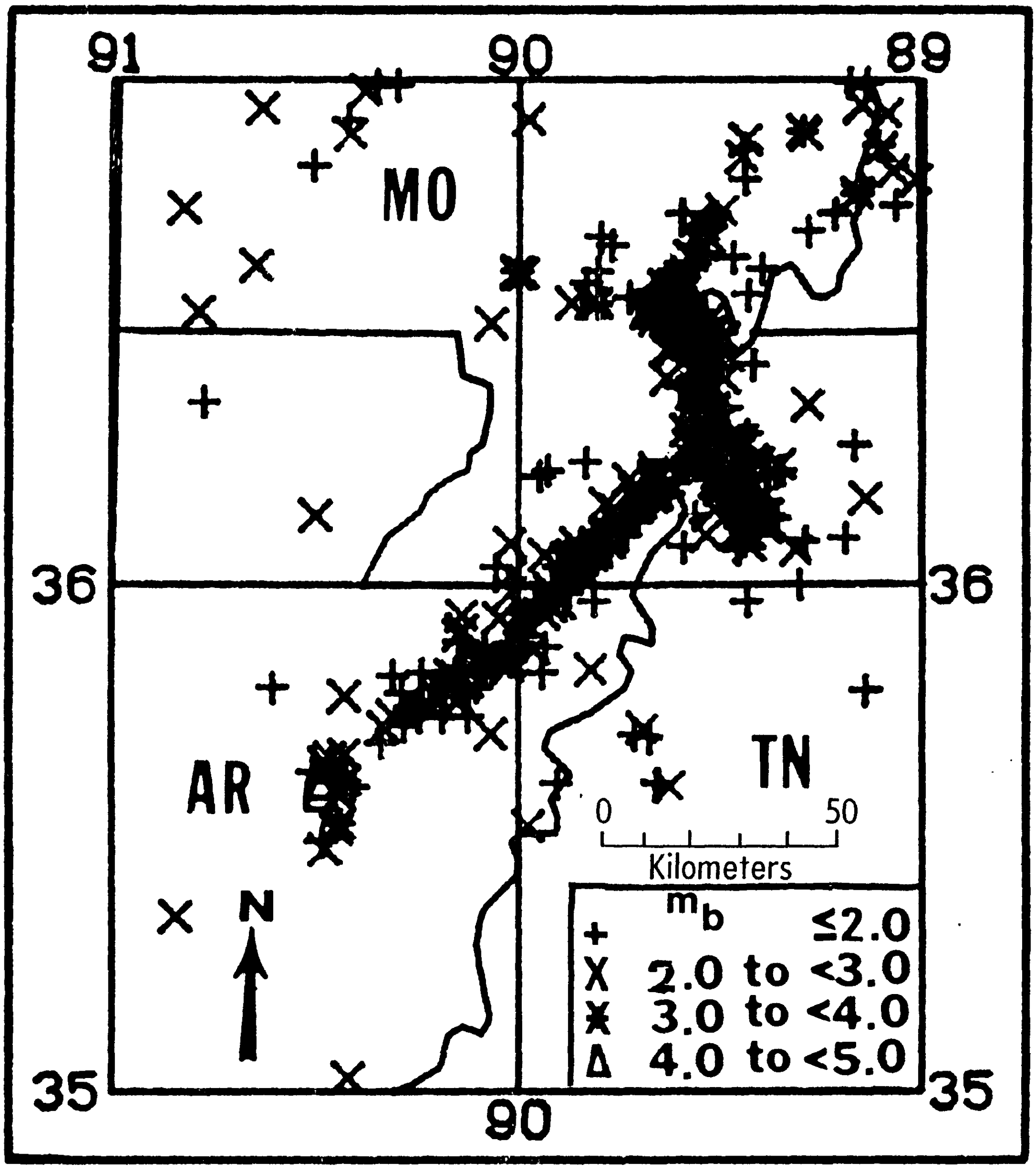


Figure 8.--Microseismicity of the New Madrid seismic zone, 1974-1981. Plotted from data obtained from Robert B. Herrmann of Saint Louis University.

PROBABILITY OF LARGE EARTHQUAKES IN THE MISSISSIPPI VALLEY

By S. T. Algermissen

EARTHQUAKE OF MAXIMUM MAGNITUDE

Nuttli (1981) has assigned the largest shock of the 1811-1812 a M_s (surface wave magnitude) of 8.7, equivalent to an m_b (body wave magnitude) of 7.3. These magnitudes are at the upper limits of both magnitude scales, which means, from a practical point of view, that the M_s and m_b magnitude scales saturate at these levels. Saturation of the scales means that the amplitudes of P-waves and surface waves with periods of one second and 20 seconds respectively reach limiting amplitudes for body wave magnitudes of about 7.5 and surface wave magnitudes of about 8.7. The m_b magnitude is derived from the amplitude of P-waves at about one second period. The M_s magnitude is derived from the amplitude of surface waves with periods of 20 seconds. Larger earthquakes (earthquakes releasing more energy than earthquakes with m_b ~7.3 and M_s ~8.7) are known to have occurred (for example, in Alaska in 1964) and their magnitude can be scaled by use of the moment magnitude M_w (Kanamori, 1977). Earthquakes with large moment magnitudes for which both the M_s and m_b scales are saturated are not likely to produce significantly larger amplitude ground motions than $M_s = 8.7$ ($m_b = 7.3$) earthquakes out to distances of the order of 100 km. At greater distances, earthquakes with large moment magnitudes may produce significantly larger amplitude ground motion at longer periods. Earthquakes will shake increasingly larger areas (as M_w increases) at damaging levels.

The entire length of the New Madrid zone is only about 240 km which suggests that the stress drop in the 1811-1812 earthquakes may have been higher than for earthquakes along plate boundaries such as occur in California.

A number of investigations have developed magnitude-fault rupture length relationships using various data sets (for a summary see Slemmons, 1977). Based upon a length of about 240 km for the New Madrid Zone, most of these relationships would predict smaller maximum magnitudes than are known to have occurred in the zone although the dispersion of the data sets is very large.

Because of the uncertainty in the stress drop associated with earthquakes in the Midwest and the large dispersion of the magnitude-fault length data sets, fault length does not offer a very high resolution method of estimating maximum magnitude events in the Midwest.

Because of the large magnitudes of the four principal shocks of the 1811-1812 sequence and since these are the largest shocks known to have occurred in historical times in North America (exclusive of Alaska), it is at least reasonable to assume that repetition of the 1811-1812 series in the Mississippi Valley represents an adequately conservative model for disaster planning and response. This assumption is made in the present study.

RECURRENCE OF LARGE SHOCKS

The average recurrence rates of large earthquakes can be estimated reasonably well from the historical record of earthquake occurrence provided that the area is not too small, that is, the area is sufficiently large that a number of large shocks have been known to have occurred historically. The seismicity of the midwestern United States is relatively low and the 1811-1812 series of large shocks is unique although some archeological evidence and certain native American legends suggest earlier large earthquake occurrence. A number of estimates have been made of the average recurrence rate for large earthquakes in the Mississippi Valley. Since significant seismogenic faults (and consequently fault slips) have not been positively identified in the Mississippi Valley, estimates of the recurrence times of large shocks have been based on the historical earthquake data. Table 5 summarizes some of the estimates. The important conclusion from table 5 is that there is general agreement among a wide range of investigations on the average recurrence interval for large shocks when the recurrence rate is estimated from the historical seismicity. In the absence of geologic (fault slip) or other confirmatory data, it is not easy to estimate the reliability of the estimates of the recurrence rates of large shocks based on the historical data.

TABLE 5.--Estimates of average recurrence times for large earthquakes in the Mississippi Valley

[Leaders (------) indicate no data]

Source	Magnitude or maximum MM intensity	Estimated recurrence (years)	Method used
Nuttli (1974)-----	7.0-7.4 (m_b) 7.0-7.4 (m_b)	510 710	Maximum likelihood; weighted least squares.
Algermissen (1973).	XI (m_b ~7.2)	500	Least squares (1811-12 events included).
McClain and Myers (1970).	X	175	------
Mann and Howe (1973).	7.7 (M_S) X	600-700	------
Algermissen (1972).	XI (m_b ~7.2)	500-600	Extreme value analysis.

NATURE OF LIQUEFACTION AND LANDSLIDES IN THE NEW MADRID EARTHQUAKE REGION

by Stephen F. Obermeier

This section is intended to be understandable to land-use planners and nontechnical administrators. In addition, it is sufficiently technical to provide guidance for assessing the possibility of liquefaction and some types of landslide problems that would be caused by recurrence of 1811-12 magnitude earthquakes or of any large earthquakes in the region.

The fundamental causes of liquefaction and their consequences are considered. Liquefaction-related problems are then discussed for different earthquake intensity regions. In regions having Modified Mercalli intensities (M.M.) of X and higher, liquefaction will be widespread and cause numerous disasters if there is recurrence of an 1811-12 strength earthquake. Liquefaction will also be commonplace in lowlands near streams in regions with intensities of IX.

Landslides will take place in uplands, particularly on loess-covered slopes near major rivers. Some will be very large. Typical landslide sizes and their geologic-topographic settings are discusssed. Landslides will also be common along small and large streambanks, and can lead to collapse or damage of many bridges.

LIQUEFACTION, LIQUEFACTION POTENTIAL, AND LIQUEFACTION-INDUCED PROBLEMS

Earthquake-induced liquefaction is reasonably well understood from an engineering perspective. The conditions required for liquefaction are briefly reviewed in the area affected by New Madrid earthquakes.

The consequences of liquefaction can include flow landslides, lateral spreading landslides (lateral spreads), quick condition (bearing capacity or tilting) failures, and differential settling of the ground. Possible remedial solutions for some of these are noted.

A method is outlined for evaluating the liquefaction potential in the New Madrid region for different Modified Mercalli intensity values. This method is later used to make maps of the regional potential for the states, at a map scale of 1:1,000,000.

Conditions for Liquefaction

Liquefaction is defined as "the transformation of a granular material from a solid state into a liquefied state as a consequence of increased pore-water pressures" (Youd, 1973). In the liquefied state, the material basically behaves as a fluid mass. The increased pore pressure is understood as being caused either directly or indirectly by earthquake shaking.

Pore-water pressure buildup in saturated cohesionless soils is caused by the application of cyclic shear stresses induced by ground motions (Seed, 1979). These stresses are generally considered to be due primarily to the upward propagation of shear waves. A soil element on level ground undergoes loading conditions as depicted in figure 9, the stress applications being somewhat random but nonetheless cyclic. Because of the shearing, cohesionless soils that are sufficiently loose tend to become more compact (that is, occupy less volume). This causes an increase in the pore-water pressure and a decrease in intergranular stress. With continued application of cyclic shear stresses, the pore pressure of loose sands can approach a value equal to the total overburden pressure, even though the shear strains are still small. Further cyclic shearing can cause the pore pressure to increase suddenly to the confining pressure, causing large shear straining (even flowing).

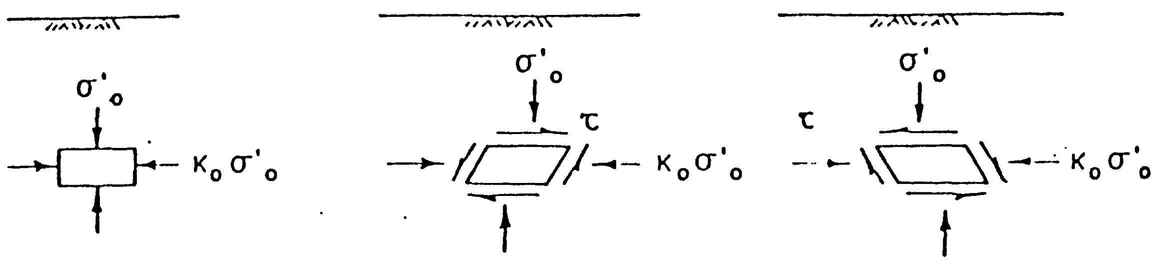
Denser cohesionless materials, while not nearly as susceptible to large shear straining, may still develop a residual pore pressure equal to the confining pressure and produce liquefaction after earthquake shaking. After the cyclic stress applications stop, there is still an upward flow of water. It is likely that the upward flow of water to the ground surface from an underlying layer having a high pore water pressure is the major causative factor in carrying sand to the ground surface and causing "sand blows" (Housner, 1958; Seed, 1979).

Liquefaction during earthquake shaking commonly originates in a zone from 6 to 15 feet (2 to 5 m) below the ground surface, but can originate at a depth greater than 65 feet (20 m) (Seed, 1979). Generally the water table must also be near (say, within 10 to 15 feet) (3 to 5 m) the ground surface for there to be very serious problems. Figure 10 illustrates that the zone of liquefaction depends on the relationship between the cyclic shear stresses generated by the earthquake and the resistance to liquefaction of the soil.

Seismological factors of prime importance that control liquefaction during shaking include the intensity of the cyclic shear stresses and the number of applications of the shear stresses (Seed, 1979). In the field this translates to shaking intensity (that is, peak acceleration) and duration. Analytical engineering methods for handling variable cyclic shear stress applications and irregular cyclic stress applications typical of real earthquakes are presently well developed and yield quite acceptable results, providing the stress histories are known or can be predicted with reasonable accuracy.

In regions significantly shaken by New Madrid earthquakes, the most common materials prone to liquefaction have textures entirely or dominantly of sand. Loose clean sands are the most common and widespread susceptible materials, although gravelly sands and silty very fine sands can also liquefy. There are numerous (hundreds of) river and creek depositional terraces in the region affected by New Madrid earthquakes.

Clean silts with only very small amounts of clay and low cohesion are also susceptible to liquefaction, although probably not nearly to the extent of clean sands. Clean silts are commonplace on many upland areas near major streams which carried meltwaters from Wisconsinan-age (in the age range of about 100,000 until 10,000 years ago) glaciers. The meltwaters carried large volumes of silt-sized material which was later deposited on flood plains during warm seasons; then, during cool seasons when melting was diminished and flood plains were dry, wind picked up the silts and redeposited them on adjacent areas. These wind-deposited silts are known as loess. Thick loess



Initial stresses　　　　Cyclic load sequence

τ - earthquake-induced horizontal shear stress

σ'_o - initial vertical effective overburden stress

K_o - ratio of initial lateral/vertical effective stress

Figure 9.--Idealized field loading conditions.

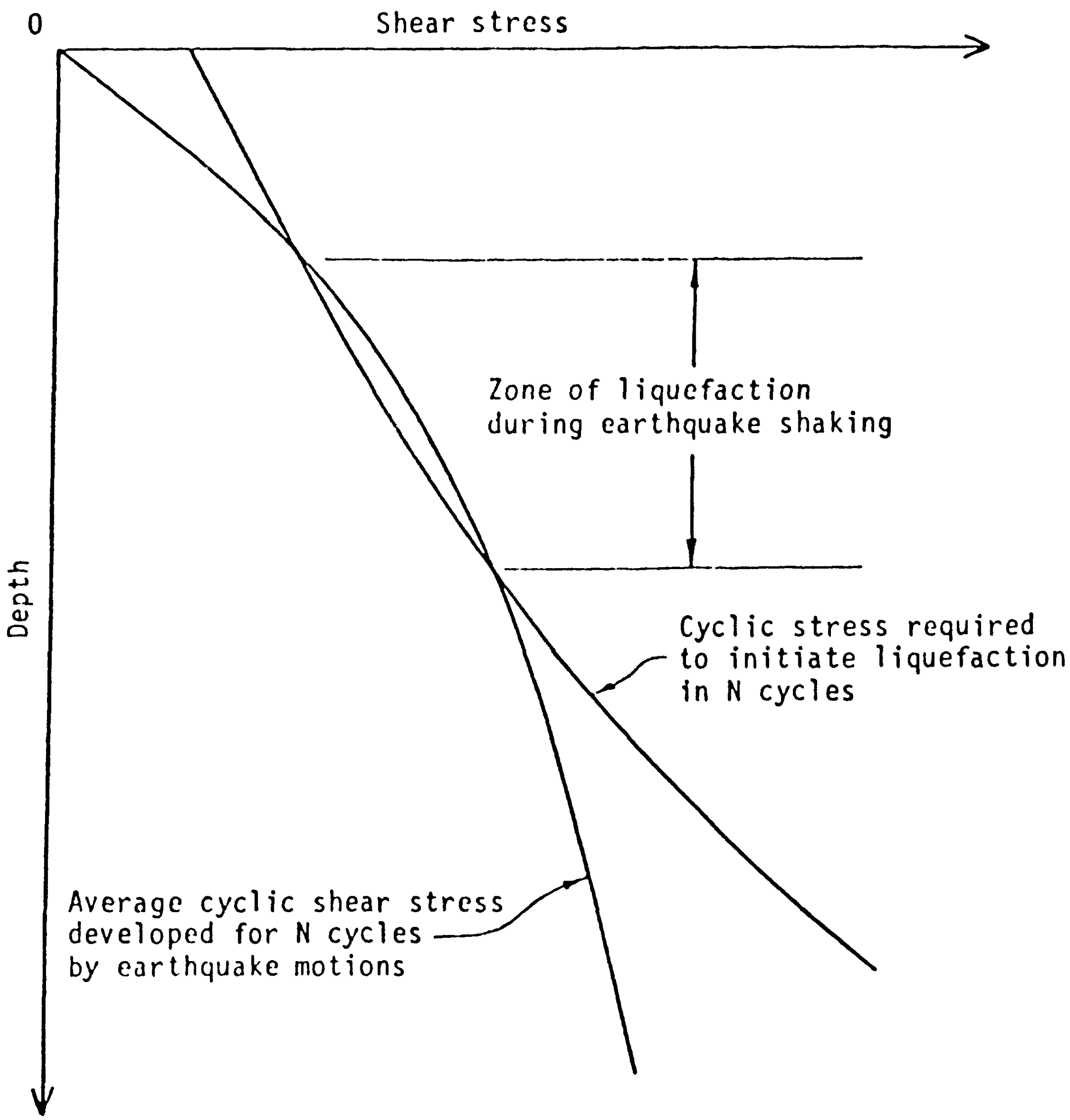


Figure 10.--Schematic depiction of the location of the zone of liquefaction during earthquake shaking.

is commonplace along the Mississippi River throughout the region having Modified Mercalli intensities of IX or higher on figure 14. In some places the loess is water-saturated and subject to liquefaction.

Some of the silts in the glacial meltwaters were carried into large bodies of quiet water, which were lakes in effect, and the silts were laid down in the lake bottoms. There are vast, thick glacial lake deposits north of Cairo, Illinois. Many of these old lakes presently have high ground-water tables, and the silts are so clean and soft as to be susceptible to liquefaction. Beneath the silts in these old lake beds, there are very loose sands at many places.

Some clay-bearing soils may also liquefy in the event of a New Madrid-type earthquake. The clayey soils that are prone (Seed and others, 1983) appear to be those with less than 15 percent finer than 0.005 mm, water content nearly equal to or greater than the liquid limit, [1/] and a liquid limit less than 35. Almost without exception, the only soils with these properties are in present-day flood plains where there are also very loose sands, or else in very wet swampy areas.

Consequences of Liquefaction

Liquefaction leads to three basic types of ground failure (Seed, 1968) - flow landslides, landslides with limited movement (lateral spreads), and quick-condition failures. In addition, ejection of soil (as by sand blows), and differential loosening and densifying of soil causes differential settling of the ground. These consequences of liquefaction are discussed for the different types of failures in sands, and then in silts and clays. Much of the information is taken from Youd (1973).

Damage from liquefaction-induced ground failure is commonly a major portion of total earthquake damage for moderate to large earthqakes. In the Alaskan earthquake of 1964, ground failure caused more than half the economic losses.

Flow landslides:

Liquefaction in loose sands can lead to almost unlimited flow, providing the surface slope exceeds about three degrees. If the mobilized soil is unrestrained, large soil masses can move long distances as viscous fluids or blocks of intact materials riding on liquefied flows. Examples of the type of earth structure and landslide dimensions are from dike failures in Holland (Koppejan and others, 1948). Dike slopes before failure were about 35 degrees, with banks as high as 130 feet (40 m). After failure many slopes were 4 degrees or less, which led to disastrous breaches in the dikes. In the San Francisco earthquake of 1906, there were numerous flows; one moved several hundred yards (Crandall, 1908). There are many places along the Mississippi

[1/] The liquid limit is the water content at which a remolded sample has a soft consistency; the liquid limit is the state at which the sample is on the semisolid-liquid boundary. Liquid limit is measured in a standardized test described in any elementary soil mechanics text. Water content is the ratio, (weight of water)/(weight of dry soil), in percent.

River where the levees could fail in a similar manner, letting flood waters flow into the lowlands behind the levees.

On silts and especially clays, large and tremendously damaging lateral flows are probably not as likely to develop as in sands, though laboratory test data and field performance data are so sparse that it is not possible to make definitive statements.

Lateral-spreading landslides:

Where conditions are favorable for liquefaction but the sands are too dense to flow freely, or the surface slope is between about 0.5 and 3 degrees limited flow can take place. Even where sands are loose on slopes as low as 1 degree or less, horizontal displacements are commonly a few feet to as much as 6 feet (0.7 to 2 m), and these displacements can leave large open cracks at the surface. Lateral spreads are often commonplace during moderate and strong earthquakes. In the 1811-12 earthquakes, this type of landslide was extremely common (probably many thousands) and widespread in the entire region between the Mississippi River and Crowley's Ridge, from Cairo, Illinois, to near Memphis, Tennessee. Many of these have lengths of 500 to 1000 feet (150 to 300 m), and are even wider. The earthquakes probably caused many large lateral spreads in the lowlands west of Crowley's Ridge.

During the 1964 Alaska earthquake, about 250 bridges were damaged to an extent requiring substantial repair or replacement. Almost all the bridge damage was caused by compression of the structures as a result of lateral spreading toward river channels of liquefied flood-plain deposits.

On silts and clays lateral spreading would probably not be nearly as severe as in sands during an 1811-12 magnitude earthquake, but spreading could still cause some major structural damage to buildings and bridges.

Quick-condition failures:

Seepage forces caused by upward percolating pore water commonly drastically reduce the strength of granular materials, for minutes to days after earthquake shaking. If the strength is reduced to the point of instability, this state is known as a "quick condition" (this is the same as "quicksand" to the general public). This condition is generally found only in thick sand deposits that extend from below the water table to the ground surface.

Loss of bearing capacity is a common type of quick condition failure and is common on ground surface slopes between about 0 and 0.5 degrees. Buoyant rise of buried tanks, empty swimming pools and water treatment tanks is another common result. Landslides can also take place from this effect. In the 1964 Niigata earthquake in Japan, high-rise apartment buildings had quick condition, bearing capacity failures and rotated so much that people could walk on the previously vertical exterior (see figure 11); embankments also subsided into the weakened sands.

Differential settlements:

Wherever seepage forces carry sand and water to the surface, buildings can be undermined. This in turn can cause differential settling of buildings, and perhaps lead to bearing capacity failures. Though probably not often totally destructive of buildings, it can distort and damage structures. Differential settlement of the ground and sand blow craterlets were unquestionably very common in the 1811-12 earthquakes within the area of intensity XI of figure 14. Figure 12 shows a sand blow craterlet caused by liquefaction in the Charleston, South Carolina, earthquake of 1886. Clearly removal of this much material from beneath a building can cause severe damage.

Engineering Evaluation of Liquefaction Potential

Regional evaluation of the liquefaction potential of clean sands is commonly done in the field, by testing the soil in-place with the Standard Penetration Test (SPT) blow count method. A sampling tube is driven into the ground by dropping a 140-lb (63.5 kg) weight from a height of 30 inches (176.2 cm). The penetration resistance is reported in number of blows of the weight required to drive the sampler 1 foot (30.5 cm). The SPT blow counts (N values) are then used in conjunction with anticipated earthquake-induced shear stresses (a function of accelerations) to determine if liquefaction may take place. Figure 13 shows boundary curves (by Seed and others, 1983) which define where liquefaction is likely or unlikely to occur for earthquakes with different magnitudes. The figure applies to clean sands with almost no silt, on level ground. (Figure 13 can be modified for use with silty sands by simply adding 7.5 to the N_1 value before entering the chart). For a given magnitude, data points below the curve will almost certainly not liquefy, and data points above the curve have a high probability of liquefying sufficiently to cause sand blows (and landslides and other liquefaction-related problems). The curves were developed from studies of earthquake-induced liquefaction at many sites around the world.

The field cyclic stress ratio of figure 13 is the ratio of the average cyclic shear stress ($\tau_{h\ avg}$) developed on horizontal surfaces of the sand as a result of the cyclic earthquake loading to the vertical effective stress (σ_o^1) on the sand layer before the cyclic stresses were applied.

The cyclic stress ratio developed in the field due to earthquake shaking is computed from equation (1):

$$(1) \qquad \frac{\tau_{h\ avg}}{\sigma_o^1} = 0.65 \left(\frac{A_{max}}{g} \cdot \frac{\sigma_o}{\sigma_o^1} \cdot r_d\right)$$

where A_{max} = peak horizontal acceleration at the ground surface; σ_o = total overburden pressure (weight) on the sand under consideration; σ_o^1 = initial effective overburden pressure (total weight minus water pressure) on the sand

Figure 11.--Niigata earthquake phenomena. A, Tilting and sinking of buildings caused by reduction of foundation support due to liquefaction of near-surface sand deposits during the 1964 Niigata, Japan, earthquake (from Kawasumi, 1968, pl. 7). B, Residents salvaging furniture and personal possessions by carrying them down the exterior walls of apartment building tilted by liquefaction (from Kawasumi, 1968, pl. 7).

Figure 12.--Sand blow craterlet caused by liquefaction in the Charleston, South Carolina, earthquake of 1886.

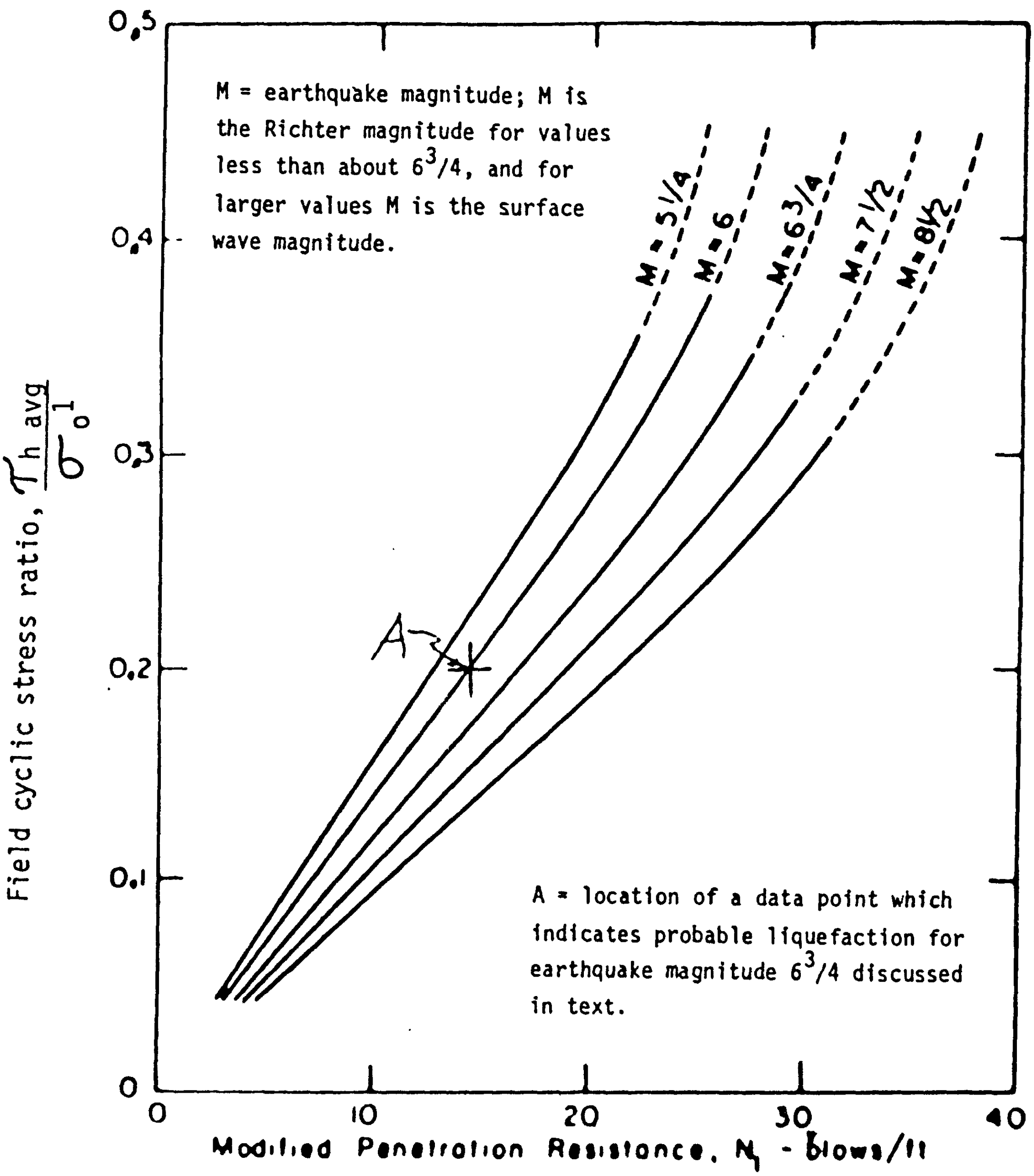


Figure 13.--Chart for evaluation of liquefaction potential for different magnitude earthquakes (from Seed, Idriss, and Arango, 1983).

layer under consideration; r_d = stress reduction factor ranging from a value of 1 at the ground surface to a value of 0.9 at a depth of about 30 ft (9.6 m); and g = the acceleration of gravity.

For one of the most common field conditions on the terraces and flood plains in the New Madrid earthquake region, where the water table is about 6 feet (2 m) below the ground surface, and the weakest sands are at a depth of 12 to 16 feet (4 to 5 m), the field cyclic stress ratio is almost exactly equal to the peak horizontal acceleration; that is, if the peak horizontal acceleration is 0.20 g, the cyclic stress ratio is essentially 0.20.

On figure 13, the modified penetration resistance, N_1, is the SPT blow count value measured in the field multiplied by a correction factor that accounts for the influence of field stress conditions on the measured blow count; for the field conditions discussed in the paragraph above, the multiplication factor is 1.4.

To illustrate use of the curves, let it be assumed that the peak horizontal acceleration at the ground surface is 0.20 g for an earthquake magnitude (M) of $6^3/_4$, and the SPT blow count in clean sand is 10 on a nearly level terrace for the depth and water table conditions discussed previously. These conditions are given by point A on figure 13; liquefaction would be very probable.

As noted previously, figure 13 is strictly applicable only for level or nearly level ground. On steeper slopes, higher accelerations are required to cause liquefaction, and more sophisticated methods are used to determine if liquefaction may develop. Still, use of figure 13 helps assess if there is the possibility of problems on the slopes.

The procedure sketched above, known as the "simplified procedure" of Seed and Idriss (1971) indicates only where liquefaction is likely. Disastrous ground failure may or may not result from an occurrence of liquefaction. In general, liquefied loose sands are much more likely to flow, move large distances, or cause disasters than medium dense sands, even though both sands may liquefy; more rigorous methods are necessary for evaluating the complete scenario.

For clean silts and clay-bearing soils, there are no charts analogous to figure 13. Laboratory test methods must be used at the present time to appraise their behavior in any detail. However, it is certain that serious liquefaction can take place in these materials only whenever they are quite soft. The softness of silts and clays can also be estimated by the SPT method.

Let us now examine how to apply figure 13 to the New Madrid earthquake region. According to many historical accounts of the 1811-12 earthquakes, and according to modern measurements on small earthquakes in the region, the duration of shaking is much longer than is typical of other earthquakes throughout the world. Correction of figure 13 to account for the prolonged duration of very strong earthquakes (according to data developed by Seed and others (1975) and Annaki and Lee (1977) shifts the curves to the right, probably about 5 percent. Thus the shift is relatively minor.

According to Street and Nuttli (1984), the three largest 1811-12 earthquakes had magnitudes (Ms) between 8.4 and 8.7. For purposes here, $8^1/_2$ will be used. To use figure 13 in determining what soils are susceptible to liquefaction, we need now to know the accelerations.

The writer (Obermeier, 1984) has related the pattern of 1811-12 liquefaction features to SPT blow counts throughout much of the alluvial lowlands severely affected, and then used a chart much like figure 13 to back-calculate the 1811-12 earthquake accelerations. From that basis, the writer believes that a maximum horizontal acceleration on rock of about 0.10-0.15 g characterizes average conditions in the region with Modified Mercalli intensity IX, of figure 14. Higher acceleration values would be expected nearer the epicenter, and where soil-rock relationships cause a modification at the ground surface. For accelerations of this level in rock, accelerations in overlying shallow weak alluvium are commonly amplified by a factor of about $1^1/_2$ or so (Hays, 1980). It is impossible to make precise evaluations of amplification in the New Madrid region, because of the lack of knowledge about characteristics of large earthquakes. Thus the data given by Hays probably give about the best available estimates.

Hence, for the region with intensity IX, at the ground surface peak horizontal accelerations as much as 0.15 g should be expected to be commonplace. From figure 13, for a magnitude $8^1/_2$ earthquake, N_1 values of 16 or less should liquefy. This translates to N values of about 11 or less for sands on typical terraces and flood plains in the depth generally most subject to liquefaction; this also translates to N values of about 6 or less for silty sands. For soft silts, probably only those with SPT values of 4 to 5 or less are susceptible. The writer believes that some clays with SPT blow counts less than 2 to 3 may be susceptible in this region.

Closer to the epicenter, where Modified Mercalli intensity values and accelerations are higher, a similar approach can be used to estimate N_1 values that indicate susceptibility. Within about 30 to 40 miles (50 to 65 km) of the epicenter back-calculation of the 1811-strength earthquake by the writer (Obermeier, 1984) yields peak rock horizontal accelerations of about 0.20 g. This basically doubles the N values for sands, and probably for weak silts, that are susceptible. For clays, the writer believes that only those with SPT blow counts of 3 or less may be susceptible.

The procedure just outlined is used later to determine which geologic materials are susceptible to liquefaction, for individual states at a scale of 1:1,000,000. Alternate procedures for estimating accelerations are in papers by the writer (1984) and Nuttli and Herrmann (1984). The values by Nuttli and Herrmann are somewhat higher (about 25-50 percent) than the writer's, but this difference is too small to be important for regional assessment.

Solutions to Liquefaction

Solutions to potential liquefaction problems basically involve preventing the possibility of liquefaction. Once a liquefied mass has started moving, the forces are often huge and problems severe.

The best solution is to avoid the site. If that cannot be done, possible solutions are grouting, lowering the ground water table, excavating trenches in weak materials and backfilling them with well-compacted soil to prevent lateral movments, or installing gravel columns to relieve pore pressures. Loose sands can sometimes be made more dense by compacting. Some materials must be removed and replaced with stronger material. Many solutions are very expensive.

LANDSLIDES NOT CAUSED BY LIQUEFACTION

There were two geologic-topographic settings where landslides were especially prominent in the 1811-12 earthquakes. The most spectacular, largest landslides took place in the steep loess slopes, especially those east of the Mississippi River from Cairo, Illinois, to Memphis, Tennessee. Fuller (1912) reports that the large slides in loess bluffs extended as far south as Vicksburg, Mississippi. Some typical dimensions and geologic settings associated with these slides are noted. A methodology is outlined for locating potential landslide sites, given the recurrence of an 1811-12 type earthquake.

The other setting where landslides were commonplace in 1811-12 was along streambanks. Clearly many of these must have been caused by or related to liquefaction, but many if not most must have been rotational slumps or topples of banks undercut by streams. The relevance of these types of failures to present-day conditions is discussed, for the recurrence of an 1811-12 type earthquake.

Landslides in Steep Loess Uplands

Fuller (1912) suggested that some large horizontal glide blocks of loess in the bluffs east of the Mississippi River were caused by the 1811-12 earthquakes. Randy Jibson (U.S. Geological Survey, oral communication 1984) has recently collected and analyzed data which confirm Fuller's suggestion. Jibson notes that for the larger landsides, the head scarp is commonly 300 $\pm$ 150 feet (100 $\pm$ 50 m) back from the steep slopes or bluffs. The initial slope of the land behind the steep slopes was typically only 3 to 4 degrees. Jibson also has found that the material that failed was the clay (of the Jackson Formation) beneath the loess. This clay is so impermeable that it trapped water, and the water-softened clay was very weak.

Landslides in loess during wet seasons are also presently rather commonplace at other places where the loess lies on water-softened, clay-rich soils. In the Saint Louis area, for example, there are numerous landslides where loess is on Pennsylvanian-age clays of the coal measures. There and throughout Missouri, the slides presently take place even on slopes less than 18 degrees (Jerry Wallace, civil engineer and geologist, retired, Missouri Highway Department, personal communication). Some of the loess landslides also take place as silt-rich loess slides on clay-rich loess. The clay-rich loess is generally much older than the silt-rich loess, the clay originating from chemical weathering of loess deposited before the last (Wisconsinan) glacial advance.

All landslides discussed above probably took place with liquefaction having a limited or no role in development of the failure. However, there is the distinct probability that earthquake-induced liquefaction can have a major role in causing many intermediate-or small-sized landslides in uplands. Liquefaction in "loess" is especially likely where the loess has within it thin clean sand layers or where cohesion is extremely low. Although loess is typically made up of silt-sized material, near the source (that is, flood plains of major rivers) it commonly is interlayed with thin layers of wind-deposited very fine, very loose sand (that is, dune sand). In addition, rain falling on loess shortly after deposition left thin strata of clean loose sands at unpredictable locations within the loess.

With this background, where then are the sites that must be viewed as susceptible to failing in another 1811-12 type earthquake? The writer believes that both previously failed and many presently stable loess slopes are candidates for failure. The clay-rich soils on which slides previously moved were greatly weakened by the shearing movement (basically, they have been slickened). These slickened clays have been permanently weakened, and their present-day strengths are probably on the order of about one-half or less that of the unfailed clays. (In engineer's terminology, they would have "residual shear strength".)

Areas on the regional intensity map (figure 14) with Modified Mercalli intensities of X and higher should be considered as subject to large block glides or slumps at places where loess is on slopes steeper than about $3^1/_2$ to 1, especially where there are seeps or evidence of water at the base of the loess. These slides may extend as far back as 450 feet (150 m) from the top of the very steep banks and bluffs in exceptional cases.

In areas with intensities less than X, only rarely would the largest slides extend so far back from loess bluffs, but it is probably not unreasonable to expect there to be many failures that go back from the steep slopes or bluffs by as much as 50 to 75 feet (15 to 25 m).

Upland areas with lakes situated in loess deposits are also especially prone to failure. The dams may not fail but landslides could easily be extensive around the ends of the embankment, in the loess, and could cause catastrophic failure.

Landslides Along Streams

Landslides would be extremely common along all streams, especially those with steep banks. Banks on streams ranging from little creeks to major rivers would be very susceptible, for Modified Mercalli intensities of IX, and especially for higher intensities. Numberous retaining walls would collapse, and severely damage or destroy small bridges. Many large structures would also be subject to damage.

It is virtually impossible to characterize special settings or conditions which may cause collapse of stream banks or retaining walls, because the possibilities are so numerous. Soils of all textures and strengths are susceptible. Only site-specific studies can assess the susceptibility.

Dams impounding streams are not considered, because they are beyond the scope of this paper.

VARIATIONS IN MODIFIED MERCALLI INTENSITIES

by Margaret G. Hopper

CAUSES OF VARIATIONS IN INTENSITY PATTERNS

The intensity patterns of two large earthquakes with epicenters close together are frequently similar. For example, higher intensities are usually experienced in alluvial river valleys, lower intensities on bedrock. Some other localities with unusually high or low intensities are more difficult to explain. The intensity scale is an attempt to quantify a qualitative type of information, and in the process the scale greatly simplifies a very complex phenomenon. Factors which are thought to affect the resulting intensity at a given site include: earthquake magnitude and depth; focal mechansim; epicentral distance; acceleration, velocity, amplitude, period, and wavelength of the seismic waves; duration of strong shaking; type of ground; geologic structure; slope of ground; ground water; and natural period of structures and sites. In addition, assignment of intensity values to observed effects should include consideration of type of construction, quality, and workmanship. Much of the preceding list is from Barosh (1969).

Comparison of the intensity patterns of the four earthquakes shown in figures 2, 4, 5, and 6 reveals some similarities. For the data-scarce 1811 earthquake (figure 2) the patterns that have been drawn are mostly smooth curves, nearly circular. There is a slight hint of higher attenuation to the south, lower to the northeast, but too few data occur on the map to give much confidence in the exact locations of the isoseismals. For the 1843 earthquake, figure 4, the situation is improved. The attenuation is definitely higher on the southwest, lower on the northeast along the Ohio River, on the northwest along the Mississippi River, and on the southeast. The 1895 earthquake, figure 5, with epicenter farther north, shows similar low attenuation northeast and northwest. The 1968 earthquake, figure 6, though a smaller earthquake located north of the New Madrid seismic zone and north of the other earthquakes considered, has an excellent data set allowing detailed contouring of isoseismals. Note that it shows low attenuation along all the river valleys, higher attenuation to the south and south-southwest. Figure 6 also clearly shows that within a given isoseismal area, the intensities are not uniform. For example, in the area of intensity IV Modified Mercalli there are also a number of III's and V's, and even VI's. Isoseismals are normally constructed to outline the predominant intensity in an area, that is, the highest intensity which is common in an area.

As discussed above, intensity may not attenuate uniformly in all directions. When data are sufficient isoseismals are seldom circles, but rather extend farther along certain courses (for example, river valleys) and have reentrants, or lower intensity regions, in other areas. To preserve these patterns of unusually high or low intensity areas, the isoseismals of the 1843 and 1895 earthquakes have been used as the basis of the regional map (figure 14) developed in this study.

EFFECTS DUE TO LIQUEFACTION AND LANDSLIDING

Areas susceptible to ground effects, such as liquefaction and landsliding, can also cause variations in Modified Mercalli intensity patterns.

Liquefaction occurs when earthquake shaking causes a water-saturated, unconsolidated sand at depth to loose all its shear strength and become fluid. This mechanism produced the sandblows that were so prevalent during the 1811-1812 earthquakes.

Liquefaction can cause a loss of bearing capacity of any structure in the liquefied region. In Niigata, Japan, in 1964, many structures settled more than a meter, often with severe tilting. One apartment building tilted 80 degrees from the vertical but remained structurally intact (figure 11). Some buried structures floated to the surface (Seed and Idriss, 1967).

Liquefaction can also cause landslides. Several severe landslides were caused by liquefaction in Anchorage, Alaska, during the 1964 earthquake. Failure occurred in sand lenses overlain by clay; the sand failed and caused blocks of earth to move along a nearly horizontal surface toward a free face, or bluff, and then to collapse in wedge-shaped masses (Eckel, 1970).

Similar conditions likely to result in liquefaction exist in the Mississippi embayment. Liu (1981) described the conditions there: A few feet of clay and silt overlie a massive sand and gravel substratum, 50-100 feet (15-30 meters) thick. During earthquake shaking, the saturated cohesionless materials compact, causing an increase in pore water pressure in the soil and the upward flow of the water to the surface. This in turn causes flooding. Liu also pointed out that natural levees interbedded with lenses of cohesionless sand may fail by liquefaction, form flow slides into the watercourses, and cause flooding. Also, collapse of the man-made dikes in the New Madrid area into the drainage canals would cause widespread flooding (Liu, 1981).

One particular site that Liu notes, where the liquefaction potential has been investigated, is the Patoka Dam site in Indiana. Results indicate the foundation at the dam site to be subject to liquefaction from a magnitude-6.5 earthquake (Liu, 1981).

Geologic evidence of sandblows associated with the 1811-1812 and earlier earthquakes is still visible at the surface today. Detailed mapping of these sands in the Saint Francis basin has recently been completed by Obermeier (1984). The potential for liquefaction exists far beyond the Saint Francis basin, however.

Youd and Perkins (1978) suggested that an opportunity exists for liquefaction, in sediments susceptible to liquefaction, as far as 150 km from the epicenter of a great earthquake. Since four of the cities studied in this report are within this distance range of some segment of the New Madrid seismic zone (and the other three cities are within 200 km), the potential for liquefaction must be assumed to exist in all the cities that are underlain by liquefiable sediments. In each case, this is the area shown as the highest intensity on figures 20-40. Carbondale (figure 20), though close enough to an epicenter located on the northern part of the seismic zone for liquefaction to occur, is not thought to have geologic conditions conducive to liquefaction.

PREDOMINANT PERIODS OF GROUND MOTION

Particular consideration needs to be given to the effects caused by the longer-period seismic waves at large distances from great earthquakes, especially for earthquakes occurring in the central United States. These long-period effects are another source of the variation displayed by earthquake isoseismals or intensity patterns. Two topics of particular importance of this study will be discussed: 1) effects on tall buildings, and 2) effects on ground and water.

The moderate-size (m_b = 5.5) 1968 earthquake in southern Illinois is reported to have done slight damage and frightened people in Chicago skyscrapers, 430 km away from the epicenter; to have been felt on the twelfth floor of a 16-story building at the Massachusetts Institute of Technology in Cambridge, Massachusetts, 1,500 km away; and to have been felt in tall buildings in southern Ontario, Canada (Necioglu and Nuttli, 1974). Such effects are a consequence of the similarity of the predominant periods exhibited by the earthquake at those distances to the natural periods (fundamental modes of vibration) of the buildings. In the epicentral region damage is caused by the short-period, high-acceleration vibrations predominant there; farther away, the longer-period waves, having low ground acceleration for relatively large ground displacements, begin to predominate. The anomalously low attenuation of these waves in the central United States makes them potentially destructive over large distances. This low attenuation together with the dispersion, or variation in velocity of different wavelengths of surface waves, results in a prolonged duration of shaking at distant points (Nuttli, 1979).

The long-period waves that extend to larger distances from a great earthquake may also produce ground and water effects. Ground effects caused by long-period waves include landslides, settling, and slumping. This may cause damage to foundations of buildings and bridges, break buried pipes and crack road surfaces. Landslides also can be triggered in susceptible places at large epicentral distances from a great earthquake. Seiches and other oscillations in surface water may occur out to hundreds of kilometers from the epicenter.

MAPS OF HYPOTHETICAL INTENSITIES FOR THE REGION

By S. T. Algermissen and Margaret G. Hopper

The ground shaking (reported in Modified Mercalli (M.M.) intensities) at a site depends primarily on three factors: 1) the size of the earthquake, that is, the amount of energy released by the earthquake, 2) the attenuation, or weakening of seismic waves, along the path between the epicenter and the site, and 3) geologic conditions at the site itself. The size of the earthquake has already been discussed. For the purposes of this study three hypothetical earthquakes are assumed: 1) a magnitude M_S = 8.6, I_o = XI M.M. earthquake located at any point in the New Madrid seismic zone. This is similar to the size of the December 16, 1811 (2:15 a.m.) earthquake (located near the southern end of the seismic zone) as estimated by Nuttli (1981). 2) An M_S = 7.6, I_o = X M.M. earthquake located at any point in the New Madrid seismic zone. 3) An M_S = 6.7, I_o = IX M.M. earthquake located at any point in the seismic zone. This approximates the size of the October 31, 1895, earthquake (located at the northern end of the seismic zone).

The magnitudes of the hypothetical shocks were chosen in such a way that the maximum intensities for the three earthquakes are exactly XI, X, and IX M.M. Thus the regional maps derived (figures 14-19) show the isoseismal lines at the same locations, but progressively lower intensity levels.

The smaller two hypothetical shocks are much more likely to actually occur than is the largest M_S = 8.6, I_o = XI earthquake. In the New Madrid seismic zone an I_o = XI earthquake has an estimated return period of 500 years (last one in 1811), I_o = X of 200 years (last one in 1811), and I_o = IX of 80 years (last one 1895) (Algermissen, 1972). Even the I_o = IX earthquake represents a considerable risk in the Midwest. There is little awareness of the potential for earthqake damage in the area, little effort for earthquake disaster preparedness, and almost no provision for earthquake vibrations in most building codes. In addition, the low attenuation of seismic energy in the central United States results in very large damage areas as can be seen in figures 14-19. Similar magnitude shocks in California would have much smaller damage areas.

Variations in intensity, or damage patterns of three large historical regional earthquakes were used to develop composite regional intensity maps for these three large hypothetical earthquakes. The method used and the resulting maps (figures 14-19) are discussed in the next section. From these regional intensity maps, projected intensities at each of the seven cities in this study have been determined for each of the three projected earthquakes.

CONSTRUCTION OF THE MAPS

The 1843 and 1895 isoseismal maps have been used as the basis of the hypothetical regional maps because they are the largest earthquakes in the New Madrid seismic zone for which sufficient data are available to make reasonably detailed isoseismal maps. The shaking levels associated with each of these two earthquakes have been extrapolated to the levels of the projected earthquakes. For example, to derive the hypothetical intensities for the M_S =

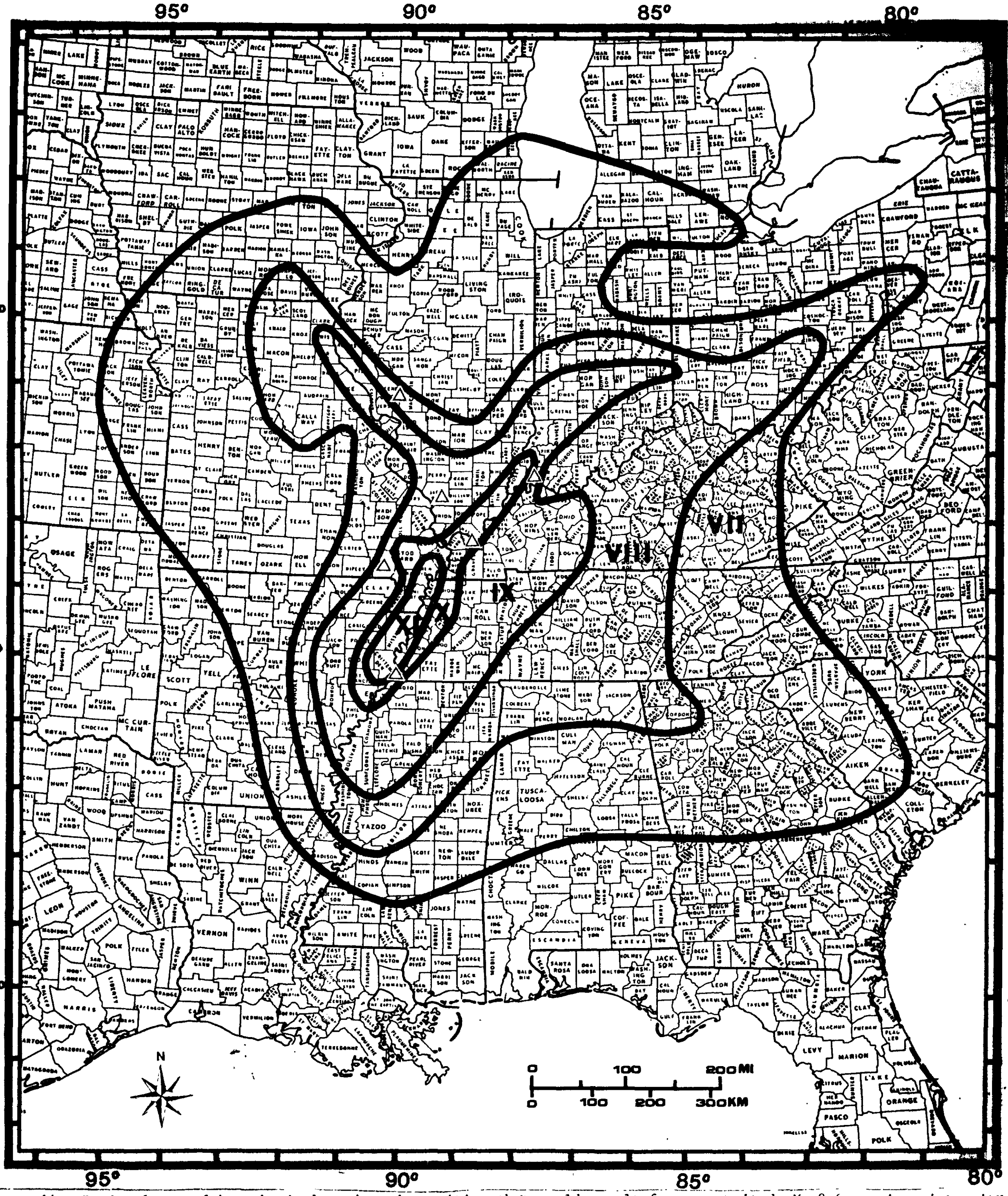


Figure 14.--Regional map of hypothetical maximum intensities that would result from a magnitude M_s=8.6, maximum intensity I_o=XI M.M., earthquake anywhere along the New Madrid seismic zone. Magnitude 8.6 was chosen because that is the estimated magnitude of the December 16, 1811, New Madrid earthquake, one of the largest earthquakes ever to occur in the United States. The estimated distribution of effects shown on the map is based on an analysis of the effects of the smaller, but better documented, shocks in 1843 (near Memphis, Tenn.) and 1895 (near Charleston, Mo.). This composite intensity map shows a more widespread distribution of effects than 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 to the southern end of the seismic zone, and the maximum of the resulting intensities was chosen for each point on the map. Thus, for an actual epicenter near the southern end of the seismic zone, intensities in the northern part of the map would be lower, and conversely, an earthquake whose epicenter was in the northern part of the seismic zone would cause intensities lower than shown on the southern part of the map. A composite map has been prepared because (1) it is not certain where in the zone a large earthquake might occur in the future, and (2) in 1811-1812 four large shocks did occur at different places throughout the zone. This composite intensity map is believed to represent the upper level of shaking likely to occur in any county regardless of the location of the epicenter within the seismic zone. Triangles show the locations of the seven cities studied in detail.

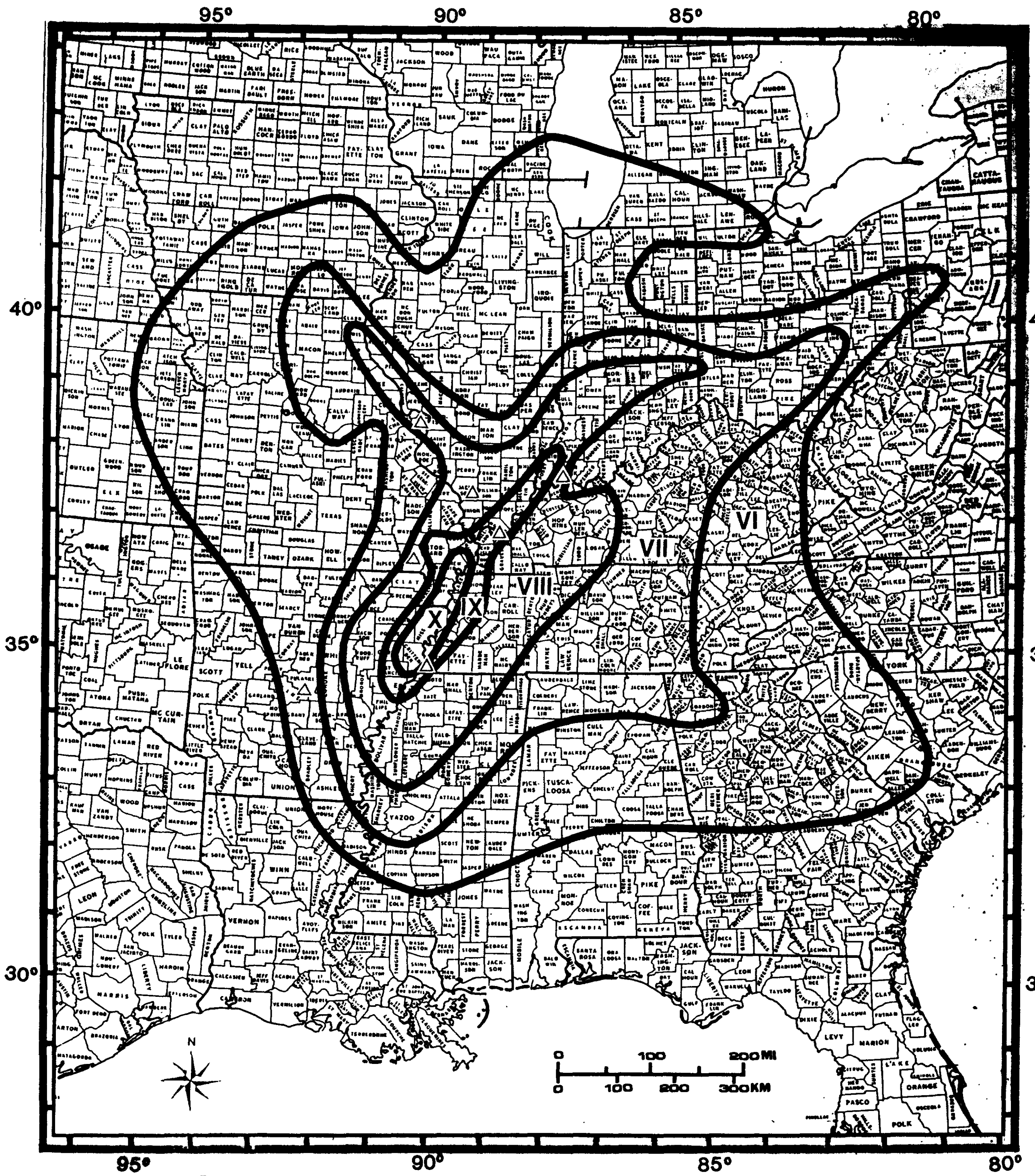


Figure 15.--Regional map of hypothetical maximum intensities that would result from a magnitude M_s=7.6, maximum intensity I_0=X M.M., earthquake anywhere along the New Madrid seismic zone. The estimated distribution of effects shown on the map is based on an analysis of the effects of the smaller shocks in 1843 (near Memphis, Tenn.) and 1895 (near Charleston, Mo.). This composite intensity map shows a more widespread distribution of effects than would result from a single earthquake of magnitude 7.6 because the distributions of effects were plotted for magnitude-7.6 earthquakes that could occur anywhere from the northern to the southern end of the seismic zone, and the maximum of the resulting intensities was chosen for each point on the map. Thus, for an actual epicenter near the southern end of the seismic zone, intensities in the northern part of the map would be lower, and conversely, an earthquake whose epicenter was in the northern part of the seismic zone would cause intensities lower than shown on the southern part of the map. A composite map has been prepared because (1) it is not certain where in the zone a large earthquake might occur in the future, and (2) in 1811-1812 four large shocks did occur at different places throughout the zone. This composite intensity map is believed to represent the upper level of shaking likely to occur in any county regardless of the location of the epicenter within the seismic zone. Triangles show the locations of the seven cities studied in detail.

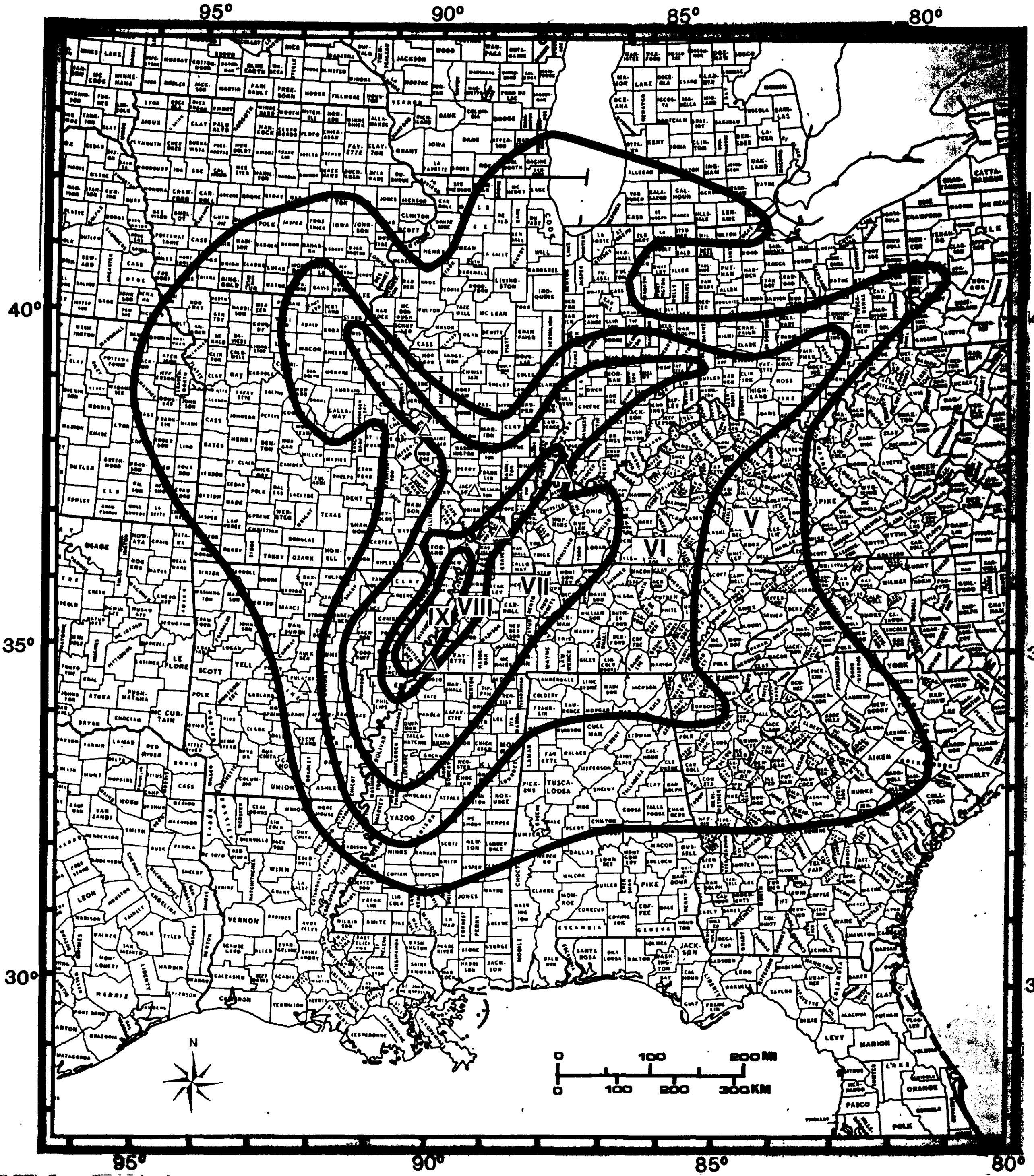


Figure 16.--Regional map of hypothetical maximum intensities that would result from a magnitude M_s=6.7, maximum intensity I_0=IX M.M., earthquake anywhere along the New Madrid seismic zone. The estimated distribution of effects shown on the map is based on an analysis of the effects of the smaller shock in 1843 (near Memphis, Tenn.) and the maximum intensity I_0=IX shock in 1895 (near Charleston, Mo.). This composite intensity map shows a more widespread distribution of effects than would result from a single earthquake of magnitude 6.7 because the distributions of effects were plotted for magnitude-6.7 earthquakes that could occur anywhere from the northern to the southern end of the seismic zone, and the maximum of the resulting intensities was chosen for each point on the map. Thus, for an actual epicenter near the southern end of the seismic zone, intensities in the northern part of the msp would be lower, and conversely, an earthquake whose epicenter was in the northern part of the seismic zone would cause intensities lower than shown on the southern part of the map. A composite map has been prepared because (1) it is not certain where in the zone a large earthquske might occur in the future, and (2) in 1811-1812 four large shocks did occur at different places throughout the zone. This composite intensity map is believed to represent the upper level of shaking likely to occur in any county regardless of the location of the epicenter within the seismic zone. Triangles show the locations of the seven cities studied in detail.

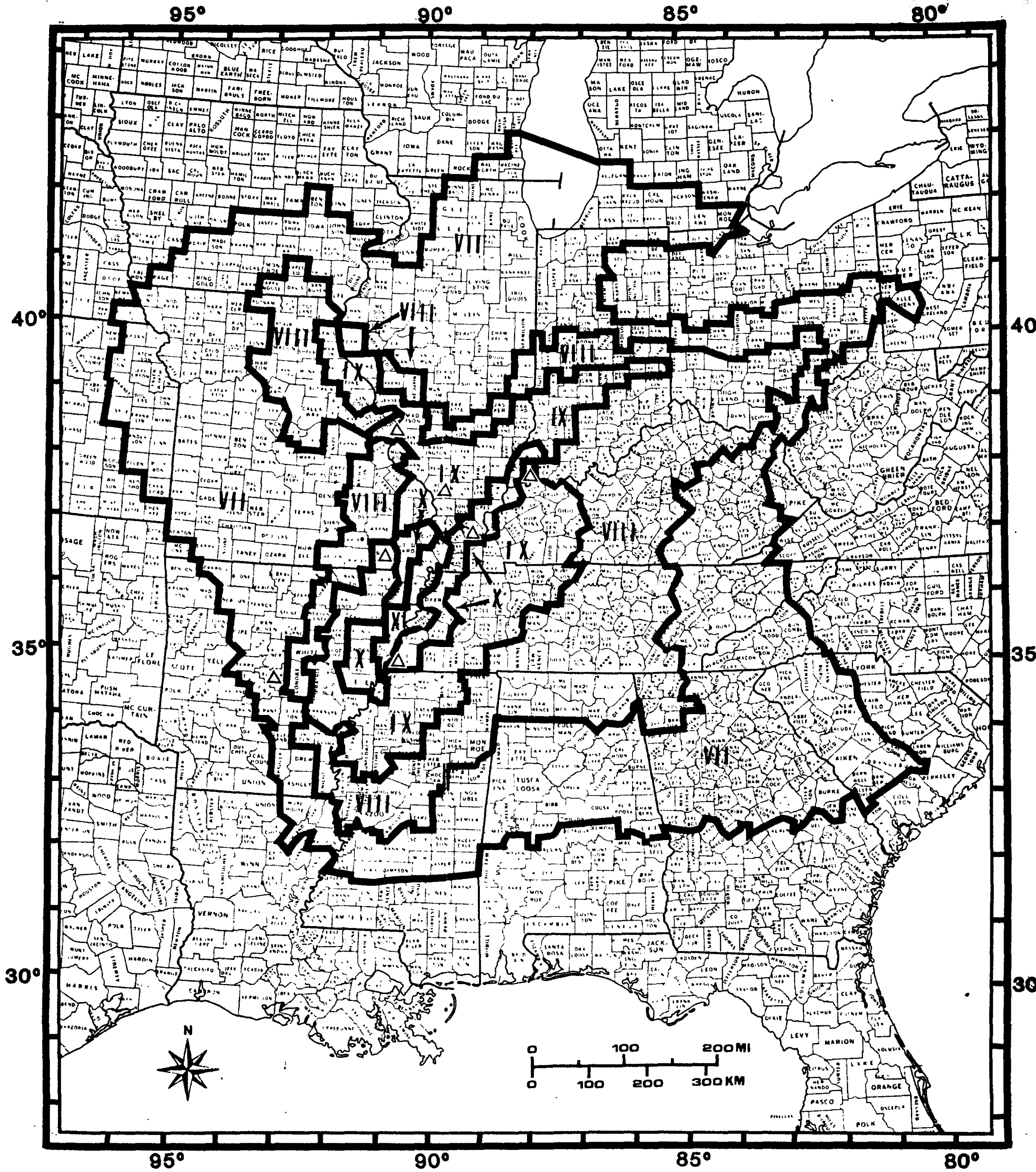


Figure 17.—Regional map by county of hypothetical maximum intensities that would result from a magnitude M_s=8.6, maximum intensity I_o=XI M.M., earthquake anywhere along the New Madrid seismic zone. Magnitude 8.6 was chosen because that is the estimated magnitude of the December 16, 1811, New Madrid earthquake, one of the largest earthquakes ever to occur in the United States. The estimated distribution of effects shown on the map is based on an analysis of the effects of the smaller, but better documented, shocks in 1843 (near Memphis, Tenn.) and 1895 (near Charleston, Mo.). This composite intensity map shows a more widespread distribution of effects than 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 to the southern end of the seismic zone, and the maximum of the resulting intensities was chosen for each point on the map. Thus, for an actual epicenter near the southern end of the seismic zone, intensities in the northern part of the map would be lower, and conversely, an earthquake whose epicenter was in the northern part of the seismic zone would cause intensities lower than shown on the southern part of the map. A composite map has been prepared because (1) it is not certain where in the zone a large earthquake might occur in the future, and (2) in 1811-1812 four large shocks did occur at different places throughout the zone. This composite intensity map is believed to represent the upper level of shaking likely to occur in any county regardless of the location of the epicenter within the seismic zone. Triangles show the locations of the seven cities studied in detail.

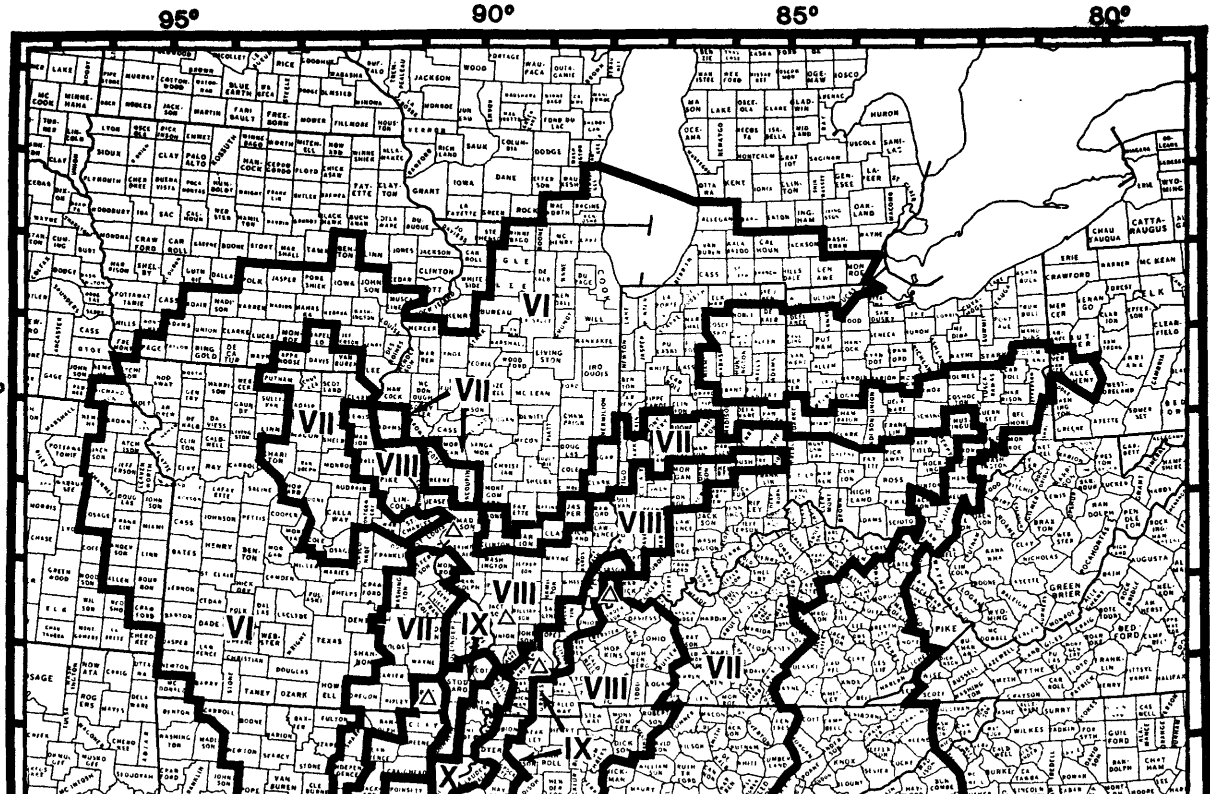


Figure 18.--Regional map by county of hypothetical maximum intensities that would result from a magnitude M_s=7.6, maximum intensity I_o=X M.M., earthquake anywhere along the New Madrid seismic zone. The estimated distribution of effects shown on the map is based on an analysis of the effects of the smaller shocks in 1843 (near Memphis, Tenn.) and 1895 (near Charleston, Mo.). This composite intensity map shows a more widespread distribution of effects than would result from a single earthquake of magnitude 7.6 because the distributions of effects were plotted for magnitude-7.6 earthquakes that could occur anywhere from the northern to the southern end of the seismic zone, and the maximum of the resulting intensities was chosen for each point on the map. Thus, for an actual epicenter near the southern end of the seismic zone, intensities in the northern part of the map would be lower, and conversely, an earthquake whose epicenter was in the northern part of the seismic zone would cause intensities lower than shown on the southern part of the map. A composite map has been prepared because (1) it is not certain where in the zone a large earthquake might occur in the future, and (2) in 1811-1812 four large shocks did occur at different places throughout the zone. This composite intensity map is believed to represent the upper level of shaking likely to occur in any county regardless of the location of the epicenter within the seismic zone. Triangles show the locations of the seven cities studied in detail.

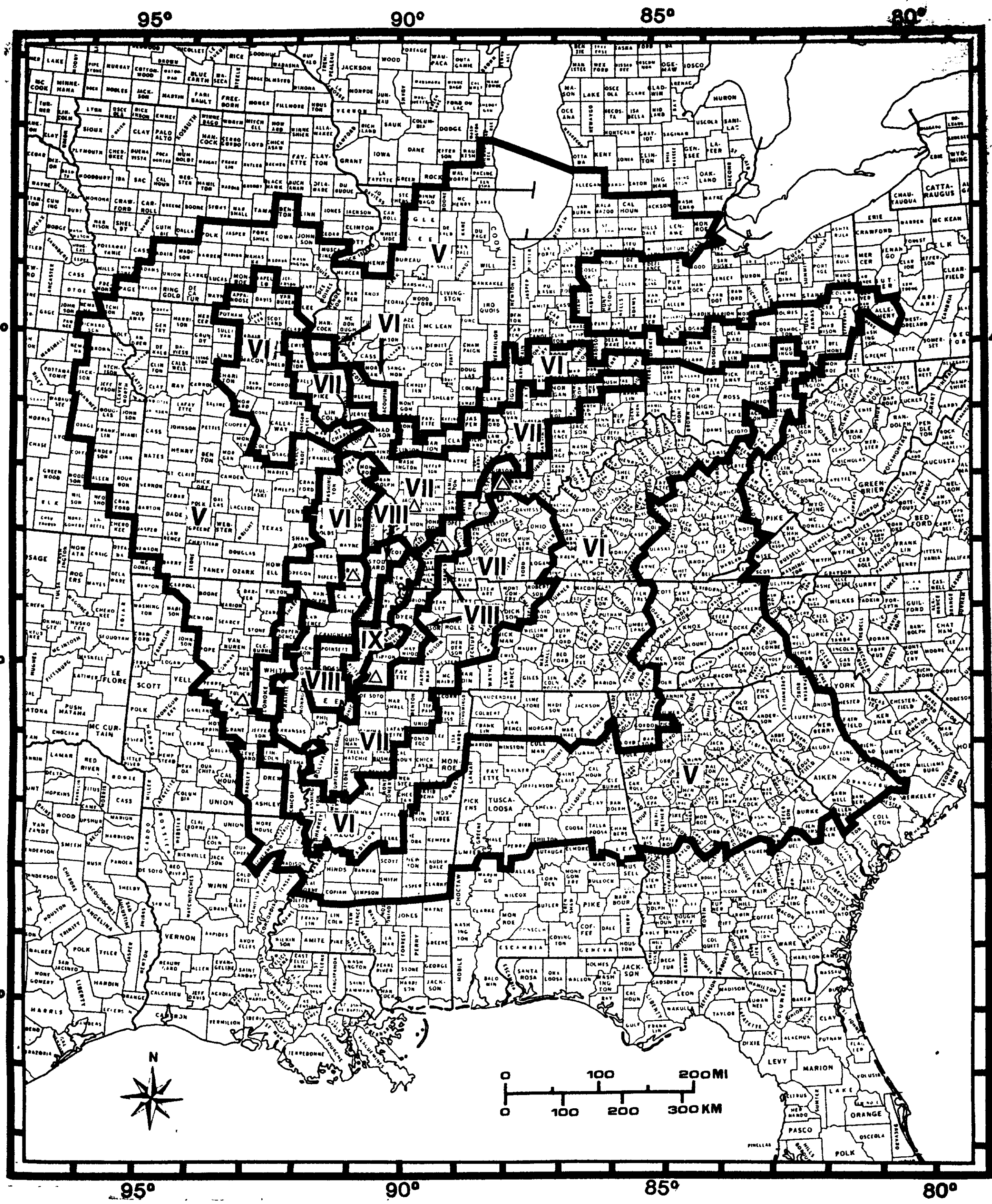


Figure 19.--Regional map by county of hypothetical maximum intensities that would result from a magnitude M_s=6.7, maximum intensity I_0=IX M.M., earthquake anywhere along the New Madrid seismic zone. The estimated distribution of effects shown on the map is based on an analysis of the effects of the smaller shock in 1843 (near Memphis, Tenn.) and the maximum intensity I_0=IX shock in 1895 (near Charleston, Mo.). This composite intensity map shows a more widespread distribution of effects than would result from a single earthquake of magnitude 6.7 because the distributions of effects were plotted for magnitude-6.7 earthquakes that could occur anywhere from the northern to the southern end of the seismic zone, and the maximum of the resulting intensities was chosen for each point on the map. Thus, for an actual epicenter near the southern end of the seismic zone, intensities in the northern part of the map would be lower, and conversely, an earthquake whose epicenter was in the northern part of the seismic zone would cause intensities lower than shown on the southern part of the map. A composite map has been prepared because (1) it is not certain where in the zone a large earthquake might occur in the future, and (2) in 1811-1812 four large shocks did occur at different places throughout the zone. This composite intensity map is believed to represent the upper level of shaking likely to occur in any county regardless of the location of the epicenter within the seismic zone. Dots with circles show the locations of the seven cities studied in detail.

8.6, I_o = XI earthquake, the intensity levels of the 1895 (I_o = IX) earthquake have been raised two intensity levels from a maximum intensity of IX to XI. Similarly, in this example, the maximum intensity of the 1843 shock has been raised 2.5 levels from mid-VIII to XI. This resulted in two I_o = XI maps, one for the northern end of the New Madrid seismic zone (based on the 1895 earthquake) and one for the southern end (based on the 1843 earthquake), which taken together show the attenuation patterns for large earthquakes likely to occur throughout the New Madrid zone. These two maps have been combined graphically by taking the maximum intensity at every point to yield the hypothetical regional intensity map for maximum intensity I_o = XI earthquakes located anywhere along the length of the New Madrid seismic zone (figure 14).

The effect of this method is simply to increase the intensity levels shown on the 1895 and 1843 isoseismal maps, figures 5 and 4. This may be done because graphs of intensity attenuation (plots of intensity versus distance from the epicenter) for earthquakes of lower maximum intensity are assumed to be parallel to similar graphs for earthquakes of higher maximum intensity. Thus the attenuation curve for a smaller earthquake may be raised in order to simulate an attenuation curve for a larger earthquake, and the map isoseismals may be raised.

One additional modification was necessary to complete figure 14. Since the hypothetical map is based on earthquakes at the north and south ends of the seismic zone, a gap is produced between the areas of intensity XI resulting from the 1895 epicentral area on the north and the area of XI resulting from the 1843 epicentral area on the south. In this gap the X's produced by the method above have been arbitrarily changed to XI's along the length of the New Madrid seismic zone. This is necessary since large earthquakes are assumed to be possible anywhere along the zone. The lack of a large earthquake located near the center of the seismic zone to be used as a third basis for the hypothetical regional map (insufficient data is available from the ones located there in January and February, 1812) has only a small effect on the outer contours. By the same reasoning, if a (single) hypothetical earthquake occurred at the north (south) end of the seismic zone, cities near the south (north) end would experience lower intensities than those shown on figure 14, but cities far away from the zone would experience about the intensities shown, no matter in which section of the seismic zone the earthquake occurred.

The maps in figures 17-19 show the same information as figures 14-16, but have been generalized to show the predominant intensity in each affected county. In figures 17-19, a particular county has been judged to be either within or outside a particular intensity area. As with contouring intensity data, the rule used is that of the highest predominant intensity in a given county. Counties more or less evenly divided between two (or more) intensities are usually included in the higher category. These maps will be of assistance to planning efforts by individual cities and counties. It must be stressed that every point in a county will not experience the intensities shown on figures 17-19. If, for example, the county of interest is on the north side of the area of figures 17-19, and the earthquake which actually occurs is on the north end of the New Madrid seismic zone, some parts of that county are expected to experience the intensities shown on figures 17-19. There might also be a few isolated instances of intensity one unit higher, as well as many areas that will have lower intensities, perhaps several intensity levels lower. The processes producing simple intensities are very complicated and can result in structural damage to one building while a similar building nearby sustains little or no damage. Also, note that, for an earthquake at the south end of the New Madrid seismic zone, a county on the north side of the area of figures 17-19 will probably be at least one intensity unit lower than shown, and vice versa. Discussion of the application of figures 14-19 to specific locations follows the next section.

AREAS OF PROJECTED MINIMAL DAMAGE

Special attention has been given to finding areas likely to experience relatively low intensities. The effects on expected type of ground motion of predominant periods at different distances from the New Madrid seismic zone were also considered.

The attenuation of intensity is not uniform in all directions from an epicenter; in some directions intensity diminishes much more rapidly than in other directions, causing areas of relatively low intensity. Such areas of lower than average intensity may readily be picked out on the hypothetical regional intensity maps, figures 14-16--for example, the area of intensity VII in south-central Missouri in figure 14. It may be seen by inspection of figure 14 that the intensities attenuate much more rapidly on the west and southwest than anywhere else. To the northwest (along the Mississippi River), to the northeast (along the Ohio River), and to the southeast (into Georgia), the intensities attenuate much more slowly than elsewhere. To the north, east, and south, the intensities attenuate in a more normal fashion, neither unusually high nor low.

It is assumed that, for disaster planning purposes, an "area of minimal damage" means not only an area where the intensity is low compared to nearby areas, but also an area where the intensity is below VIII M.M. Thus an area of intensity VIII (structural damage) would not be considered an area of minimal damage even if surrounded by areas of IX and above. Moreover, areas of intensity VII (architectural damage) and VI (threshold of any type of damage) are areas of minimal damage even though nearby areas have the same, or lower, intensities. Thus the areas of minimal damage are those areas shown as VII, VI, and ≤VI in figures 14-16 and on the maps of the seven cities. Regionally, their nearest occurrence to the epicentral area is on the west and southwest, but they also occur, slightly farther away, on the north, east, and south.

If figures 17-19 are to be used by, say, a county administrator, to plan for emergency procedures before, during, and after an earthquake, the following points should be kept in mind:

1) The intensities shown on figures 17-19 for his county are a guide to the highest levels of intensity projected to be prevalent in some part of his county. Every point in the county will not experience these intensities; some places within the county will be lower, even in the part of the county where the guide intensities occur often.

3) The same guide intensities in two counties at very different epicentral distances will result in different kinds of damage. The damage will be similar in level of destructiveness, but not in type. A county closer to the epicenter (assumed limited to be somewhere within the New Madrid seismic zone) and experiencing an intensity of, say, VIII, will have damage to low-rise, rigid structures, caused by the short-period, high-acceleration vibrations. It may also have ground effects, such as liquefaction in its alluvial areas and landslides on its bluffs. A county at a greater distance from the epicenter, also with a guide intensity of VIII, may have damage to its high-rise structures, but little or none to its low-rises, and less or no liquefaction. This is the result of the longer period surface waves predominant at farther distances from the epicenter, periods closer to the resonant periods of high-rise structures. This is discussed more fully in the section on predomiant periods above.

4) Buildings that are expected to be used for relief purposes after an earthquake must be selected on the basis of structural soundness and probable ground response at that site. Assume that the guide intensity may actually occur to a number of buildings located in the alluvial river valleys, where vibrations are often amplified. If the guide intensity is VIII or more, also assume that liquefaction may occur in such alluvial areas and that landslides are likely, especially on steep, water-saturated bluffs. Since damage at a given intensity level also depends on the strength of the structures themselves, type and quality of the buildings should be considered. Beyond the immediate epicentral area, local site conditions, including both the ground and the type and quality of any structure on it, are more important for estimating the potential damage at that site or building than anything else.

MAPS OF HYPOTHETICAL INTENSITIES FOR SEVEN CITIES

By Ernest Dobrovolny, Stephen F. Obermeier, and Margaret G. Hopper

Maps of the seven cities studied individually are shown for each of the three projected earthquakes (M_s = 8.6, 7.6, 6.7) in figures 20-40. The intensity in general in the area of a city can be determined from the map of hypothetical regional intensities, figures 14-16. Seismic zonation at the scale of an individual city also requires some knowledge of geologic conditions at each site. Site conditions important for the evaluation of intensity include topographic slope, geologic materials, and water saturation. These conditions determine the potential for higher or lower than average shaking, and the potential for such geologic effects as liquefaction, flooding, and landsliding. The projected regional intensity at each city and the individual site conditions are combined to develop intensity maps for the area within the corporate limits of each of the seven cities (figures 20-40). To access these conditions, field investigations were made for each of the seven cities in this study.

The assigned intensities on each city map are intended to be the maximum intensities likely--that is, those that would occur if the assumed earthquake occurred on the part of the New Madrid seismic zone nearest that city. All of the cities would not experience these worst-case intensities at the same time. For example, if the assumed magnitude-8.6 earthquake occurred near the south end of the zone, Memphis would in fact experience the IX's and X's shown in figure 14, but Evansville, which is north of the zone, and which is projected in figure 23 and figure 14 to have a maximum intensity of IX, would likely experience only intensity VIII effects. Similarly, if the earthquake were at the north end of the seismic zone, Evansville would have the IX shown, while Memphis would probably experience only intensity VIII-IX effects. However, since in the 1811-1812 series four great shocks all occurred within a short period of time (December 16, 1811 to February 7, 1812), it is possible that the cities might all experience the maximum intensities more or less contemporaneously.

The intensities shown on figures 20-40 take into account both the intensities on the regional maps (figures 14-16) and the local geologic conditions at each city. The regional maps give the highest common intensities for each city, but it is the local geologic conditions that determine the actual differences in intensities within each city. For example, one city (Carbondale, figures 20-22) has so little significant geologic variation as to be assigned only one intensity throughout. Paducah (figures 32-34), on the other hand, has conditions likely to produce most severe damage along the river and successively lower intensities, in areas with different conditions, away from the river; the most stable locations in Paducah are thought to be two intensity levels lower than the area along the river. Thus three intensity levels are shown for Paducah. Similarly, three intensity levels are shown for Saint Louis (figures 38-40). Poplar Bluff and Little Rock (figures 35-37 and 26-28) are also thought to have differences of two intensity levels, but with no intermediate-level intensity. Thus at Poplar Bluff the intensity drops abruptly at the edge of the bluff along the Black River, with much higher intensities on the Mississippi River alluvial

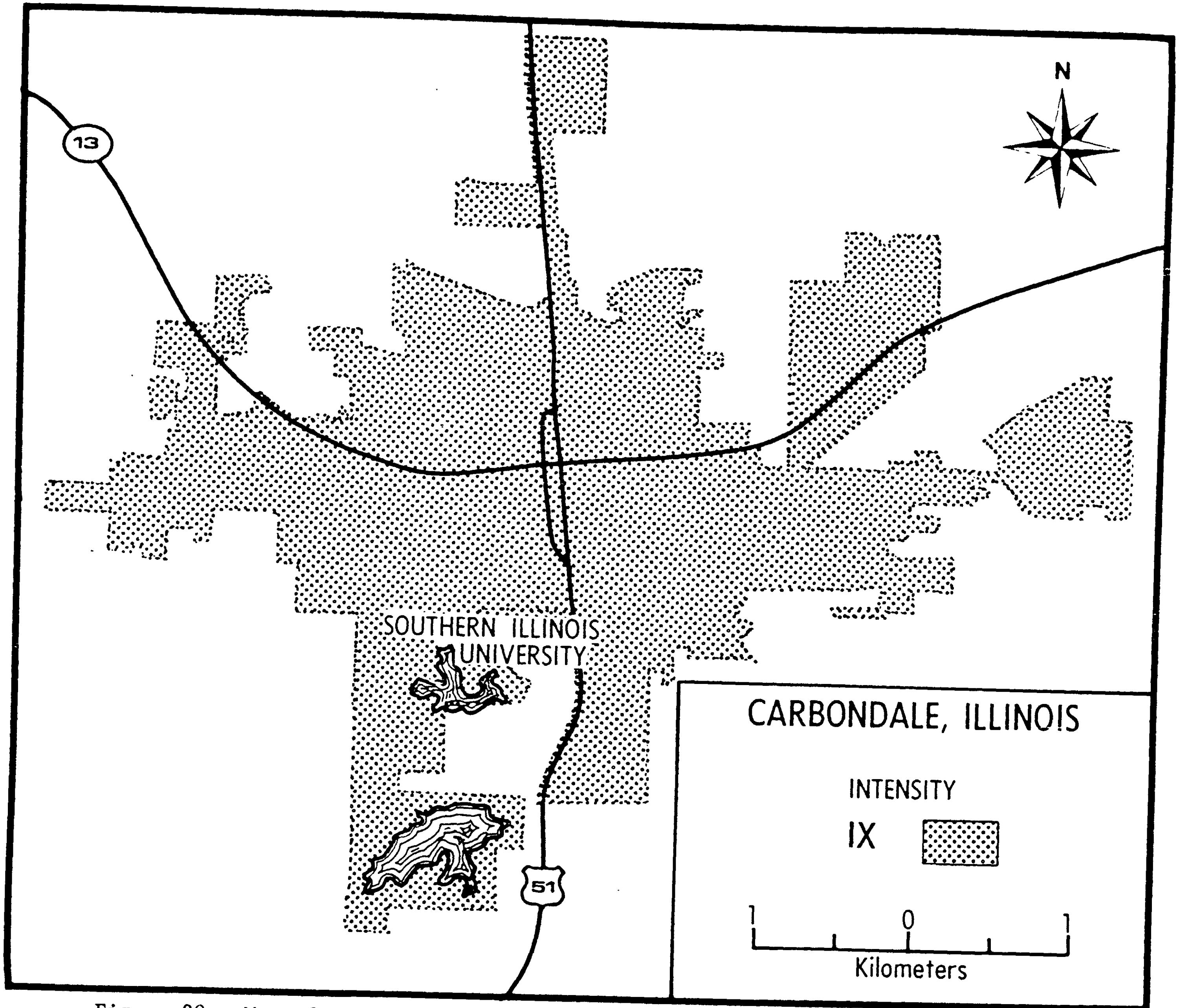


Figure 20.--Map of hypothetical maximum intensity for Carbondale, Illinois for a magnitude M_s-8.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, the intensity for Carbondale is IX M.M. for the entire city. For an epicenter near the south end of the New Madrid seismic zone, the intensity at Carbondale would be lower.

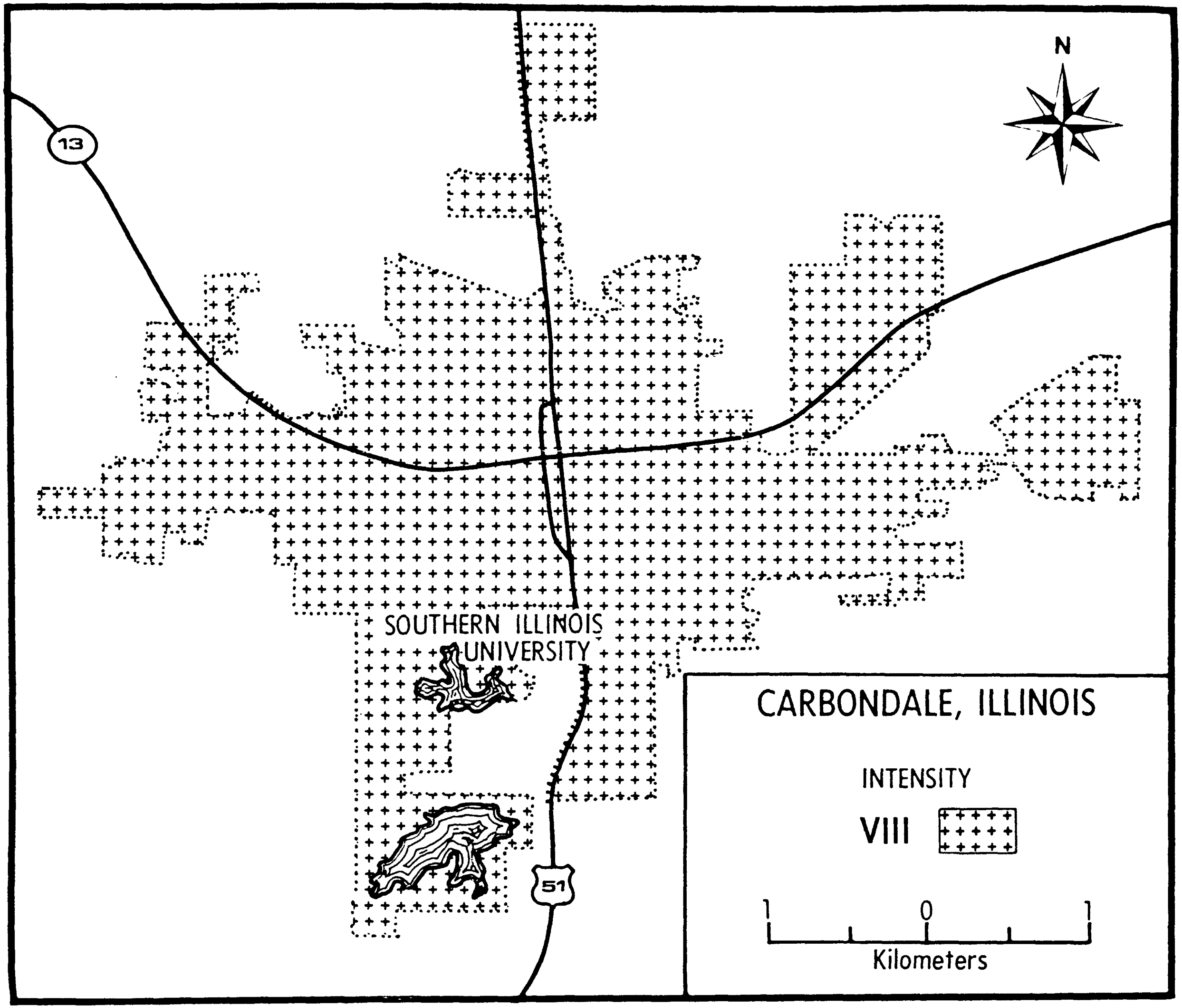


Figure 21.--Map of hypothetical maximum intensity for Carbondale, Illinois for a magnitude M_s-7.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, the intensity for Carbondale is VIII M.M. for the entire city. For an epicenter near the south end of the New Madrid seismic zone, the intensity at Carbondale would be lower.

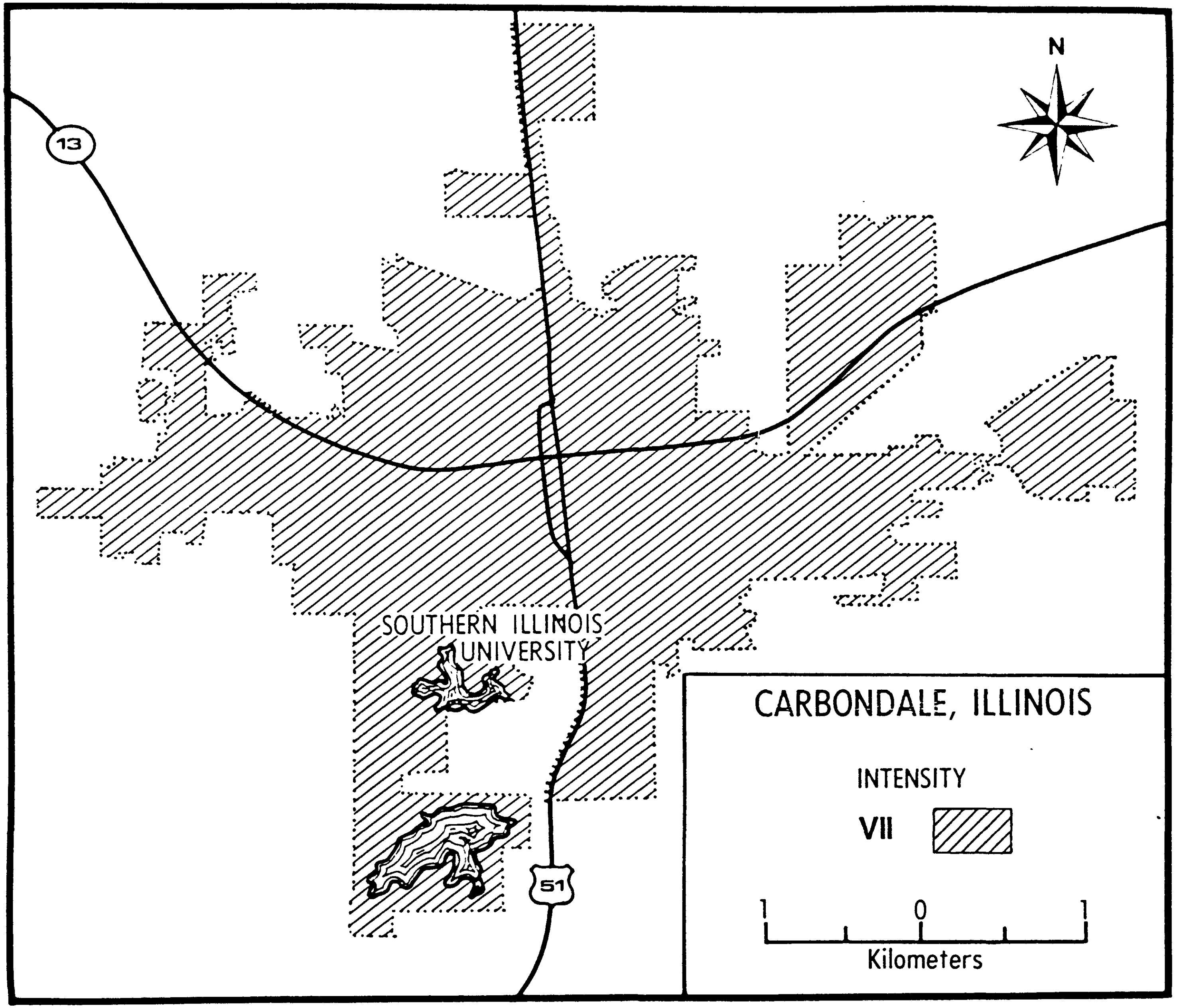


Figure 22.--Map of hypothetical maximum intensity for Carbondale, Illinois for a magnitude M_s-6.7 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, the intensity for Carbondale is VII M.M. for the entire city. For an epicenter near the south end of the New Madrid seismic zone, the intensity at Carbondale would be lower.

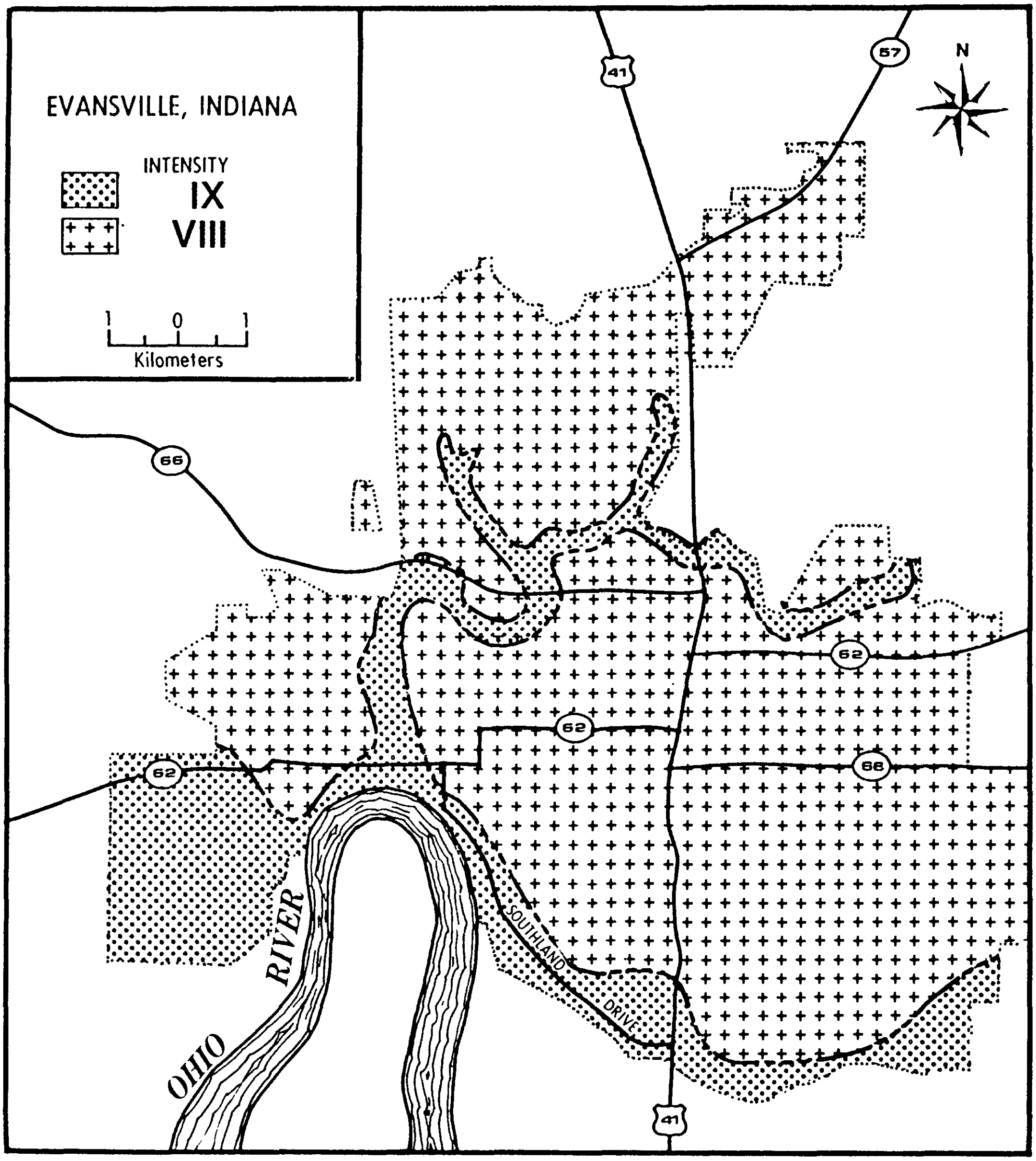


Figure 23.--Map of hypothetical maximum intensities for Evansville, Indiana, for a magnitude M_s=8.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Evansville are: IX M.M. along the Ohio River flood plain and its tributary and VIII for the lacustrine sediments of the rest of the city. For an epicenter near the south end of the New Madrid seismic zone, the intensity at Evansville would be lower.

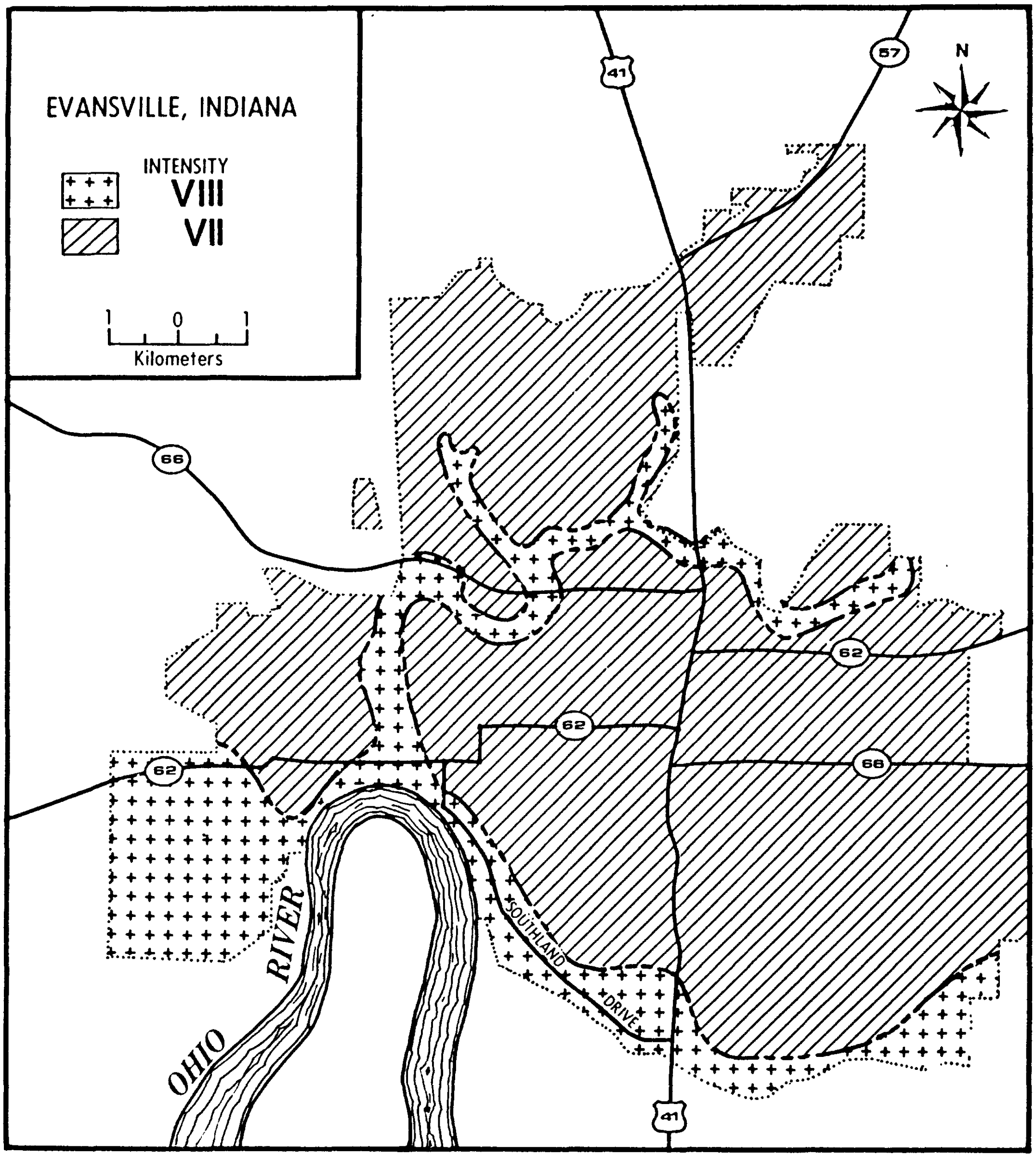


Figure 24.--Map of hypothetical maximum intensities for Evansville, Indiana, for a magnitude M_s=7.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Evansville are: VIII M.M. along the Ohio River flood plain and its tributary and VII for the lacustrine sediments of the rest of the city. For an epicenter near the south end of the New Madrid seismic zone, the intensity at Evansville would be lower.

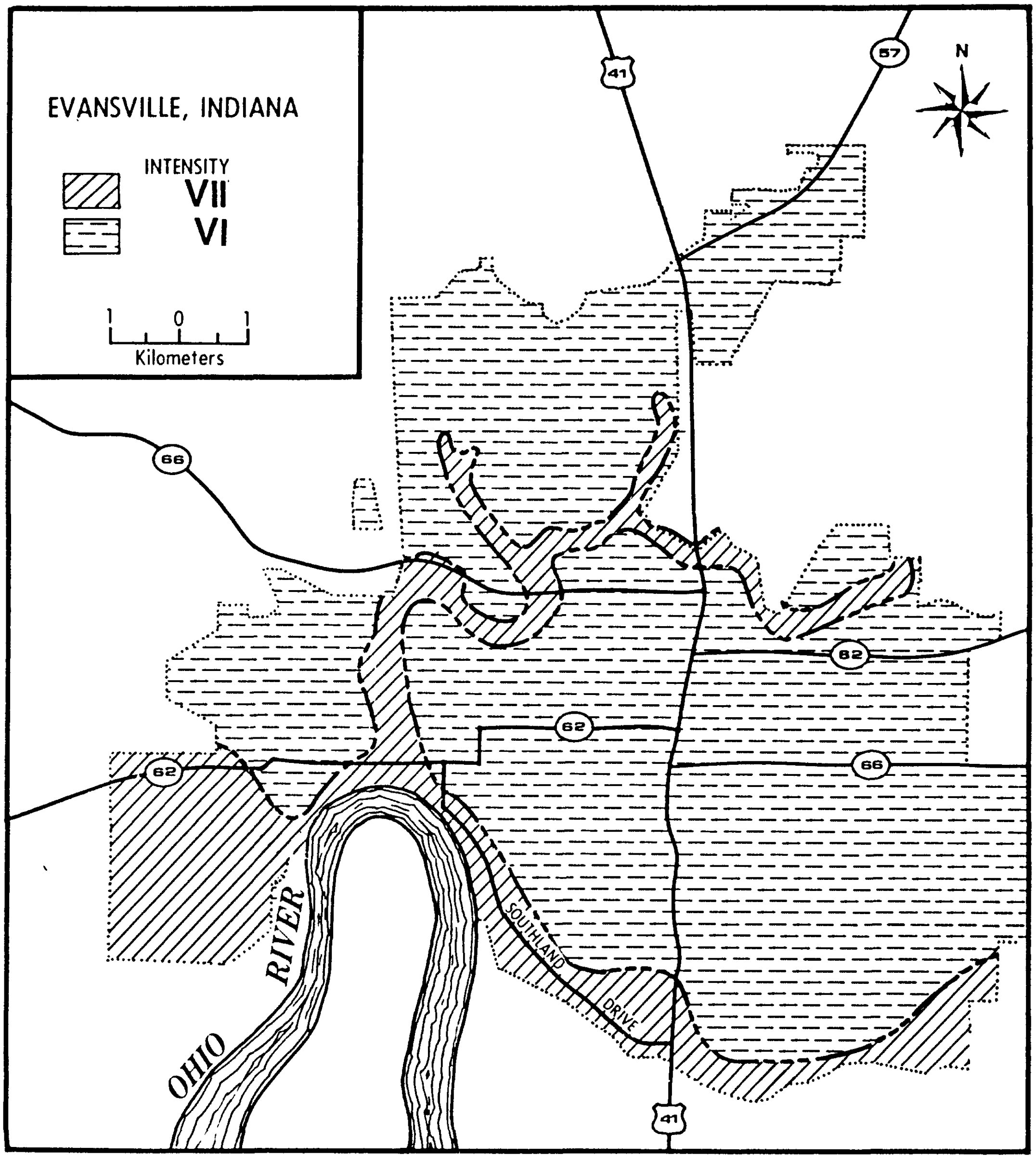


Figure 25.--Map of hypothetical maximum intensities for Evansville, Indiana, for a magnitude M_s=6.7 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Evansville are: VII M.M. along the Ohio River flood plain and its tributary and VI for the lacustrine sediments of the rest of the city. For an epicenter near the south end of the New Madrid seismic zone, the intensity at Evansville would be lower.

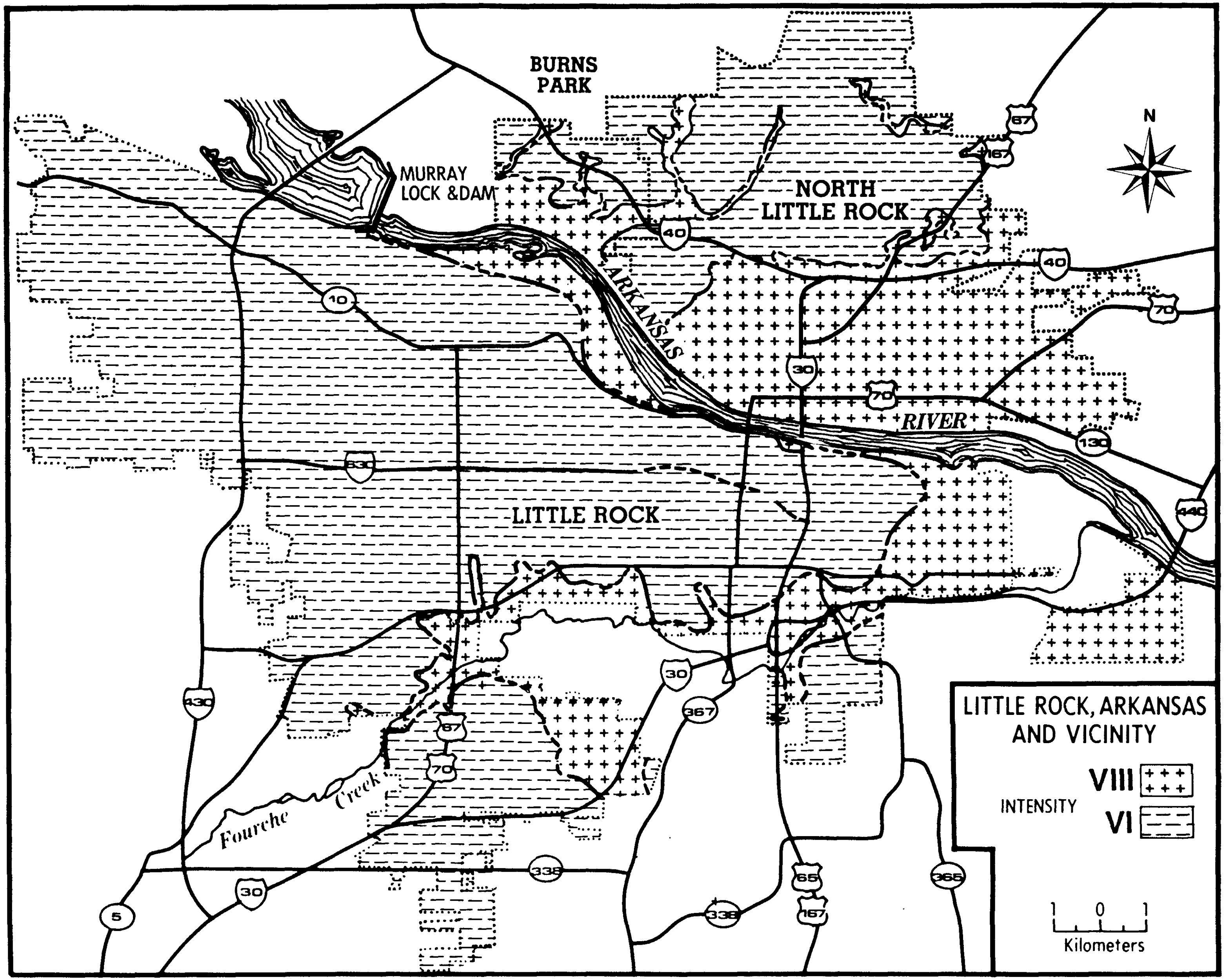


Figure 26.--Map of hypothetical maximum intensities for Little Rock, Arkansas, for a magnitude M_S=8.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the south end of the New Madrid seismic zone, intensities projected for Little Rock are: VIII M.M. on the river alluvium, but only VI on the sandstones, shales, and limestones of the hills. For an epicenter near the north end of the New Madrid seismic zone, the intensities at Little Rock would be lower.

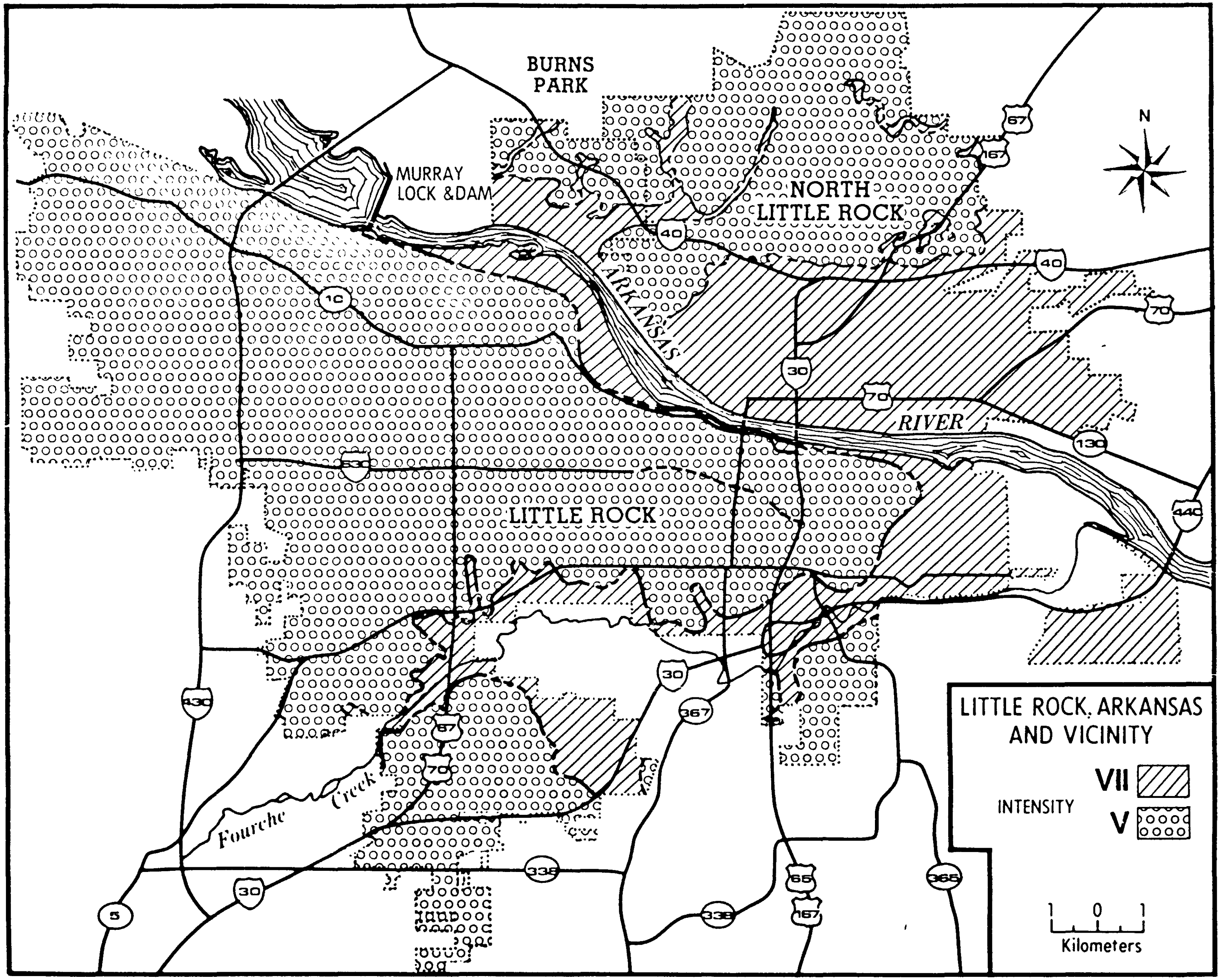


Figure 27.--Map of hypothetical maximum intensities for Little Rock, Arkansas, for a magnitude M_s=7.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the south end of the New Madrid seismic zone, intensities projected for Little Rock are: VII M.M. on the river alluvium, but only V on the sandstones, shales, and limestones of the hills. For an epicenter near the north end of the New Madrid seismic zone, the intensities at Little Rock would be lower.

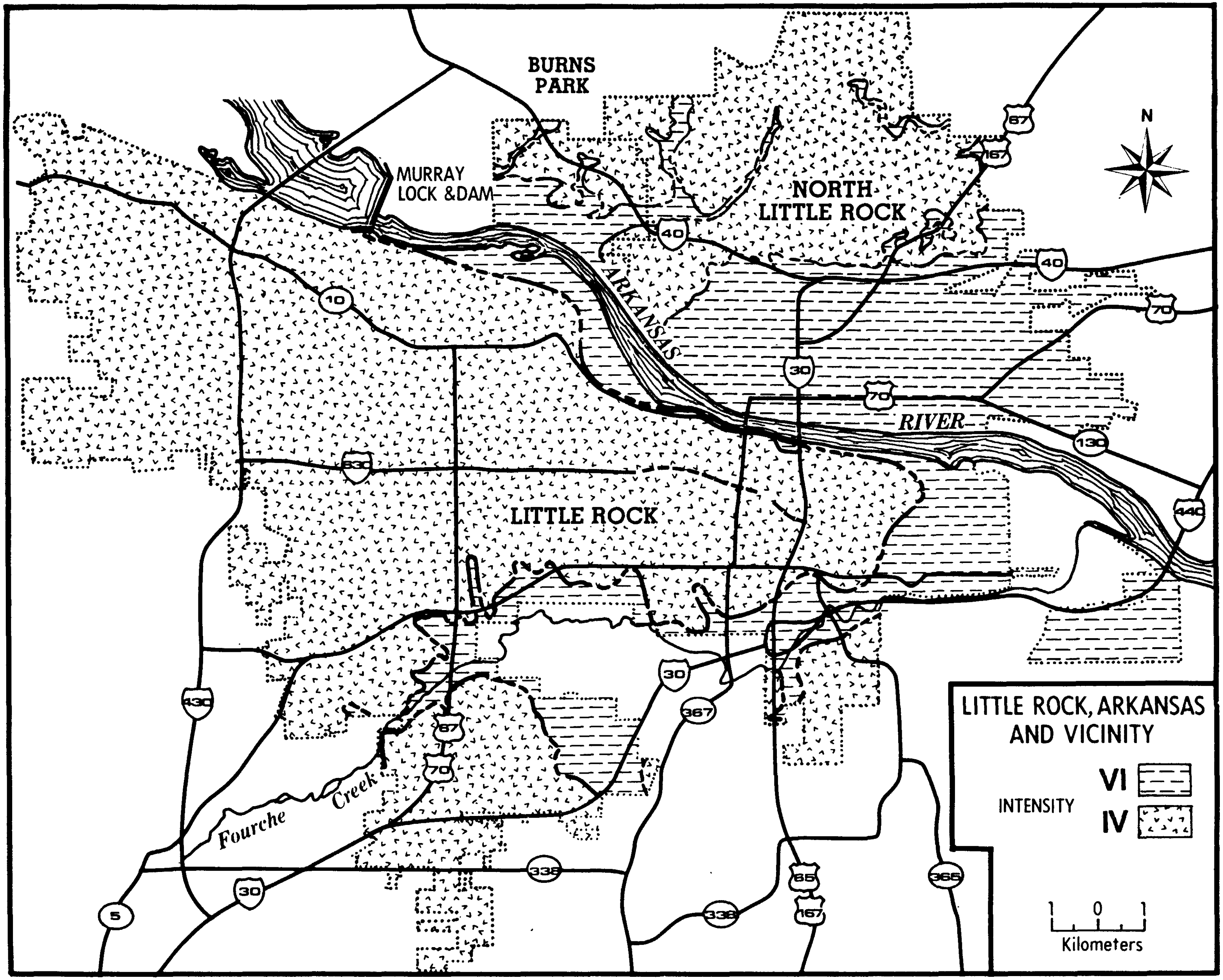


Figure 28.--Map of hypothetical maximum intensities for Little Rock, Arkansas, for a magnitude M_s=6.7 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the south end of the New Madrid seismic zone, intensities projected for Little Rock are: VI M.M. on the river alluvium, but only IV on the sandstones, shales, and limestones of the hills. For an epicenter near the north end of the New Madrid seismic zone, the intensities at Little Rock would be lower.

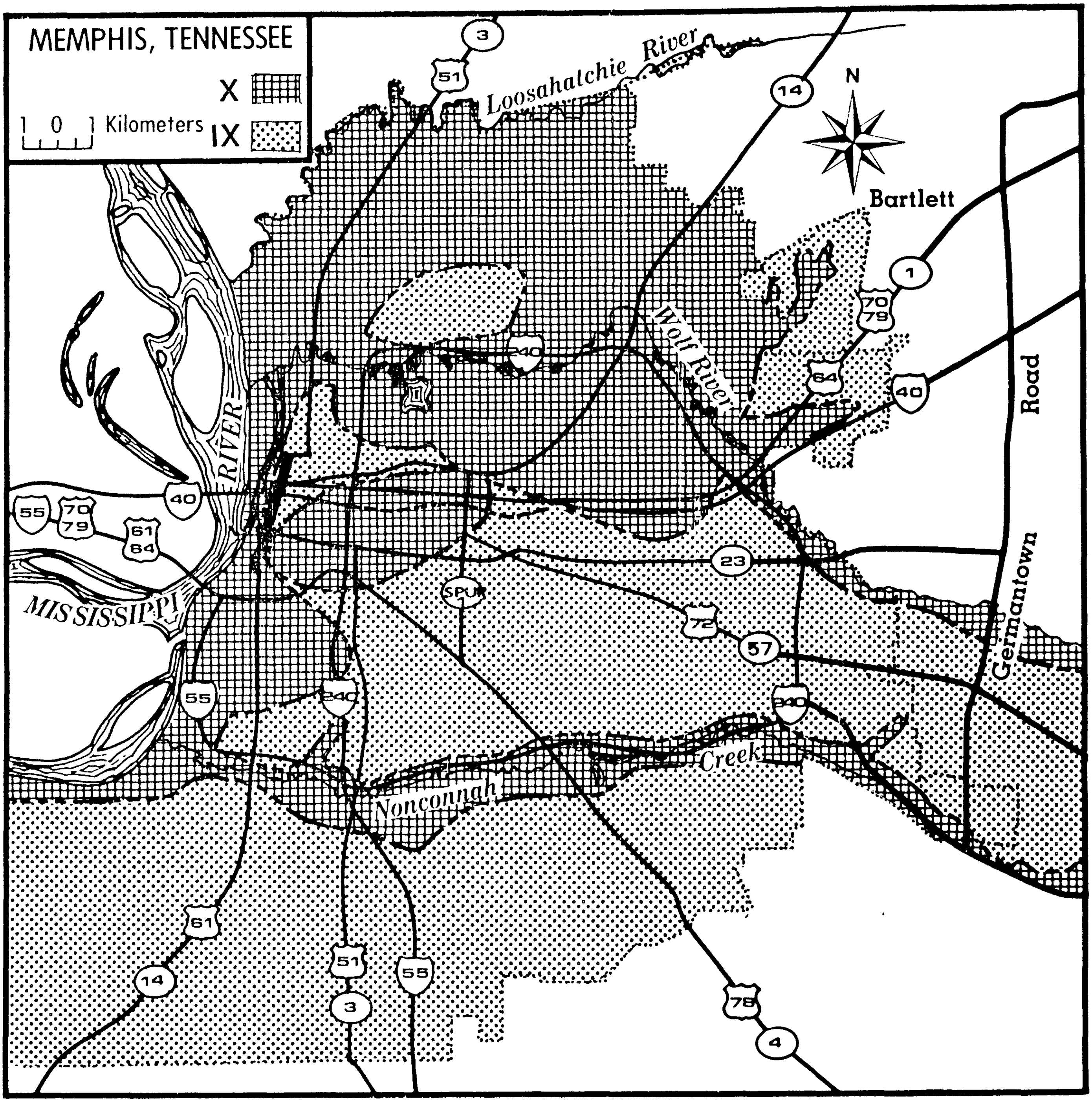


Figure 29.--Map of hypothetical maximum intensities for Memphis, Tennessee, for a magnitude M_s=8.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the south end of the New Madrid seismic zone, intensities projected for Memphis are: X M.M. in the alluvial valleys and in the areas found by Sharma and Kovacs (1980) to have high amplification factors (figure 44) or to be susceptible to liquefaction (figure 43), and IX in the rest of the city. For an epicenter near the north end of the New Madrid seismic zone, the intensities at Memphis would be lower.

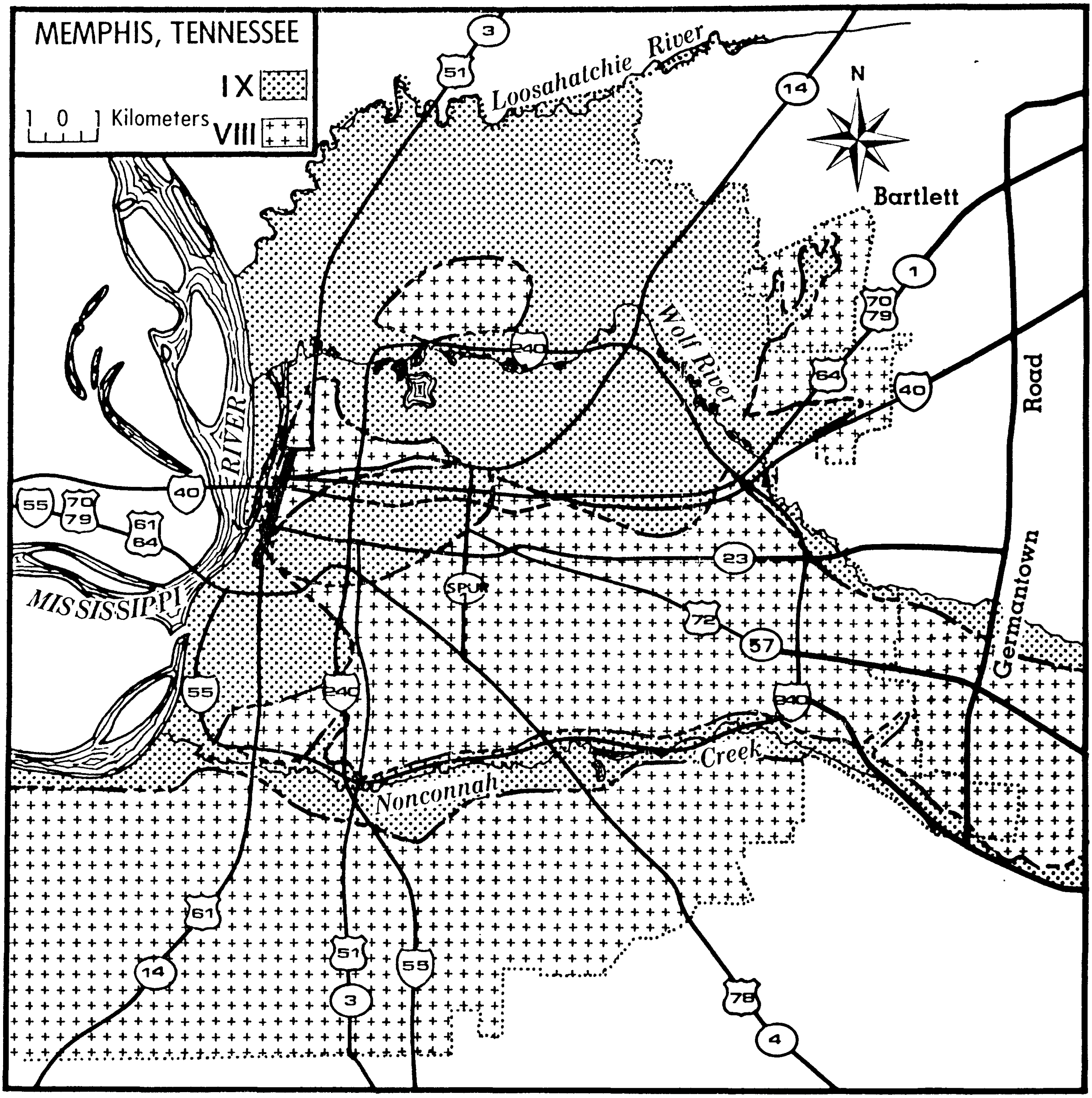


Figure 30.--Map of hypothetical maximum intensities for Memphis, Tennessee, for a magnitude M_s=7.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the south end of the New Madrid seismic zone, intensities projected for Memphis are: IX M.M. in the alluvial valleys and in the areas found by Sharma and Kovacs (1980) to have high amplification factors (figure 44) or to be susceptible to liquefaction (figure 43), and VIII in the rest of the city. For an epicenter near the north end of the New Madrid seismic zone, the intensities at Memphis would be lower.

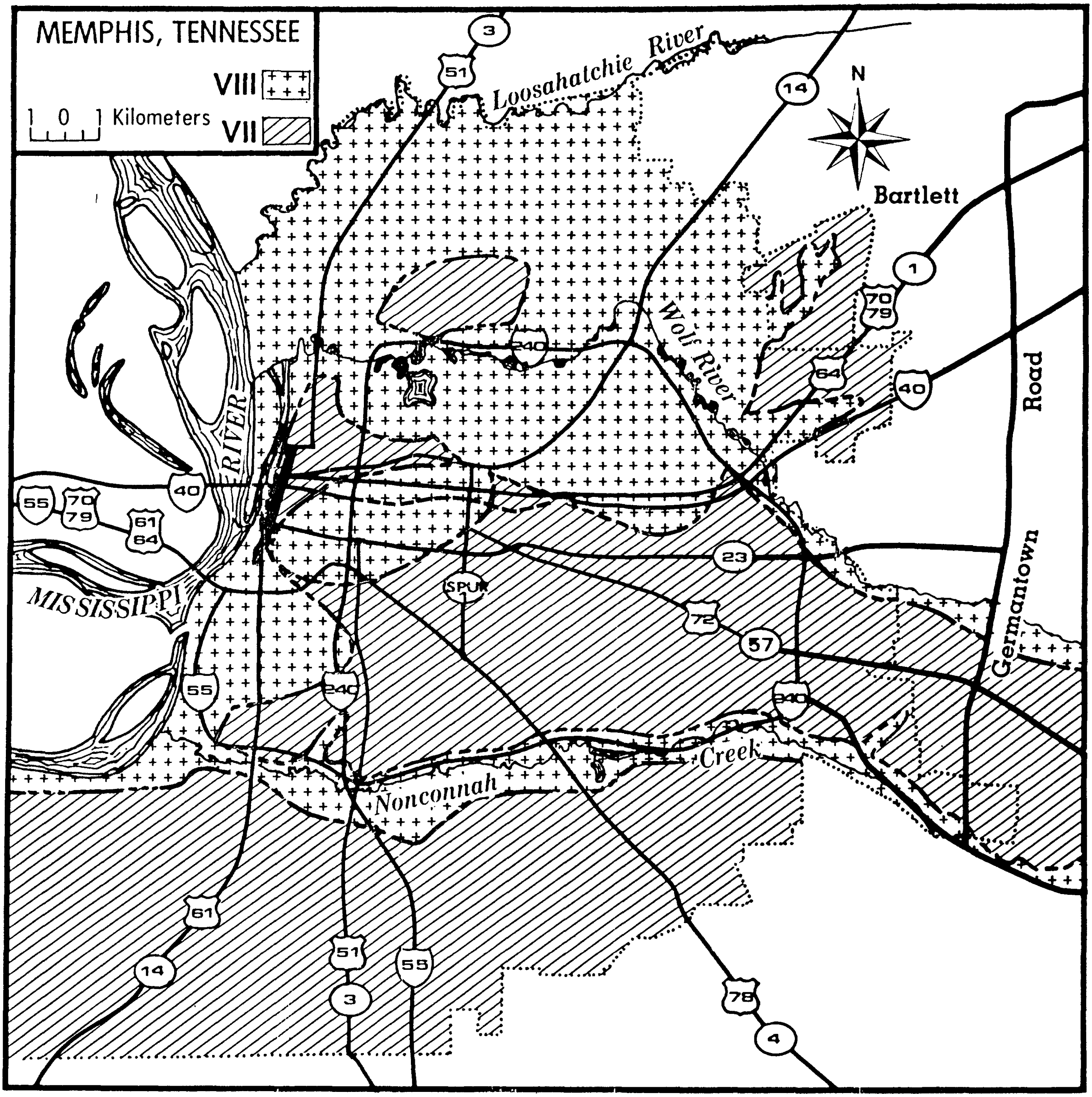


Figure 31.--Map of hypothetical maximum intensities for Memphis, Tennessee, for a magnitude M_s=6.7 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the south end of the New Madrid seismic zone, intensities projected for Memphis are: VIII M.M. in the alluvial valleys and in the areas found by Sharma and Kovacs (1980) to have high amplification factors (figure 44) or to be susceptible to liquefaction (figure 43), and VII in the rest of the city. For an epicenter near the north end of the New Madrid seismic zone, the intensities at Memphis would be lower.

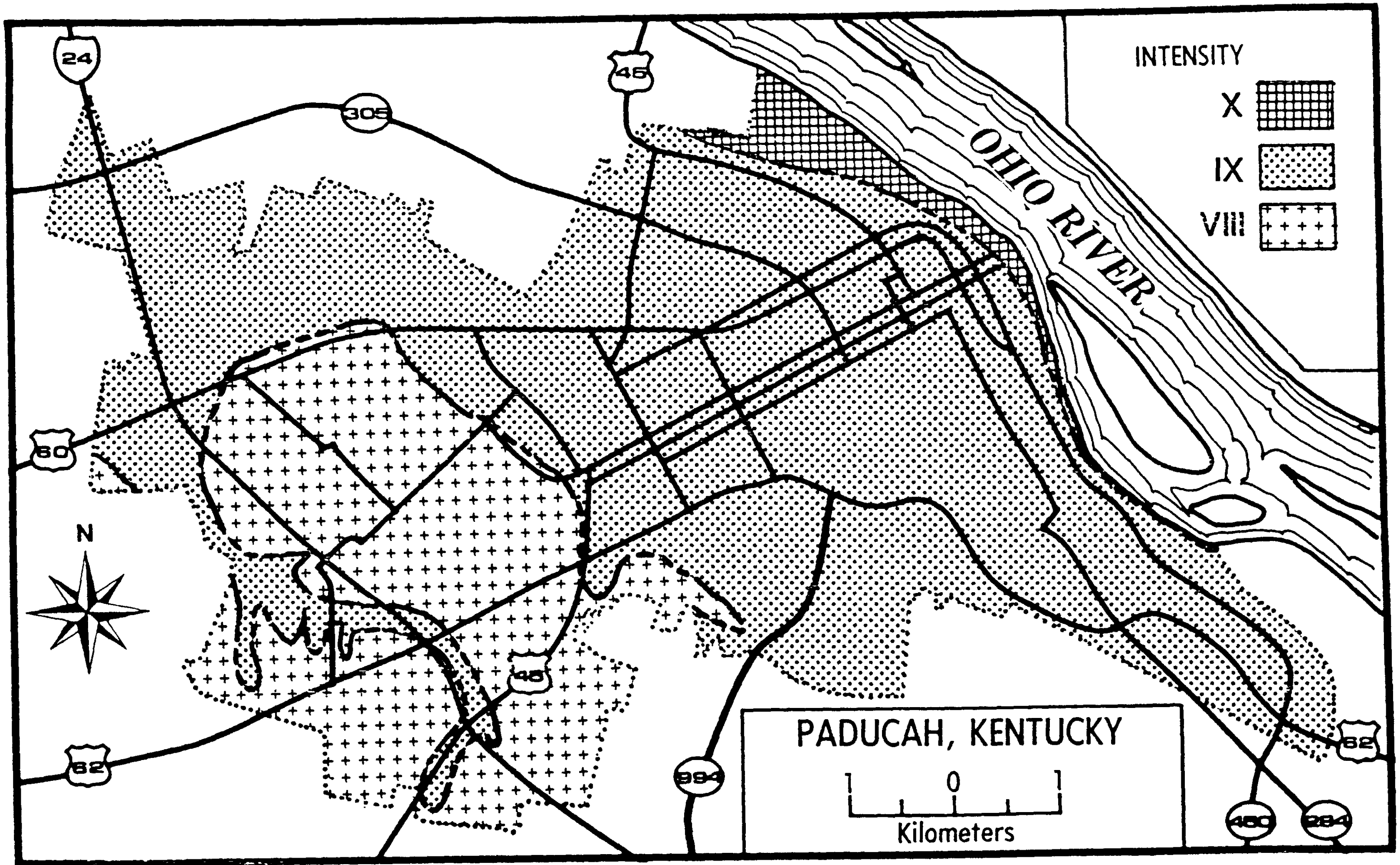


Figure 32.--Map of hypothetical maximum intensities map for Paducah, Kentucky, for a magnitude M_S=8.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Paducah are: X M.M. on the river alluvium, IX on the lacustrine deposits underlying most of the city, and VIII in the hills southwest of the city. For an epicenter near the south end of the New Madrid seismic zone, the intensities at Paducah would be lower.

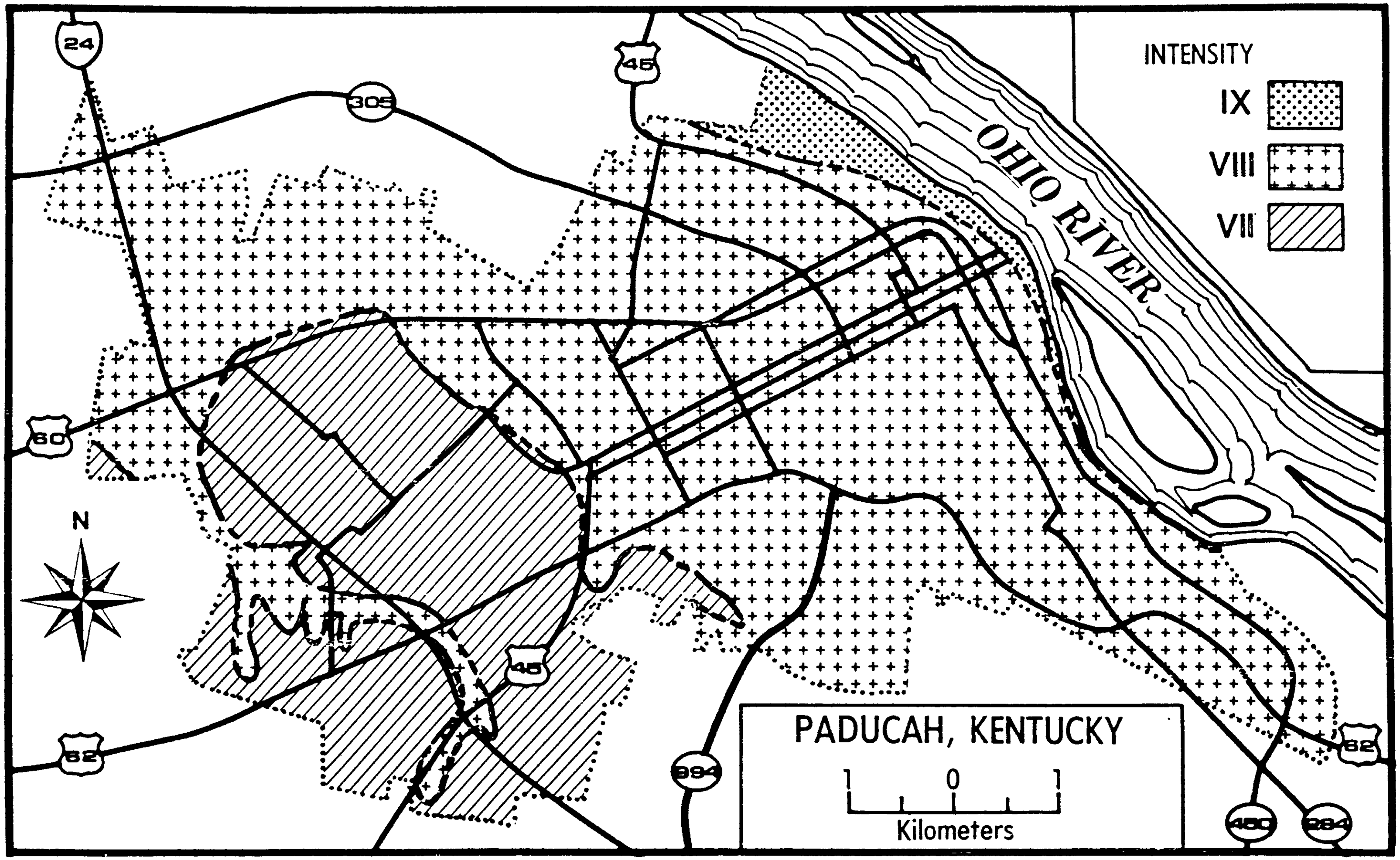


Figure 33.--Map of hypothetical maximum intensities map for Paducah, Kentucky, for a magnitude M_S=7.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Paducah are: IX M.M. on the river alluvium, VIII on the lacustrine deposits underlying most of the city, and VII in the hills southwest of the city. For an epicenter near the south end of the New Madrid seismic zone, the intensities at Paducah would be lower.

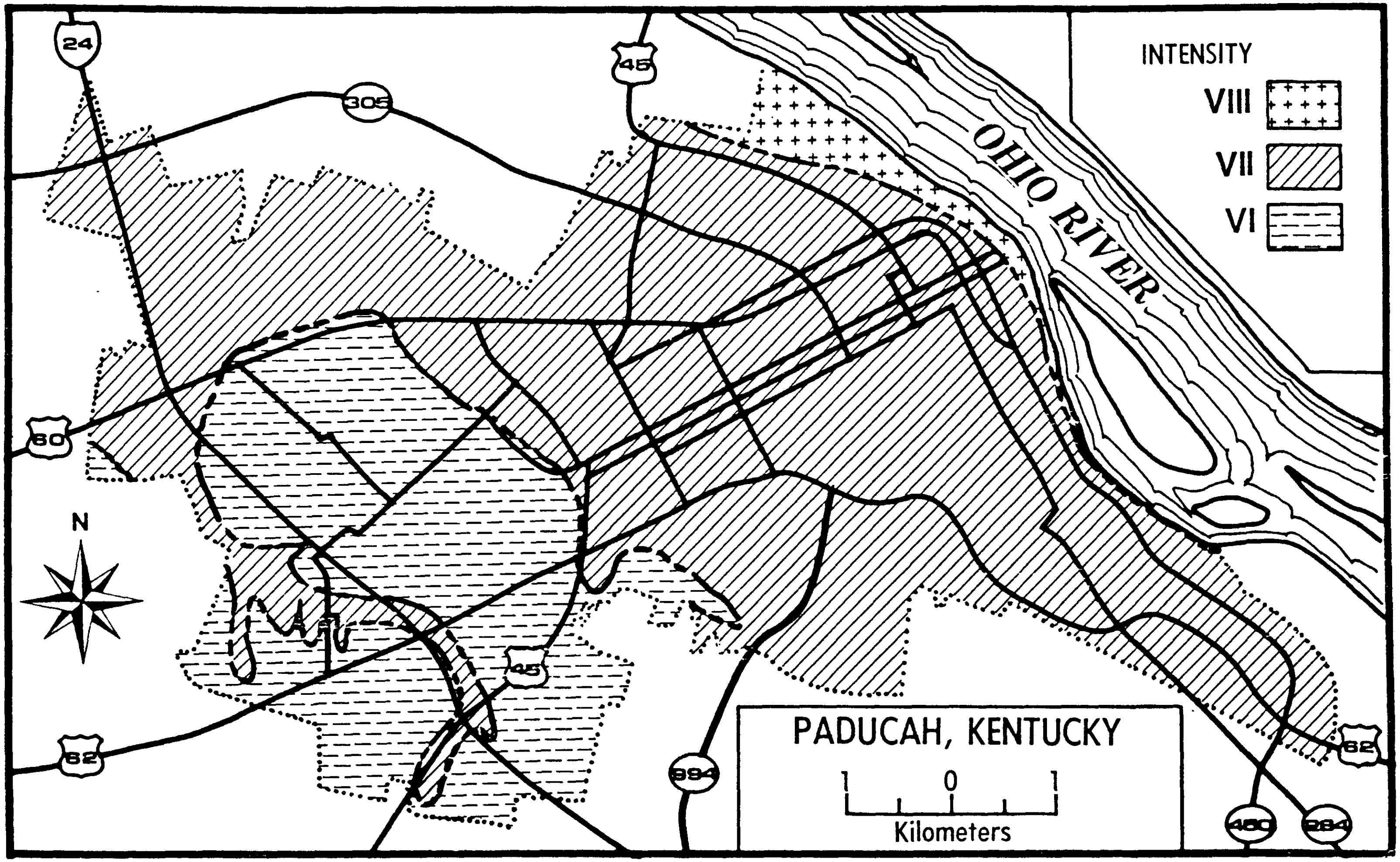


Figure 34.--Map of hypothetical maximum intensities map for Paducah, Kentucky, for a magnitude M_S=6.7 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Paducah are: VIII M.M. on the river alluvium, VII on the lacustrine deposits underlying most of the city, and VI in the hills southwest of the city. For an epicenter near the south end of the New Madrid seismic zone, the intensities at Paducah would be lower.

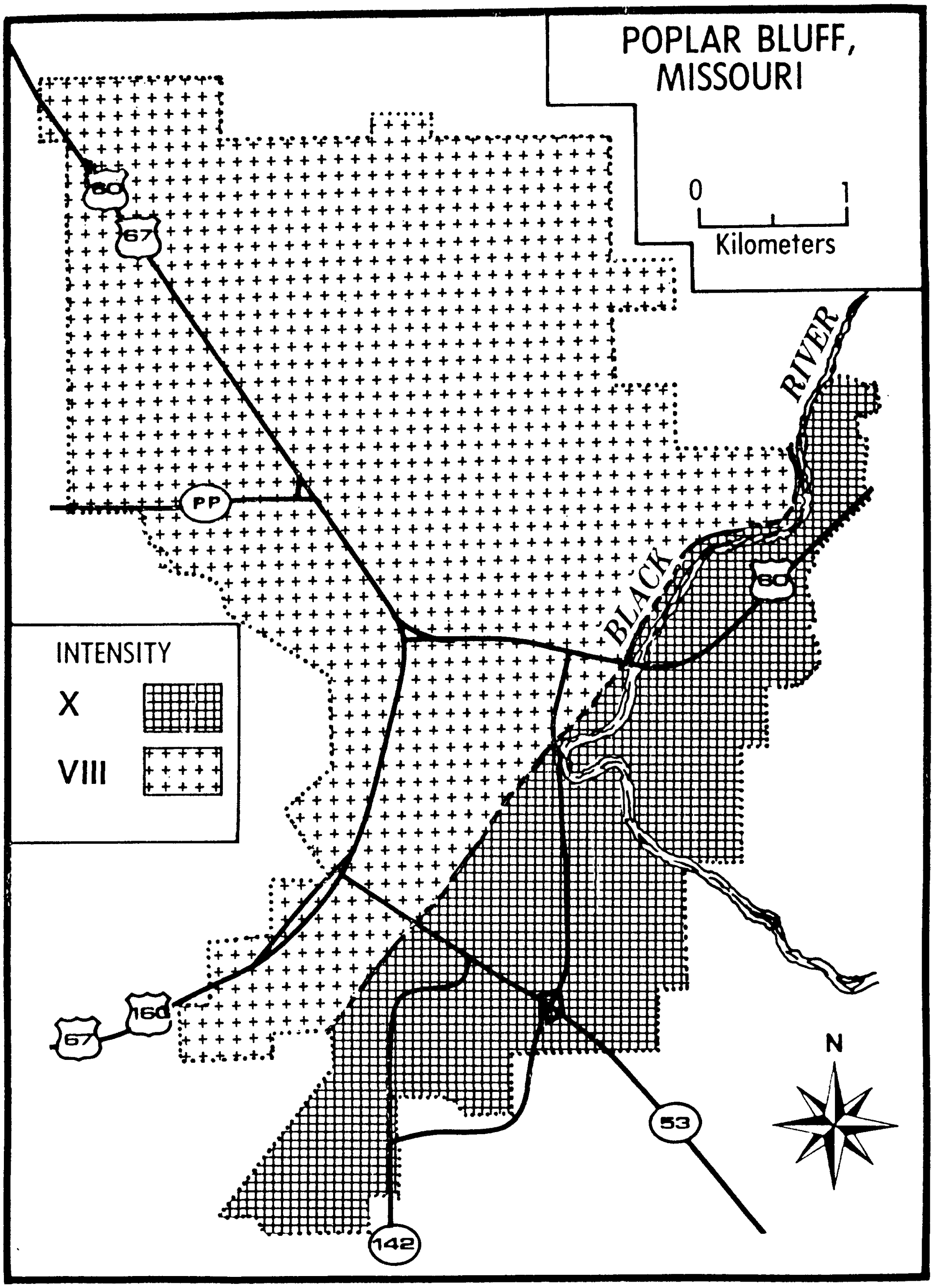


Figure 35.--Map of hypothetical maximum intensities for Poplar Bluff, Missouri, for a magnitude M_s=8.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Poplar Bluff are: X M.M. on the Mississippi flood plain southeast of the city, but only VIII on the uplands to the northwest. For an epicenter near the south end of the New Madrid seismic zone, the intensities at Poplar Bluff would be lower.

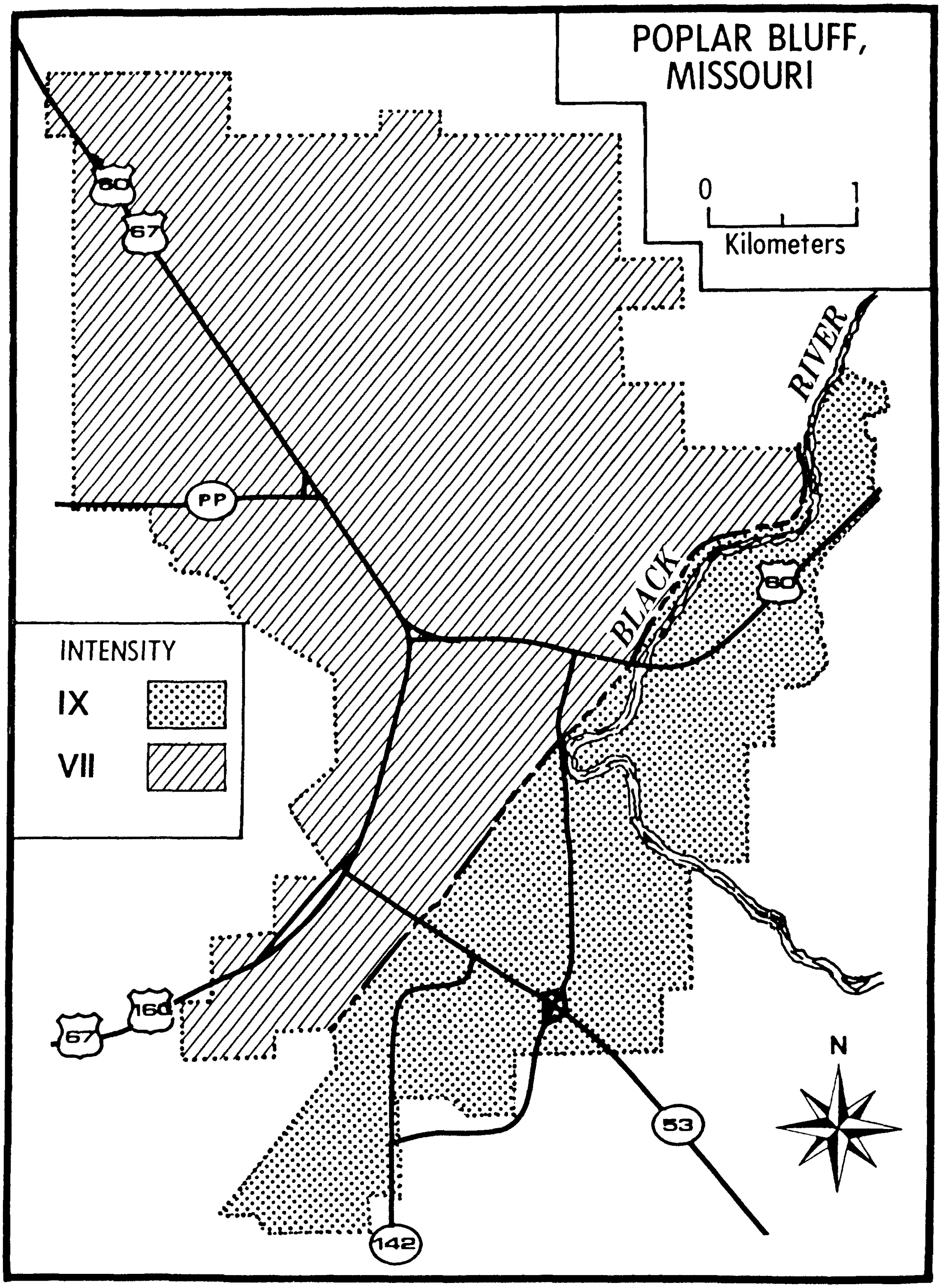


Figure 36.--Map of hypothetical maximum intensities for Poplar Bluff, Missouri, for a magnitude M_s=7.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Poplar Bluff are: IX M.M. on the Mississippi flood plain southeast of the city, but only VII on the uplands to the northwest. For an epicenter near the south end of the New Madrid seismic zone, the intensities at Poplar Bluff would be lower.

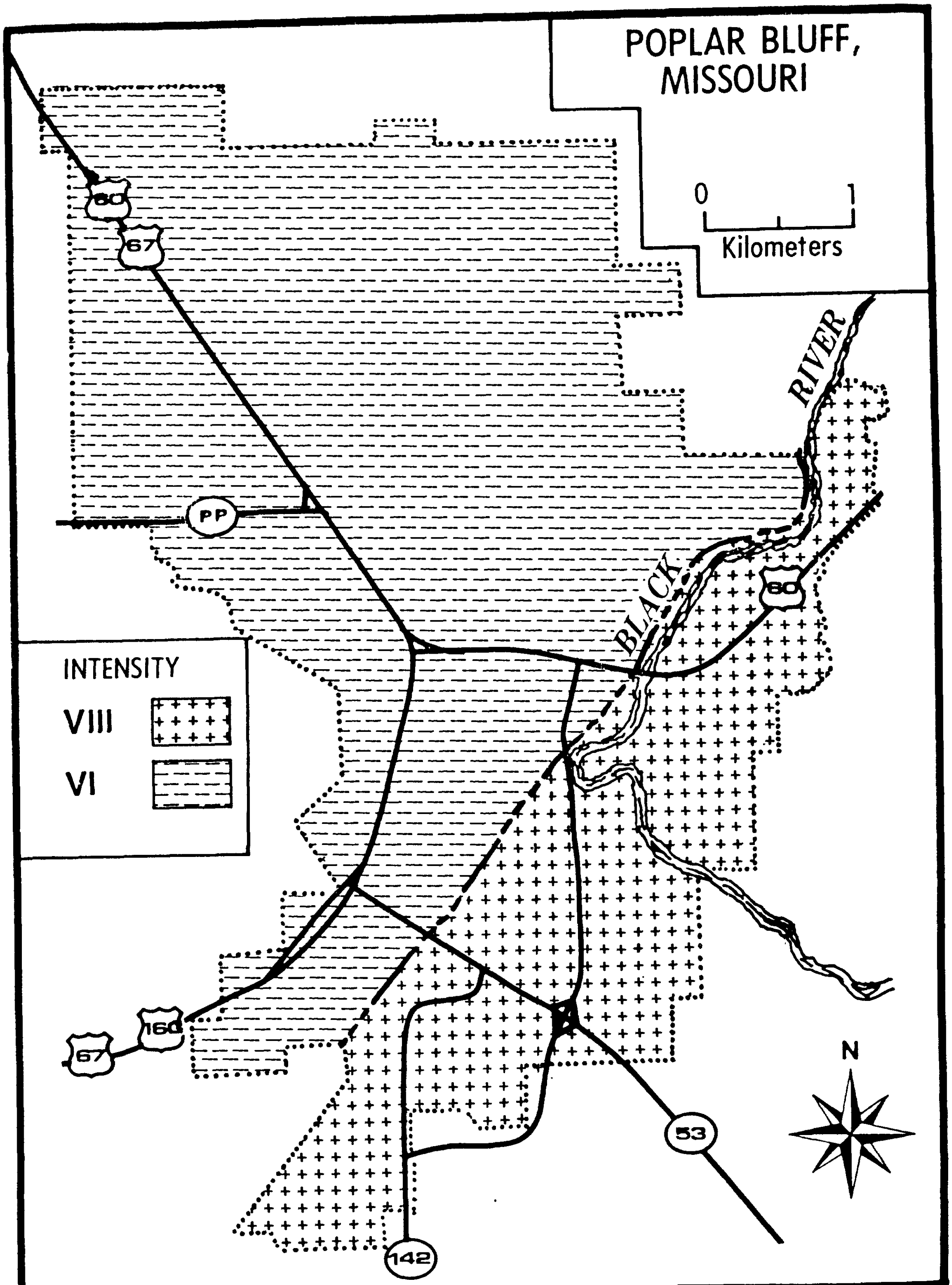


Figure 37.--Map of hypothetical maximum intensities for Poplar Bluff, Missouri, for a magnitude M_s=6.7 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Poplar Bluff are: VIII M.M. on the Mississippi flood plain southeast of the city, but only VI on the uplands to the northwest. For an epicenter near the south end of the New Madrid seismic zone, the intensities at Poplar Bluff would be lower.

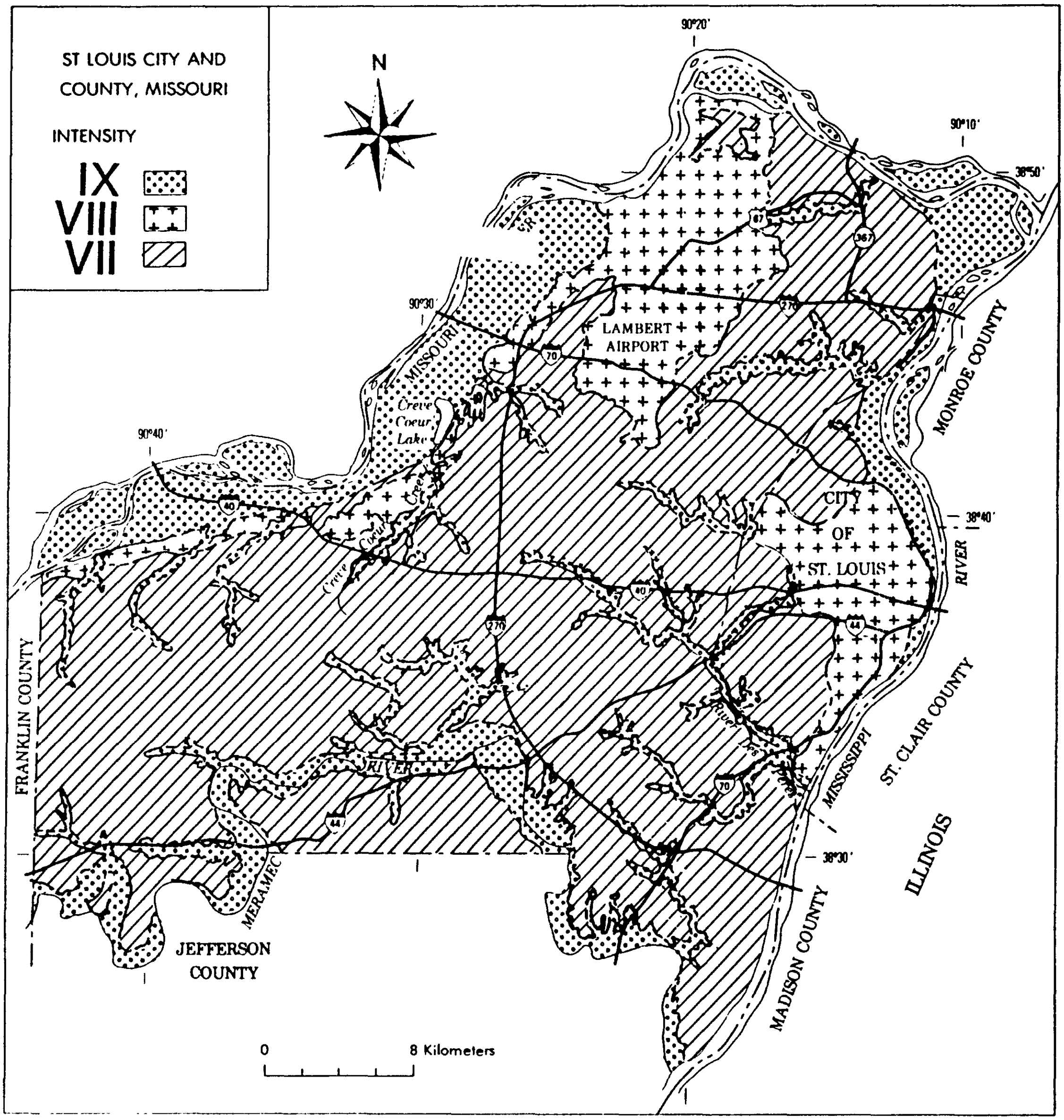


Figure 38.--Map of hypothetical maximum intensities for Saint Louis, Missouri, for a magnitude M_s=8.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Saint Louis are: IX along the flood plain alluvium and low alluvial terraces of the Mississippi, Missouri, and Meramec Rivers; VIII in areas of uncontrolled fill, in areas of steep loess slopes, and on the high lake terrace (Lambert Airport area); and VII in the rest of the county. For an epicenter near the south end of the New Madrid seismic zone, the intensities at Saint Louis would be lower.

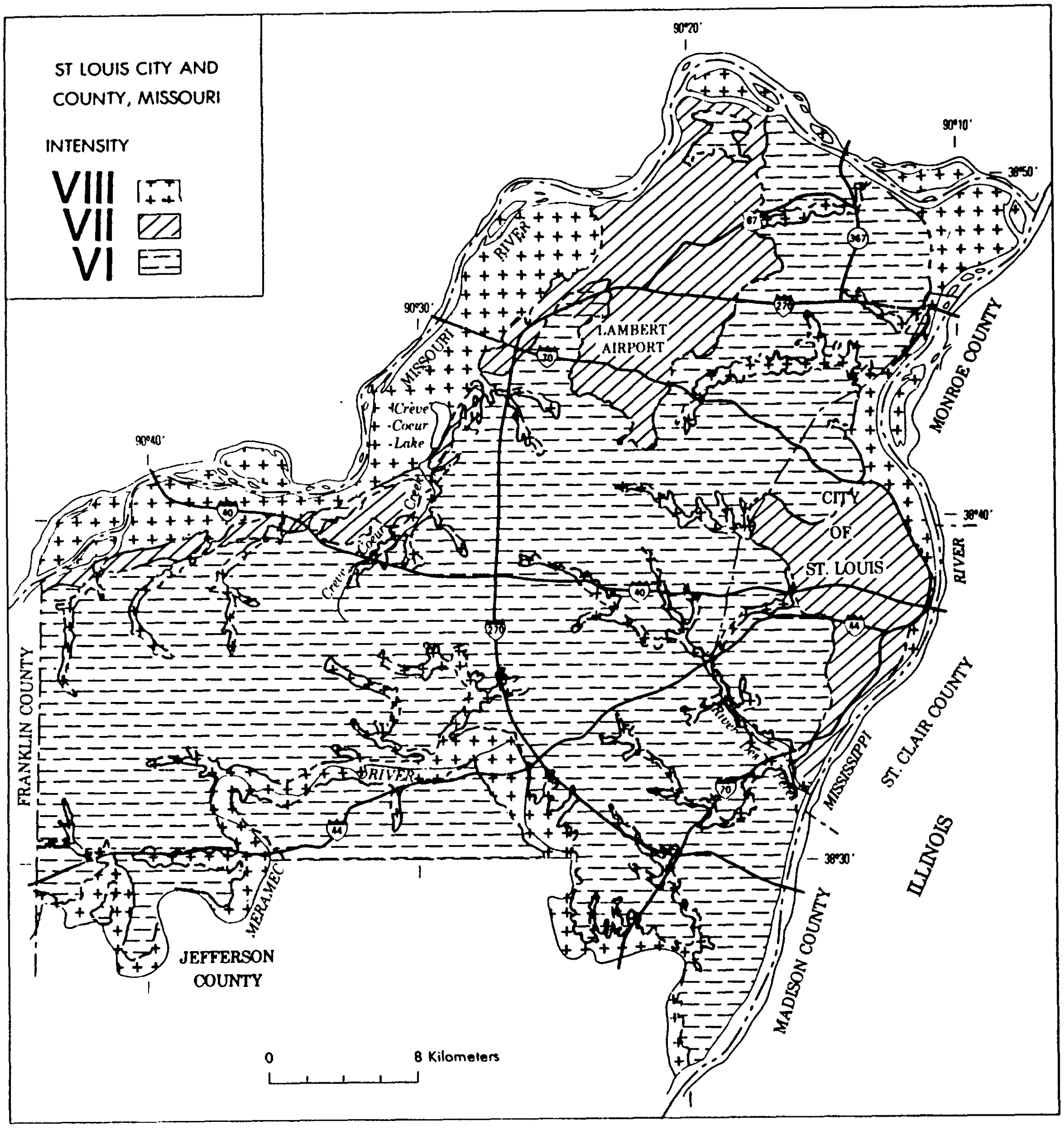


Figure 39.--Map of hypothetical maximum intensities for Saint Louis, Missouri, for a magnitude M_s=7.6 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Saint Louis are: VIII along the flood plain alluvium and low alluvial terraces of the Mississippi, Missouri, and Meramec Rivers; VII in areas of uncontrolled fill, in areas of steep loess slopes, and on the high lake terrace (Lambert Airport area); and VI in the rest of the county. For an epicenter near the south end of the New Madrid seismic zone, the intensities at Saint Louis would be lower.

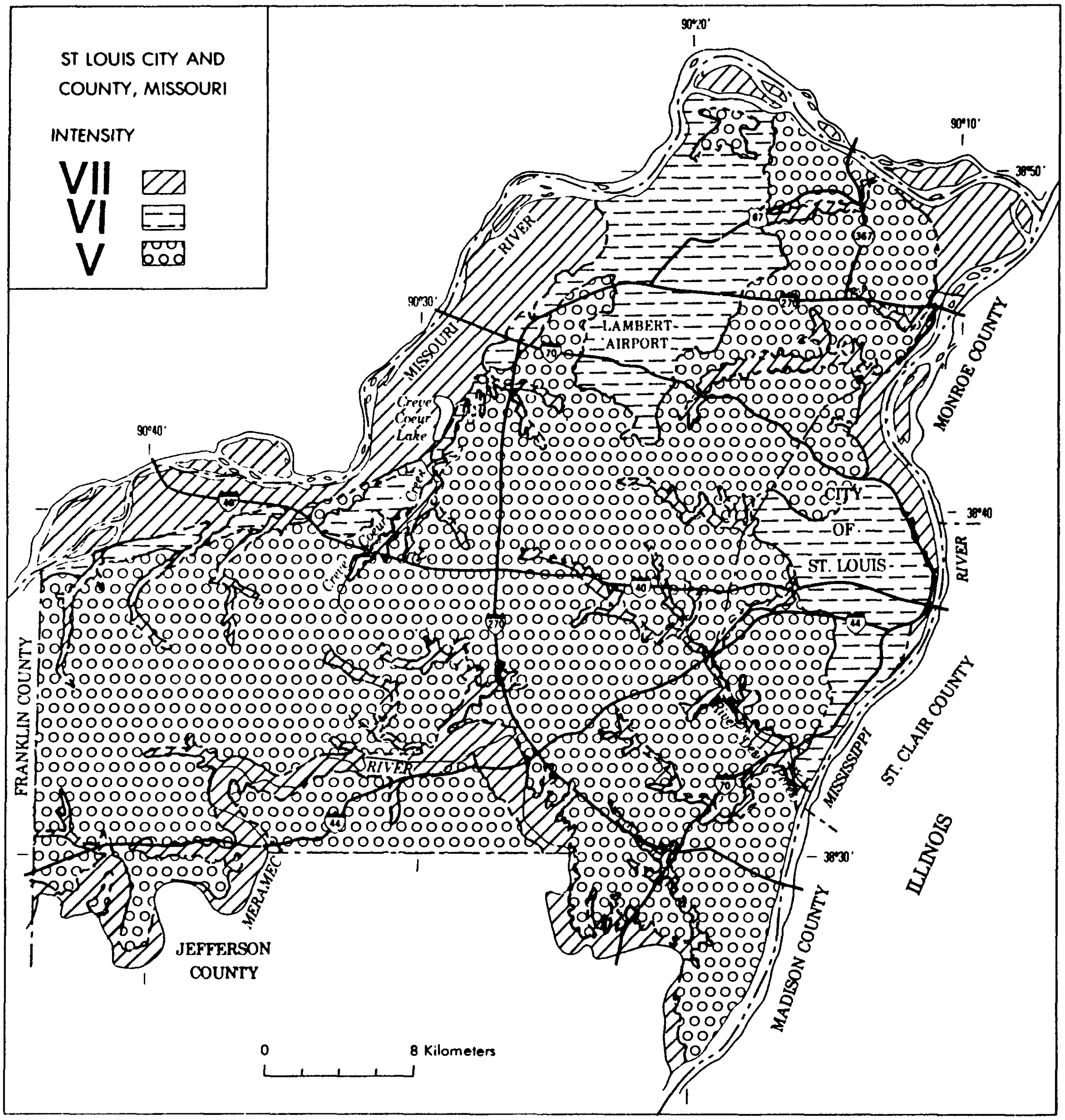


Figure 40.--Map of hypothetical maximum intensities for Saint Louis, Missouri, for a magnitude M_s=6.7 earthquake anywhere along the New Madrid seismic zone. For an actual epicenter near the north end of the New Madrid seismic zone, intensities projected for Saint Louis are: VII along the flood plain alluvium and low alluvial terraces of the Mississippi, Missouri, and Meramec Rivers; VI in areas of uncontrolled fill, in areas of steep loess slopes, and on the high lake terrace (Lambert Airport area); and V in the rest of the county. For an epicenter near the south end of the New Madrid seismic zone, the intensities at Saint Louis would be lower.

plain than on the uplands. Finally, geologic conditions at Evansville (figures 23-25) and Memphis (figures 29-31) suggest a difference of one intensity level.

Each of the seven cities is discussed in more detail below.

ESTIMATION OF INTENSITIES AT CARBONDALE, ILLINOIS

Physiographic Description

Carbondale is situated in the till plains of the Central Lowland province (Fenneman, 1938) in an area of very low topographic relief.

Underlying material

The northern part of the city is underlain by lake deposits consisting of well-bedded silt and some clay; the southern part is underlain by hard, silty, sandy, and clayey till with some sand and gravel (Lineback, 1979). These deposits are probably at least 50 feet (15 m) thick and overlie interbedded sandstone, shale, limestone and coal of Pennsylvanian age (Williams and others, 1967).

Physical Property Tests and Other Information

Selected standard penetration tests (18 inch drop of a 40-lb hammer) show N values that range from 9 blows/foot near the surface to 40 at depths of 50 feet (15 m) (Pulley, Gary, Assistant Soils Engineer, Illinois Department of Transportation, Carbondale, Illinois, oral communication, September 15, 1982). (In shallow alluvium N values are generally about 10; in denser materials N values are higher. Liquefaction potential is highest at low N values.)

Potential for Landslides, Liquefaction, and Other Geologic Effects

Landslides:

Landslides in response to strong earthquakes are unlikely.

Liquefaction:

The liquefaction potential is low.

Hypothetical Intensity Maps for Carbondale

The highest projected intensity at Carbondale is IX M.M. from the regional map for the magnitude M_s = 8.6 earthquake (figure 14). This intensity would occur for that earthquake anywhere near the north end of the New Madrid seismic zone. Carbondale would experience only intensity VIII for a magnitude-8.6 (M_s) earthquake near the south end of the seismic zone. The smaller projected earthquakes would produce intensities of VIII M.M. (M_s = 7.6 shock) and VII (M_s = 6.7 shock) for epicenters near the north end of the seismic zone. The 1895 epicenter (on which the hypothetical intensities are based) is only 81 km from Carbondale (see table 4 and Appendix 2), accounting for the high intensity projected there; there is no information about what happened in Carbondale in 1895. Although the 1968 earthquake is closer (69 km) to Carbondale, and overturned oil tanks in Carbondale (Coffman and Cloud, 1970), it is not in the New Madrid seismic zone, and earthquakes of the largest sizes studied here (M_s = 8.6 and 7.6) are not deemed likely at the 1968 epicenter.

The seismic zonation of Carbondale is based primarily on the site geologic conditions. Although different geologic units can be differentiated at the surface, they are not deemed significantly different with respect to intensity values. Nor are landslides or liquefaction effects particularly likely at Carbondale. Thus the map of Carbondale shows only one Modified Mercalli intensity value. Again note that this is the highest projected intensity, and that every building in Carbondale is not expected to be damaged at the highest intensity level. Some buildings will not be damaged at all. Rather, the most significant damage will be at this level.

ESTIMATION OF INTENSITIES AT EVANSVILLE, INDIANA

Physiographic Description

Evansville is situated along the Ohio River in the Interior Low Plateaus province (Fenneman, 1938). Topographic relief within the city proper is low; some of the banks along the Ohio River are steep.

Underlying Material

Much of the city is underlain by lake deposits consisting of clay, silt, and sand that are Pleistocene in age (Gray and others, 1970); Recent alluvium occurs along the flood plain of the Ohio River; thickness of these materials was not given in the data reviewed, but is inferred to be in the tens of feet rather than in the hundreds of feet. Beneath these surficial materials are well indurated shale, sandstone, limestone and some coal belonging to the McLeansboro Group of Pennsylvanian age.

Physical Property Tests and Other Information

Specific test data were not available as of this writing. However, test data is available in the files of private consulting firms. According to Richard Eifler, (City Engineer, oral communication, 1982) landslides are not a problem throughout most of the city; however, along the river bluff near Reitz School oversteepening of a side hill cut during railroad and highway construction caused a landslide.

Potential for Landslides, Liquefaction, and Other Geologic Effects

Landslides:

A strong earthquake probably would not cause landslides throughout most of the city; however, landslides probably would occur along the steeper bluffs adjacent to the Ohio River. Some compaction and differential settlement of flood plain alluvium probably would also occur.

Liquefaction:

While a liquefaction potential exists throughout much of the city, it is low and would be localized; the liquefaction potential in the alluvium along the Ohio River flood plain is probably high.

Hypothetical Intensity Maps for Evansville

The highest projected intensities at Evansville are VIII and IX M.M., for a magnitude-8.6 earthquake near the north end of the New Madrid seismic zone (figures 14 and 23). An earthquake near the south end of the seismic zone would produce only VII and VIII at Evansville for the same shock. The smaller projected earthquakes would produce intensities of VII and VIII M.M. (M_s = 7.6 shock) and VI and VII (M_s = 6.7 shock) for epicenters near the north end of the seismic zone. Evansville is approximately 200-400 km away from earthquakes located along the New Madrid seismic zone (table 4 and Appendix 3), and there are no reports for Evansville from any of the larger earthquakes in the zone, except that the 1895 earthquake was felt. Also, there was slight damage (VI) from the nearby (81 km) 1968 earthquake north of the New Madrid seismic zone.

The higher of the two projected intensities at Evansville follows the alluvium of the Ohio River flood plain and its tributary. In this area liquefaction is a strong possibility in the event of either the M_s = 8.6 or M_s = 7.6 shock along the northern end of the New Madrid seismic zone. Also in this area, landslides might occur along the bluffs overlooking the Ohio River. The potential for liquefaction and landslides, as well as for vibration damage, is less on the lake sediments of the rest of the city, the area shown on figure 23 as VIII.

ESTIMATION OF INTENSITIES AT LITTLE ROCK AND NORTH LITTLE ROCK, ARKANSAS

Physiographic Description

Little Rock and North Little Rock are situated on the border between the Ouachita province and the Mississippi Alluvial Plain (Fenneman, 1938). Most of the metropolitan area is located along the Arkansas River, west of the Mississippi Alluvial Plain, and north of Fourche Creek in the subdued topography of the Ouachita Mountains. Within the metropolitan area these mountains have a total topographic relief of about 150 feet (46 m) above the Arkansas River. By comparison the Mississippi Alluvial Plain and the Arkansas River flood plain exhibit little topographic relief.

Underlying Material

Most of Little Rock and North Little Rock are underlain by the Jackfork Sandstone of Pennsylvanian age (Haley and others, 1976); some shale is interbedded with the sandstone and a fairly thick shale bed is present at the base of the bluff along the Arkansas River near the Murry Lock and Dam. These rocks have been intricately thrust faulted; the faults are inactive; most of them trend east-southeast and the attitudes of the beds vary over short distances.

A part of Little Rock north of Fourche Creek is underlain by Tertiary age interbedded sand, calcareous clay, limestone, silty clay, and silt of the Midway and Wilcox Groups (Haley and others, 1976, and Gordon and others, 1958); these materials are here about 65 feet (20 m) thick. In North Little Rock, most of the city north of I-40 is underlain by Pennsylvanian age shale and sandstone, of the Jackfork Sandstone.

Along the Arkansas River and where it passes into the Mississippi alluvial plain the underlying material generally consists of dense silty sand, sand, silty clay, and gravel.

Residual soils developed on the Jackfork Sandstone are a gravelly silt loam, shallow to fairly deep, and moderately permeable; soils developed on the Wilcox and Midway Groups are a silty to sandy loam, shallow to fairly deep, and slowly to moderately permeable (Haley and others, 1975, and Soil Conservation Service, 1967).

Physical Property Tests and Other Information

Well logs of three test hole borings were provided by Mr. Jake Clements (Engineer with the Materials and Tests Division, Arkansas Highway Department, Little Rock, unpub. data, 1982). Two logs at the Arkansas River crossing of I-440 indicate that the material consists mainly of silty sand in the upper 20 to 30 feet (6 to 9 m) and sand and gravel below that to the depths of the holes, which terminated at 62 feet (18.9 m) and 110 feet (33.5 m); the material is nonplastic, and N values for standard penetration tests range from about 10 in the upper part to 32 and 52 in the lower parts. The log in alluvium along Fourche Creek east of the intersection with U.S. Highway 65 consists mainly of silty clay, and sand and gravel near the bottom of the hole at a depth of 55-60 feet (17-18 m); N values are variable; they range from 5 to 10 in the upper part and 41 in the lower 5 feet (1.5 m) of the test section.

According to Mr. William Bush (Geologist, Arkansas Geological Commission, oral communication, 1982) landslides are a minor problem in the vicinity of Little Rock. A landslide occurred at the south end of High Street north of the Chicago, Rock Island and Pacific railroad tracks; it was caused by oversteepening of an artifical cut (Michael Batie, City Engineer, Little Rock, oral communication, 1982). There is also evidence of sloughing and minor landsliding in the bluff along the Arkansas River near the Murry Lock and Dam.

Geologic mapping in the vicinity of Little Rock has not revealed any surficial features that could be attributed to liquefaction (Boyd Haley and William Bush, oral communication, 1982).

Potential for Landslides, Liquefaction, and Other Geologic Effects

Landslides:

Landslides in response to strong earthquake vibrations are unlikely throughout most of the metropolitan area. However, sloughing and small landslides could occur along some of the steeper bluffs.

Liquefaction:

The liquefaction potential is very low for the part of the metropolitan area underlain by the Jackfork Sandstone and by units of the Midway and Wilcox Groups. The liquefaction potental is probably low to moderate for the part of the metropolitan area underlain by flood plain deposits of the Arkansas River and the Mississippi Alluvial Plain.

Hypothetical Intensity Maps for Little Rock and North Little Rock

At Little Rock and North Little Rock (figures 26-28) the hypothetical intensities change from the highest projected intensity (VIII M.M. for the $M_s = 8.6$ shock near the south end of the seismic zone) for river and stream alluvium to two intensity levels lower (VI for $M_s = 8.6$) for the neighboring sandstone, shale, and limestone hills of the rest of the city. The smaller projected earthquakes would produce intensities of VII and V ($M_s = 7.6$) and VI and IV ($M_s = 6.7$) for epicenters near the south end of the seismic zone. Little Rock is 170-360 km away from earthquakes in the New Madrid seismic zone, and experienced intensities of IV, V, and I-IV in 1843, 1895, and 1968 (Table 4 and Appendix 4). Earthquake-induced landslides are unlikely in Little Rock, although a few small ones might occur along some of the steeper bluffs in the event of the $M_s = 8.6$ earthquake. There is a moderate potential for liquefaction in the flood plain deposits (area shown as VIII in figure 26) during the projected $M_s = 8.6$ earthquake, although no geologic evidence of previous liquefaction in the area has been found. The projected $M_s = 7.6$ and 6.7 shocks would be unlikely to cause either liquefaction or serious (structural) damage at Little Rock.

ESTIMATION OF INTENSITIES AT MEMPHIS, TENNESSEE

Physiographic Description

Memphis (and Bartlett and Germantown) are situated in the Coastal Plain Province along the border between the East Gulf Coastal Plain and the Mississippi Alluvial Plain. The locally steep bluffs adjacent to the Mississippi River along the west edge of the city are 60 to 100 feet (18 to 30 m) high. Most of the metropolitan area is located south of Wolf River and north of Nonconnah Creek, an area of low topographic relief.

Underlying Material

A generalized description of the underlying materials in Memphis and vicinity is given in table 6 and an east-west geologic cross section through Memphis in figure 41. Both are from M & H Engineering and Memphis State University (1974).

Physical Property Tests and Other Information

The general locations for boreholes from which Sharma and Kovacs (1980) collected data are shown in figure 42. To protect confidentiality of the sources, exact locations of boreholes are omitted. By calculating relative

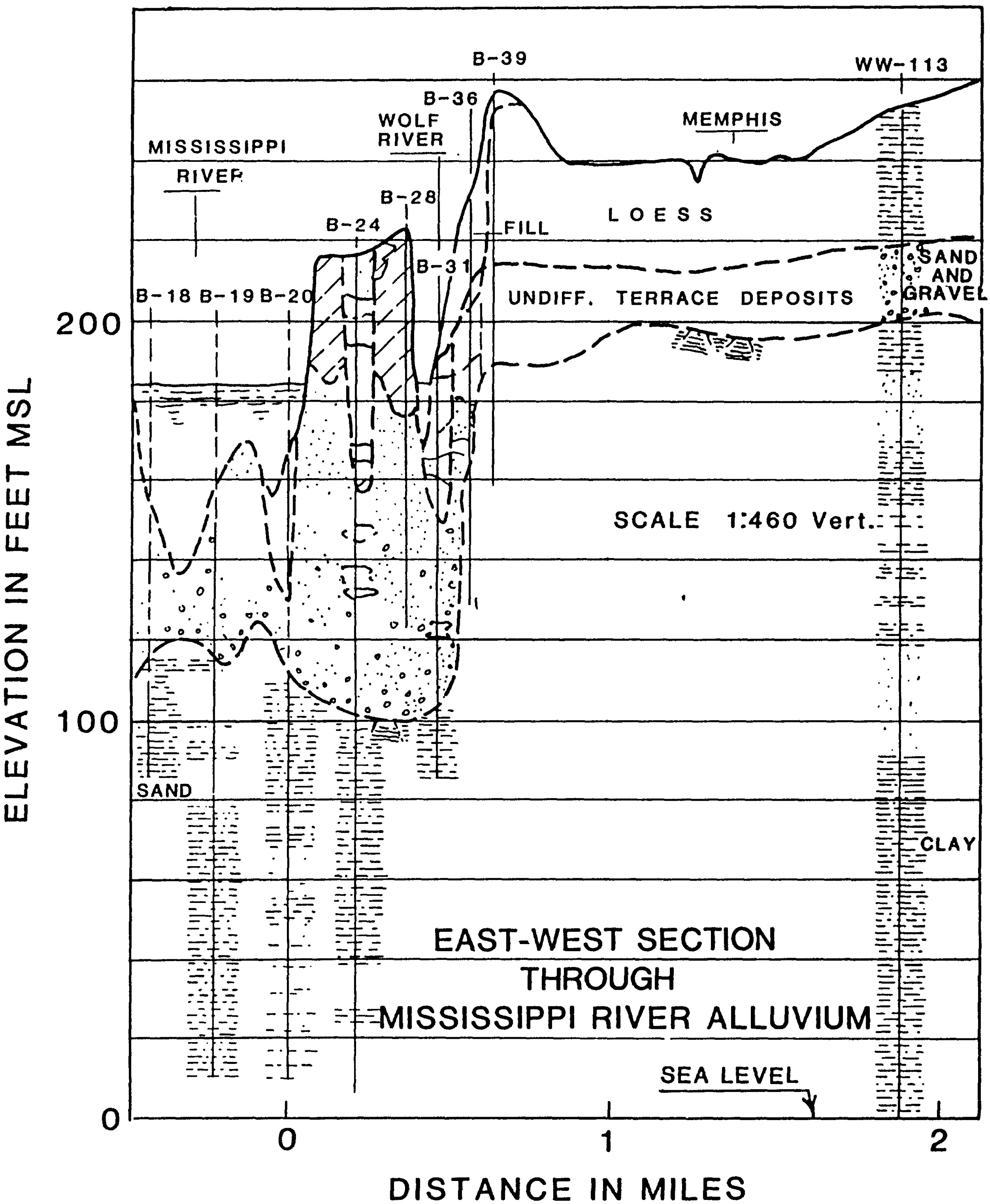


Figure 41.--East-west geologic cross section beneath Memphis, Tennessee. After Sharma and Kovacs (1980), who quote M. & H. Engineering and Memphis State University (1974).

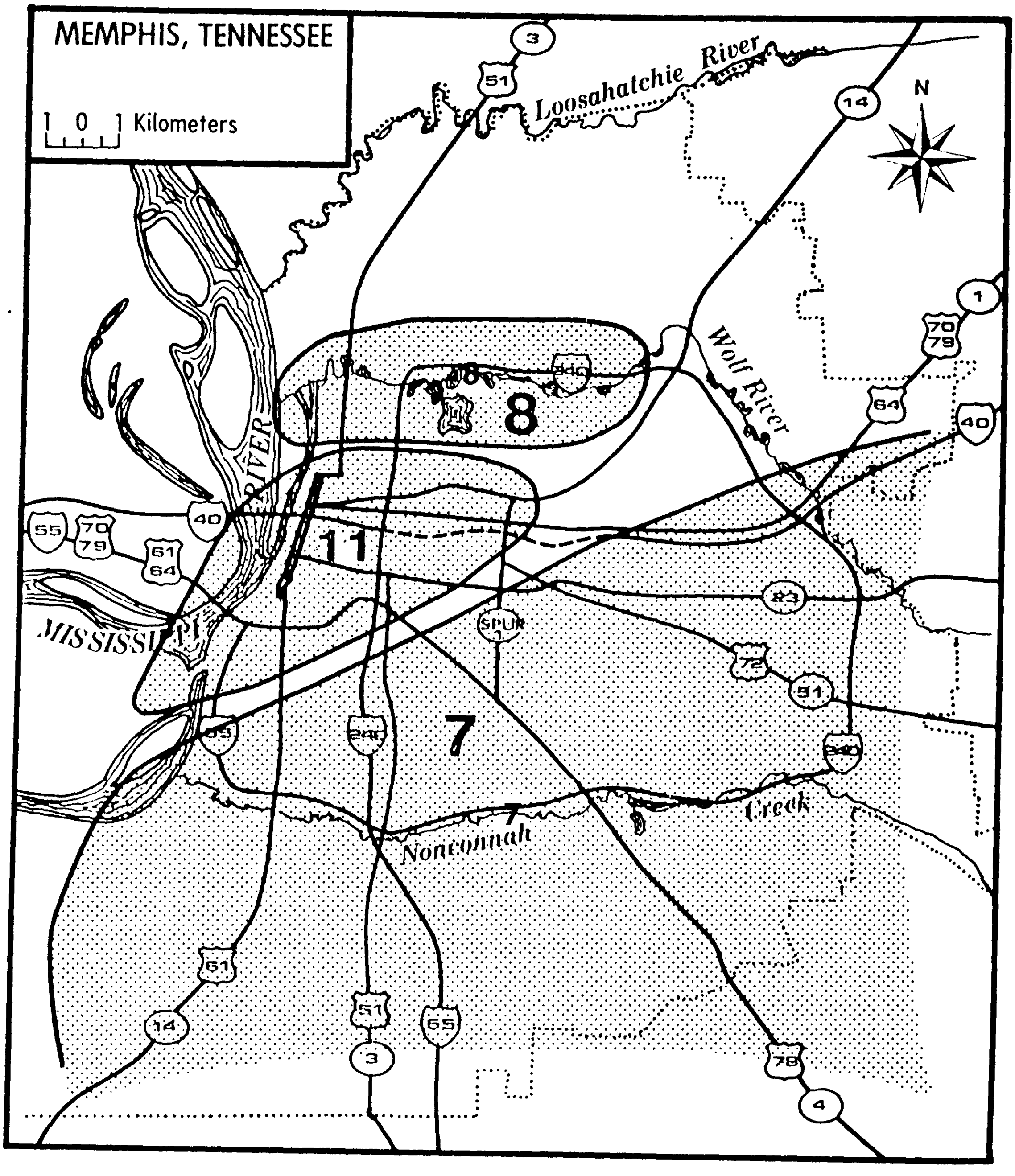


Figure 42.--Map of Memphis, Tennessee. After Sharma and Kovacs (1980). Figures within shaded areas indicate the number of sites investigated for Sharma and Kovacs' study within each shaded area.

TABLE 6.--Stratigraphic section. Section at Memphis, Tennessee

[From M & H Engineering and Memphis State University (1974)]

Series	Subdivision	Range of thickness (meters)	Description
Holocene----	Redeposited loess.	0-10	Generally water-logged silts or silty clays with an 0.5-1.5m crust in dry weather.
	Alluvial sands and gravels.	0-6	Gray, fine to medium sands with occasional gravel, low to medium relative density.
Pleistocene	Loess-----------	0-5	Wind-deposited clayey silts and silty clays.
	Sandy clay------	0-3	Very stiff silty clay, possibly old erosional surface.
	Terrace sand----	0-60	Fluviatile medium-grained sands and gravels, very dense, generally brown or red, frequently iron-oxide-cemented.
Eocene------	Jackson(?) Group	0-150	Hard, fat clays interbedded toward east and south with fine, very dense white sands.

density and shear strength from standard penetration resistance and using other factors, Sharma and Kovacs concluded that there are three zones likely to be susceptible to liquefaction (see figure 43).

Terzaghi (1931) describes a landslide that occurred at Memphis in 1926 and attributes the failure to movement of ground water. Mr. Richard Hoffman (Acting City Engineer, City of Memphis, oral communication, 1982) said that during the last several years there have been no significant problems with landslides, but that they had minor problems with differential settlement along parts of Riverside Drive where it is located on an old fill that was not placed according to present day engineering practice (oral communication, 1982).

Fuller (1912) describes landslides along Chickasaw Bluff, 50 to 100 miles (80 to 160 km) north of Memphis along the east side of the Mississippi River (see figure 3) that could be classified as horizontal block glides, and implies that they were caused by the earthquake sequence of 1811-1812.

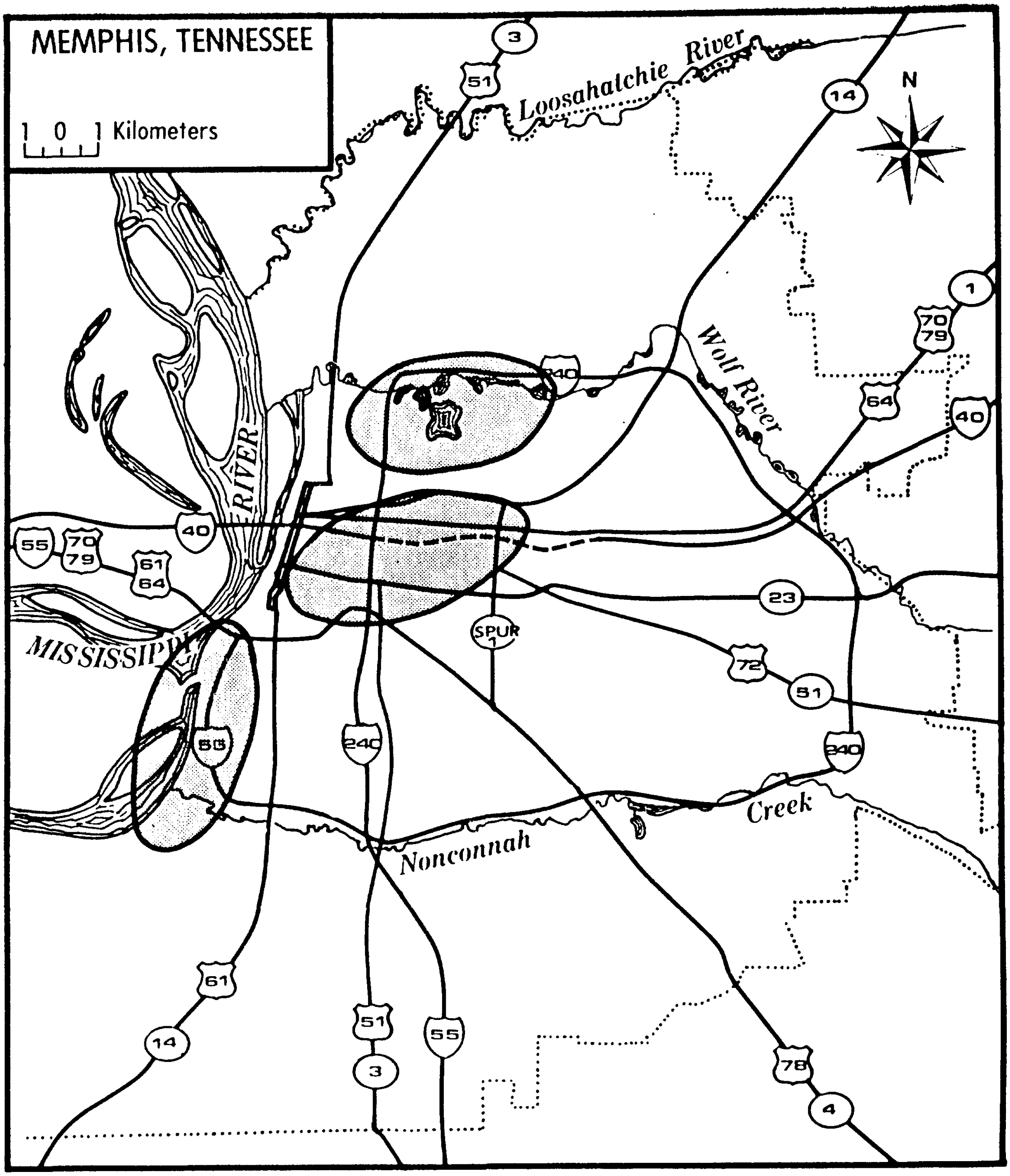


Figure 43.--Map of Memphis, Tennessee. After Sharma and Kovacs (1980). Shaded areas indicate zones where soils may be susceptible to liquefaction for earthquakes with Modified Mercalli intensity greater than VII.

Potential for Landslides, Liquefaction, and Other Geologic Effects

Landslides:

Depending upon ground water conditions, smaller landslides will probably occur along the Mississippi River bluffs in response to strong earthquake vibrations, and differential compaction will take place over many areas of artificial fill. There is a moderate to high probability that large block glide landslides would develop along the bluffs. These slides could extend back from the bluffs at least 100 feet (30 m).

Liquefaction:

Areas of potential liquefaction within the city of Memphis are shown in figure 43 (from Sharma and Kovacs, 1980). The liquefaction potential is probably high for the area underlain by Mississippi River flood plain deposits, and the flood plains and low terraces along Wolf and Loosahatchie Rivers and Nonconnah Creek.

Hypothetical Intensity Maps for Memphis

The highest projected intensities at Memphis are IX and X M.M. from the regional map for the projected $M_s = 8.6$ earthquake (figure 14). These intensities would occur in the event of the assumed earthquake at the south end of the New Madrid seismic zone. If this assumed earthquake occurred at the north end of the seismic zone, intensities at Memphis would range from VIII to IX. However, the worst case assumes an epicenter located at the 1843 epicenter (on which the southern part of the hypothetical map is based), just 32 km away from Memphis (table 4 and Appendix 5). That earthquake produced fallen chimneys and cracked brick walls at Memphis, and hundreds of people ran into the streets. The much larger 1811 earthquake, 80 km from Memphis, resulted in a IX at Fort Pickering near Memphis (Nuttli, 1973). The smaller projected earthquakes would produce intensities of VIII and IX M.M. ($M_s = 7.6$ shock) and VII and VIII ($M_s = 6.7$ shock) at Memphis for an epicenter 32 km away.

Zonation of intensities in Memphis takes into account three kinds of data: 1) local geologic conditions, 2) amplification of seismic waves over bedrock ground motion, as defined by Sharma and Kovacs (1980), and 3) areas potentially susceptible to liquefaction, also from Sharma and Kovacs (1980).

The alluvial valleys of the Mississippi, Loosahatchie, and Wolf Rivers and Nonconnah Creek are thought to represent slightly more hazardous geologic conditions than the rest of the city. All have upper alluvial strata resting on loose, fine-to-medium grained sands, which could liquefy at intensity IX or greater (M & H Engineering and Memphis State University, 1974). Also, areas of artificial fill, especially old, poorly engineered fill, are somewhat more likely to have damage. Finally, the bluffs along the Mississippi River are susceptible to landslides in the event of the large nearby earthquakes assumed here. A particularly critical area for landslides is the east bank of the Mississippi River from about I-55 to about I-40 (figures 29-31) (M & H Engineering and Memphis State University, 1974). This was the site of the 1926 landslide.

Sharma and Kovacs (1980) developed synthetic accelerograms for a potential earthquake of magnitude $m_b = 7.0$ located at 50, 100, and 200 km from Memphis. They found that attenuation for their 50-km-away shock would produce intensity IX at Memphis, a bedrock acceleration of 18% g, a predominant period of about 0.35 seconds, and a duration above 5% g of about 19 seconds. Using borehole data (proprietary) and local sources of information (figure 42), they computed selective amplification factors for various parts of Memphis (figure 44). They found higher amplifications in assumed looser materials close to the Mississippi and Wolf rivers; pockets of stiff clays showed very small amplifications. They suggest that the amplification diminishes toward the southeast because of a lower water table and denser soils away from the rivers. Their maps for the earthquakes at 100 and 200 km are similar to figure 44, but the 200-km map shows somewhat higher amplification toward the southeast. Although their 200-km-away earthquake only produces bedrock accelerations of 11% g and intensities of VII-VIII at Memphis, it has a predominant period of 0.67 seconds and a duration above 5% g of 25 seconds. Sharma and Kovacs therefore suggest that the higher amplifications for the 200-km-away earthquake are due to its longer duration and to its longer period content which is in the 0.7 to 1.0 second range of the natural period of the soils. They also point out that an even more distant earthquake, having a predominant period of 1 second at Memphis, would cause even greater amplifications, but because of the attenuation of acceleration with distance, the surface accelerations would be comparable to their design earthquakes. Moreover, because of the predominant periods generated, they conclude that the 50-km-away earthquake is likely to be more damaging to structures of 3-4 stories, while the 100-and 200-km-away earthquakes will be more hazardous to 9-10-story structures.

Structural damage may occur not only from the strength of the vibrations, but also because of loss of the bearing capacity due to liquefaction. Sharma and Kovacs (1980) also investigated the liquefaction potential of several of the layers from data available for Memphis. Their findings are shown in figure 43, and the number of boreholes from which they obtained their input data in figure 42. They assumed that sands with a relative density greater than 75% would not liquefy for a sufficient time period to initiate loss of bearing capacity.

All three of these factors (geology, amplification, liquefaction) were considered in the development of the Memphis maps, figures 29-31. The slightly higher intensity on the alluvium can be seen in the areas of X (on figure 29) along the Mississippi, Loosahatchie, and Wolf Rivers and Nonconnah Creek. Some of these areas correspond to the areas of high amplification (shown in figure 44) on the north and west sides of the city. Two of the three areas of potential liquefaction (shown in figure 43) are also included in the high amplification areas, but the central one from figure 43 can be distinguished as a separate area of potential X in figure 29. In addition, there are areas throughout the city on old, poorly engineered, artificial fill, where differential settlement may occur. Finally, landslides are likely along the Mississippi River bluffs.

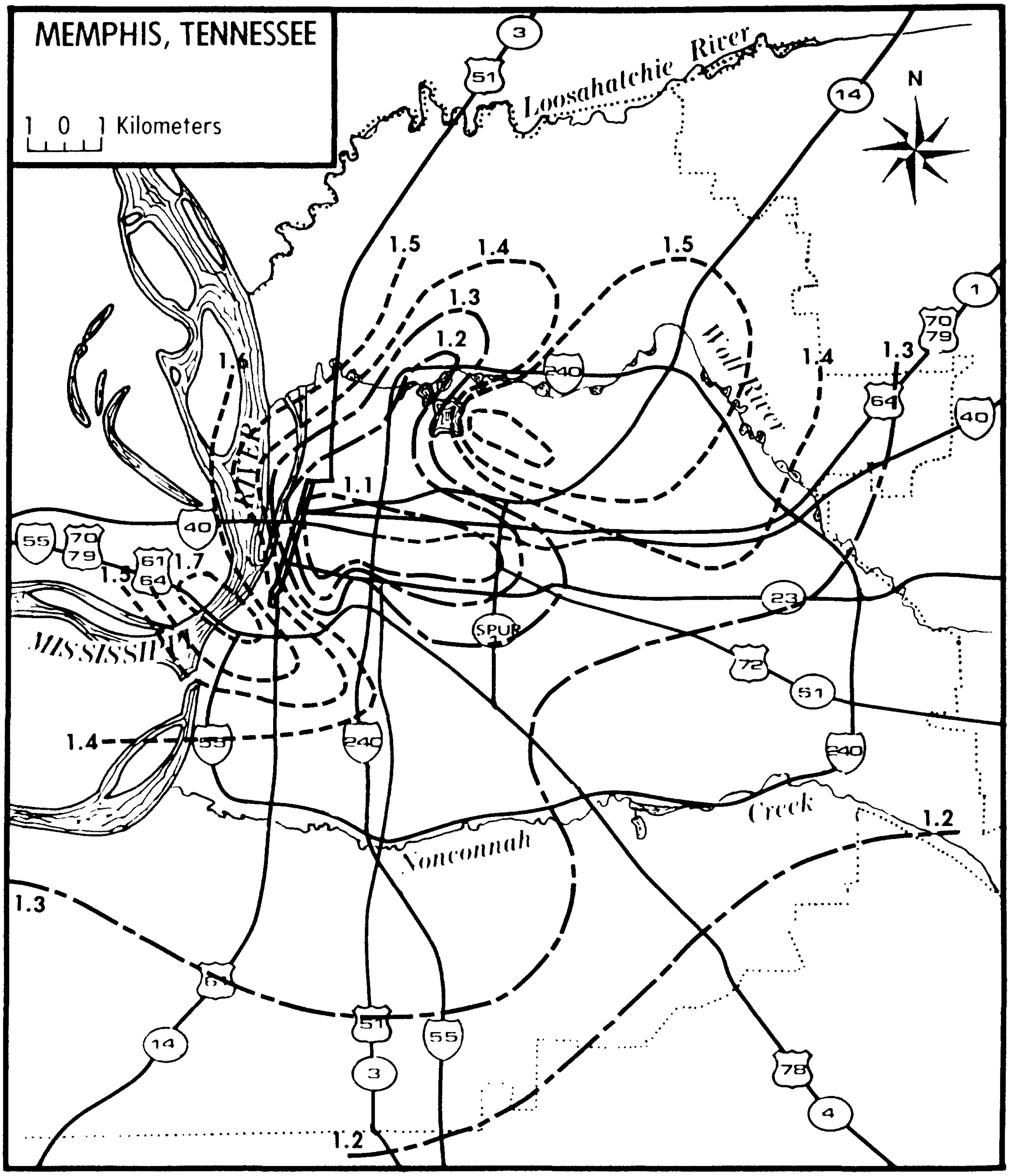


Figure 44.--Map of Memphis, Tennessee. After Sharma and Kovacs (1980). Contours are for amplification factors above assumed bedrock acceleration of 18% g at Memphis from a magnitude m_b=7.0 earthquake 50 km away from Memphis in the New Madrid seismic zone.

ESTIMATION OF INTENSITIES AT PADUCAH, KENTUCKY

Physiographic Description

Paducah is situated in the upper part of the Mississippi Embayment that is also called the East Gulf Coastal Plain (Fenneman, 1938) and near the confluence of the Tennessee and Ohio Rivers. Topographic relief is low for most of the city; total difference between the Ohio River and outlying suburbs is about 150 feet (46 m).

Underlying Material

Most of the city proper is underlain by a Pleistocene and Recent sequence consisting of silt, clay, and some sand.

Physical Property Tests and Other Information

Standard penetration tests were not available at the time of this writing. However, other tests indicate that the material has the following engineering characteristics (Nichols, 1968): 1) percolation is slow to moderate, 2) generally the moisture content is high, 3) cut slopes will stand in 20-foot (6-m) high, nearly vertical slopes when dry, but decrease greatly with increase of moisture content, 4) compressive strength is moderate when dry, but decreases rapidly as moisture content increases, 5) easily moved with hand or power equipment in most places, 6) erodes rapidly, and 7) susceptible to frost heave.

Potential for Landslides, Liquefaction, and Other Geologic Effects

Landslides:

On slopes where soil-moisture content is high, landslides should be expected in response to strong earthquake ground motion (Nichols, 1968).

Liquefaction:

Much of the ground underlying Paducah would be susceptible to compaction, high amplitude ground motion, and possible liquefaction in response to strong earthquake shaking (Nichols, 1968).

Hypothetical Intensity Maps for Paducah

The highest projected intensities at Paducah are VIII, IX, and X M.M. for the M_s = 8.6 earthquake (figure 14). This range of intensities would occur for a magnitude M_s = 8.6 earthquake near the northern end of the New Madrid seismic zone. The range would be somewhat lower for an epicenter farther south. The smaller projected earthquakes would produce intensities of VII-IX M.M. (M_s = 7.6 shock) and VI-VIII (M_s = 6.7 shock). Paducah is only 81 km away from the epicenter of the 1895 earthquake and experienced an intensity of VIII during that shock; a number of chimneys fell and several walls were cracked (table 4 and Appendix 6). Also, a few bricks fell from chimneys, resulting in intensity VI in 1968.

Intensities projected for the M_s = 8.6 shock at Paducah decrease from the X in the alluvium along the river to IX in the lacustrine deposits on which most of the city is situated, to VIII in the hills in the southwest part of the city. Landslides are possible on slopes with high moisture content, and liquefaction is a possibility, especially along the river in the area shown as intensity X on figure 32.

ESTIMATION OF INTENSITIES AT POPLAR BLUFF, MISSOURI

Physiographic Description

Poplar Bluff is situated on the border between the Ozark Plateaus and the Mississippi Alluvial Plain (Fenneman, 1938). Most of the city is located on the mildly dissected uplands of the Ozark Plateaus west of the Black River; a small part of the city occupies the flat Mississippi Alluvial Plain east of the Black River.

Underlying Materials

The surface is underlain by sandstone, chert, and interbedded fine-grained dolomite which comprises the Roubidoux Formation of Ordovician age (McCracken, 1961). Deep residual weathering of these materials has produced the surficial soils on which most of the city is constructed. The soils are somewhat compact, medium stiff, dense, and consist of silty clay, sand and some gravel. East of Black River the underlying materials are typical river alluvium, sand, silt, gravel, and clay.

Physical Property Tests and Other Information

A test borehole at the Veterans Administration Hospital is typical of several others located in the city west of Black River (Sam Smith, City Engineer and head of the Sam Smith Engineering Consulting firm, Poplar Bluff, Missouri, oral communication, September, 1982). The test hole penetrated residual soils to a depth of 57 feet (17 m) where a cherty dolomite was encountered; the residual soils consist of silt, clay, sand and gravel. N values for standard penetration gradually increase from 12 at 38 feet (11.6 m) to 78 at 54 feet (16.5 m).

Test hole data in the alluvium west of Black River was not observed. However, the silty sands and clays in the alluvium have low plasticity, and at one bridge location the material consists of a clean sand at a depth of 20 feet (6 m) (Dan Malloy, Engineer of Soils and Geology, member of the Sam Smith Engineering Consulting firm, Poplar Bluff, Missouri, oral communication, September, 1982). Also, bridge pile driving caused heaving in adjacent sidewalks.

Potential for Landslides, Liquefaction, and Other Geologic Effects

Landslides:

In response to strong seismic shock small landslides would probably occur locally along the steep bluff just west of Black River and in steep artificial slopes.

Liquefaction:

The liquefaction potential is probably low in the part of the city west of Black River. East of Black River the liquefaction potential is high.

Hypothetical Intensity Maps for Poplar Bluff

From the regional map for the M_s = 8.6 earthquake (figure 14) intensity IX is projected at Poplar Bluff. Much higher intensities (IX and X) are projected in the Mississippi flood plain southeast of the town than on the uplands to the west and northwest (figures 35-37). The difference is judged to be at least two intensity levels at Poplar Bluff, with X below in the river alluvium and VIII above on the uplands for the M_s = 8.6 earthquake. The smaller projected earthquakes would produce intensities of VII and IX M.M. (M_s = 7.6 shock, figure 36) and VI and VIII (M_s = 6.7 shock, figure 37). The projected intensity values are so high because of the assumption of an epicenter at the north end of the New Madrid seismic zone. The epicenter of the 1895 earthquake, which dominates the northern part of the regional map (figure 14), is only 94 km from Poplar Bluff (table 4 and Appendix 7), and the presumed epicenter of the February, 1812, earthquake only about 80 km away. There is no information on the 1812 effects at Poplar Bluff, but the 1895 earthquake was felt there, causing a noise like a cyclone. Also, the 1968 earthquake resulted in intensity V at Poplar Bluff.

ESTIMATION OF INTENSITIES AT SAINT LOUIS, MISSOURI

Physiographic Description

The city of Saint Louis lies in the extreme eastern part of Saint Louis County. The county is on the eastern border of Missouri, at the confluence of the Mississippi and Missouri Rivers. Upland topography varies from very gently rolling to rugged, with the lowest relief in the central part of the county, farthest away from major streams. A large high terrace, on which Lambert-Saint Louis International Airport is located, is nearly level over large areas. Steep slopes and rugged topography are prevalent in the western part of the county and along the bluffs of the river valleys. Karst (sinkhole) topography is locally present in the northern part of the county, and in the southern part of the county near the confluence of the Meramec and Mississippi Rivers. Wide, nearly level flood plains and low terraces are present everywhere along the Missouri River, and along some of the Mississippi River.

Underlying Material

The bedrock geology in Saint Louis County is essentially flat-lying sedimentary rocks, primarily limestone and dolomite with lesser amounts of sandstone and shale (Lutzen and Rockaway, 1971). Goodfield (1965) has a detailed description of the geology of surficial deposits. Almost all the upland areas have been covered by extensive deposits of loess derived from the flood plain of the Missouri River during Pleistocene (glacial) time. The deepest loess, exceeding 50 feet (15 m), is present along the bluff of the Missouri River. In general, loess thins southward and seldom exceeds 5 to 10 feet (1.7 to 3 m) in the southwestern part of the county. The oldest, basal loess deposits are commonly clay-rich. There is a rather thick (20 to 30 feet (6 to 9 m)) mantling of silt-rich loess containing little or almost no clay over the clay-rich loess throughout much of the northern part of the county. At many places this silt-rich loess has been locally reworked by running water, which then deposited thin layers of cohesionless, silty very fine sands. These thin layers are especially prevalent in small stream valleys, though present topography does not necessarily indicate where they may be present.

Beneath loess there is commonly a thin residium (residual soil) derived from the in-place weathering of bedrock. This residium is dominantly clay, but includes the more resistant material from bedrock, primarily quartz sand and chert.

The high terrace in the northern part of the county (on which Lambert-Saint Louis International Airport is situated) is made up of fine-grained materials deposited on a lake bottom (lacustrine deposits). The deposits are predominantly clay-rich, though there are some extensive, thick silt layers with almost no clay. On lower terraces and on flood plains of the Missouri, Mississippi and Meramec Rivers, there are stratified gravel, sand, silt, clay, and organic deposits. These alluvial deposits generally exceed 100 feet (30 m) in the Mississippi and Missouri valleys, and they are up to 60 feet (18 m) thick in the Meramec valley. Less extensive alluvial deposits are in some smaller stream valleys, such as Fee Fee, Bonhomme, and Creve Coeur Creeks. Fine sand and silt deposits, which are remnants of older alluvial deposits at higher elevations, commonly remain on valley slopes.

Ground water is present near the surface at many places, even in the uplands. Perched water often collects in the silt-rich loess above more impermeable materials, such as clay-rich loess or above shale. The water table is near the ground surface along many of the smaller streams, and throughout much of the high lake terrace. Locally the water table is high on lower terraces, and on flood plains the water table is at least seasonally at or very close to the surface.

Physical Property Tests and Other Information

Engineering data from foundation borings were provided by Don Becke (Geotechnical Engineer, Missouri Highway Department, Jefferson City, Missouri, unpub. data, 1982). The borings were primarily for bridges and major structures on the interstate highway system throughout Saint Louis County.

Standard penetration test N (blow count) values on both silt-rich and clay-rich loess generally range from 5 to 15, with scattered lower blow counts. The lowest values are generally in low, wet areas, with some very weak materials unpredictably located in high areas. The silt-rich loess commonly has a plasticity index of 10 or less, and is nonplastic at many places. Within the silt-rich loess there are occasional layers of clean very fine sands having very low blow counts.

The high terrace of lake deposits around the airport generally has blow counts (N values) exceeding 8, and most materials are clay-rich, though some clean silts and very fine sands are also present. Lowest blow counts are near the small streams on the terrace.

Lower terraces, such as those along Meramec River can have 15 to 20 feet (4 to 6 m) of very weak clay, silt, and sand strata, with N values ranging between 5 and 10. The flood plains of the major rivers (the Mississippi, Missouri, and Meramec Rivers) typically have 15 to 20 feet (4 to 6 m) of very weak clay, silt and sand strata; N values of many of the sands are 5 to 10. These uppermost very weak deposits overlie much stronger sand and gravel, which may extend to a depth of 100 feet (30 m).

Potential for Landslides, Liquefaction, and Other Effects

Much of this information is based on discussions with the following people: Don Becke (Geotechnical Engineer, Missouri Highway Department, Jefferson City, Missouri); Jerry Wallace (Civil Engineer and Geologist (retired), Missouri Highway Department, Saint Louis, Missouri); Dr. John Rockaway, (Professor, Geological Engineering Department, Missouri School of Mines, Rolla, Missouri); and Dr. Richard Stephenson, (Professor, Civil Engineering Department, Missouri School of Mines, Rolla, Missouri).

Landslides:

Landslides in response to strong earthquakes are likely to be commonplace on many natural and highway cut and fill slopes.

The natural slopes most prone to landslides in uplands are thick, silt-rich loess on steep slopes, where the loess is underlain by a very impermeable material (such as shale or clay-rich loess). All upland loess slopes steeper than about 3:1 must be considered as candidates, especially if seeps are present at the base of the silt-rich loess. If there is much water at the base, flatter slopes can fail. It is unlikely that the loess would flow as a viscous fluid, but rather it would move dominantly as a rotational slump. Thus, the head scarps would probably not extend far back into the slope.

Lateral spreads in loess are quite possible in upland areas near small streams, where the water table is very shallow; lateral spreads may also take place on the high lake terrace, near streams.

On lower terraces and the flood plains, bank failures (slumps) will be commonplace, and destroy many retaining walls and bridges. Lateral spreads, extending hundreds of feet back from stream banks, will probably take place along major streams.

Many highway cut sections will fail and cause very serious problems to highway traffic. Even today, there are significant landslides in the loess cuts along I-44, I-244, I-270, and US 67. Some highway fills would probably fail, especially those on the lake sediments near the airport and on flood plains of the major rivers.

Liquefaction:

Liquefaction on nearly level ground will probably be commonplace in the silt-rich loess and sediments of uplands, where the water table is within 5 to 10 feet (1.7 to 3 m) of the ground surface; however, this liquefaction will probably only damage and not totally destroy well-built, modern structures. Liquefaction in loose sands causing total destruction to any structures can occur at many places on flood plains and low terraces, along both small and large streams.

Other effects:

Much of the old part of the city of Saint Louis, and particularly the modern highway network, is built on uncontrolled fill. This fill is generally in stream valleys, but there are many rubbish-filled pits in the old part of the city. All this rubbish and fill is prone to large differential settlements in an earthquake.

In addition, parts of the downtown area are underlain by open, underground mines, where clay was long-ago mined for making tile. Their locations are generally poorly or not known. The clay mines are in Pennsylvanian-age rocks. The potential for collapse is not known, but significant sags have developed at some places.

There is also the possibility that some sink holes will collapse.

Hypothetical Intensity Maps for City and County of Saint Louis, Missouri

Intensities VIII and IX M.M. are projected in the Saint Louis area on the regional map (figure 14) for an M_s = 8.6 epicenter near the north end of the New Madrid seismic zone.

The hypothetical intensities for St. Louis City and county are IX for the flood plain alluvium and low alluvial terraces (figure 38). Values of VIII are assigned to most of the old part of the city of St. Louis, in part because of the poor earthquake resistance of many of the old structures, and the large amounts of uncontrolled fill. Values of VIII have also been given to areas where there will be many failures on steep loess slopes, and the high lake terrace. The remaining areas have a designation of VII. The smaller projected earthquakes would produce intensities of VI-VIII M.M. (M_s = 7.6 shock) and V-VII (M_s = 6.7 shock) at Saint Louis.

Intensity VIII occurred in Saint Louis during the largest and closest of the 1811-1812 earthquake series (February 7, 1812, I_o = XI-XII, epicenter 245 km from Saint Louis). VII M.M. was produced at Saint Louis by the 1811 (December 16, 2:15 a.m., I_o = XI, 317 km), 1843 (I_o = VIII, 390 km) and 1968 (I_o = VII, 162 km) shocks. VI-VII occurred in 1811 (December 16, 8:15 a.m., 298 km), and VI in 1895 (I_o = IX, 198 km).

POTENTIAL FOR LIQUEFACTION IN AREAS WITH MODIFIED MERCALLI INTENSITIES IX AND GREATER

By Stephen F. Obermeier and Norman Wingard

Areas on the regional intensity map for the magnitude-8.6 earthquakes (figure 14) with Modified Mercalli intensities (M.M.) IX and higher are assessed for their liquefaction potential. Each state is evaluated individually at a map scale of 1:1,000,000 (plates 1-7). The map units are selected on the basis of engineering characteristics of different geologic formations. The map units show only areas where there would be a moderate to high probablility of liquefaction in the event of a magnitude-8.6 shock somewhere along the New Madrid seismic zone. Additional work needs to be done to define the liquefaction potential for smaller magnitude earthquakes that could occur in the New Madrid seismic zone.

MAP UNITS AND POTENTIAL FOR LIQUEFACTION

Engineering characteristics used to select map units included Standard Penetration Test (SPT) blow counts (N values), texture of the sediments, and location of the water table. N values were selected according to criteria discussed in the section on "Engineering Evaluation of Liquefaction Potential." In areas of regional intensity IX (figure 14), only clean sand deposits with median blow counts of about 12 or less at a depth of 12 to 20 feet (4 to 6 m) when the water table was near the ground surface (or sands of equivalent potential for other settings) were considered as subject to widespread liquefaction. Silty sands with blow counts of 7 or less were also considered susceptible. For soft silts, a value of 4 to 5 was used, and for clay-bearing soils a value of 2 to 3. In areas of regional intensity X and higher, the median blow count for clean sands was increased to about 20 to 24, for silty sands about 14, for silt about 8 to 10, and for clay about 3.

There is a very good correlation between liquefaction potential and geologic age of sediments (Youd and Perkins, 1978). Typically the youngest sediments have the lowest blow counts and highest ground water table. Although the youngest sediments generally have more clay- and silt-rich strata than slightly older sediments, the youngest also have abundant loose sands. Three ages of sediments were considered: older than Pleistocene, Pleistocene, and Holocene. Pleistocene sediments are those laid down during The Great Ice Age (ranging from about 2 million years ago to 15 thousand years age). Holocene sediments are less than 10,000 years old and include those presently being laid down.

Sediments older than Pleistocene age are only so locally susceptible that they are not subject to widespread liquefaction and liquefaction-related problems, though in exceptional locations they are so weak that serious problems could arise. Thus they were not included as susceptible map units. Of these older sediments, about the only ones that would liquefy are designated on state maps as Quaternary-Tertiary sediments.

Pleistocene sediments are generally subject to very serious and widespread liquefaction-caused problems where the intensity exceeds X M.M. In the area with intensity IX, problems would still be widespread and locally serious. Holocene sediments are subject to serious liquefaction problems throughout intensities of IX and higher.

The state maps show only where liquefaction is likely to occur. The nature of liquefaction problems depends on local site conditions, and a site investigation is still needed for assessment of a structure such as a building, dam, levee, bridge, or embankment.

The maps do not show where landslides are likely to take place in upland areas. The map scales do not lend themselves for that sort of assessment. Instead, the criteria discussed in the section on "The Nature of Liquefaction and Landslides in the New Madrid Earthquake Region" can be used. For lowland areas, non-liquefaction related landslides and bank failures would be commonplace on streams ranging from small creeks to the largest of rivers. It is only possible to show larger streams on the state maps. Literally hundreds to thousands of small streams would have serious landslides and bank failure problems throughout the area of intensity IX and higher.

State geologic or surficial materials maps were used to show areas of potential liquefaction for each of the states. The geologic breakdown is somewhat different from state to state. For that reason, and because separation is not possible at a scale of 1:1,000,000, all materials that are considered as moderately or highly prone to liquefaction are shown with no distinction. There is discussion of the different susceptibilities for each of the states, however, wherever the geologic units are suitable on the state maps.

Some state maps do not show Holocene deposits. Rather, Holocene and Pleistocene are combined and designated as Quaternary deposits. Where that has been done, the text describes the topographic setting where the most liquefaction-prone sediments are present.

POTENTIAL FOR LIQUEFACTION IN ARKANSAS

Plate 1 shows areas in Arkansas generally with moderate to high susceptibility to liquefaction. The maps used to locate potentially susceptible deposits are the Geologic Map of Arkansas, 1976, scale 1:500,000; the 15-minute engineering geology maps, scale 1:62,500, in the U.S. Army Corps of Engineers reports Geologic Investigation of the St. Francis Basin (Saucier, 1964), and Geologic Investigation of the Western Lowlands Area, Lower Mississippi Valley (Smith and Saucier, 1971); and the map in the report Quaternary Geology of the Lower Mississippi Valley (Saucier, 1974). In the region of intensities X and XI, almost all Holocene alluvium (state map units Qcm, and Qso) as well as Pleistocene terrace deposits (unit Qt) are highly susceptible to liquefaction; about the only material not very susceptible to liquefaction-caused problems in the region of intensity XI are the unusually thick clay bodies, thicker than about 50 to 60 feet (15 to 18 m); in the middle to outer parts of the region of intensity X, a thickness of 30 feet (9 m) or more of clay or interlayered silt and clay (designated as topstratum in the Corps of Engineers reports) is sufficient to prevent widespread liquefaction problems. (These thicknesses are based on field studies by the senior author and by Saucier (1977) about effects of the 1811-12 earthquakes.) The thickness of some clay bodies and topstratum are shown on the maps of the Corps of Engineer reports and the map in the 1974 report by Saucier. Liquefaction in the region of intensities X and XI would almost certainly cause some flow landslides of levees, extensive lateral spreading landslides, and extensive differential ground settling. Many houses and buildings would be destroyed. Even well-built, modern highways, such as I-55, would be rendered useless and probably impassable at many places to 4-wheeled vehicles, largely because of open cracks caused by lateral spreading. Liquefied sand and water (quicksand) would probably flow from many of these large cracks for days after earthquake shaking stopped. Many bridges of all sizes would be destroyed or seriously damaged.

Areas of intensity IX are moderately to highly susceptible to liquefaction in units Qcm and Qso. In general, throughout the area of intensity IX, unit Qt has a fine-grained cap of clay and silt that overlies clean sands. The clean sands are typically moderately dense, and are only marginally susceptible to liquefaction. Where the fine-grained cap exceeds about 20 feet (6 m), only few minor problems could arise. The thickness of the fine-grained capping can be estimated with reasonable accuracy on the 15-minute Corps of Engineers maps. In addition, where dune sand (unit Qds on the state map) is water saturated, serious problems could arise. These sands are very loose.

Rivers (such as Cache, Black, White, and L'Anguille) in the area of intensity IX have very weak Holocene deposits near the rivers. All would have serious problems with lateral spreading and bank failures. It is likely that many bridges over these rivers would be made useless.

There is the likelihood of widespread flooding, especially in the lowlands, in the general vicinity of the St. Francis River. This flooding would result from the large volumes of liquefied sand and water being carried to the ground surface. This would probably occur even during a relatively dry season, and of course could cause terrible problems during a wet season. The probable extent of flooding caused by the 1811-12 earthquakes is described by Saucier (1977), and can be used as a reasonably accurate model given recurrence of the very strong earthquakes.

Much of the information used for interpretations is based on discussions and data provided by the following people:

Ben Clardy, Arkansas Geological Commission, Little Rock, Ark.

Boyd Haley, U.S. Geological Survey, Little Rock, Ark.

Roger Saucier, Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Miss.

POTENTIAL FOR LIQUEFACTION IN ILLINOIS

Plate 2 shows areas in Illinois generally with moderate to high susceptiblity to liquefaction. The map used to locate potentially susceptible deposits is Quaternary Deposits of Illinois, 1979, scale 1:500,000. In the regions of intensities IX and X M.M., many of the Holocene and late glacial-age (Wisconsinan) deposits are susceptible (state map units c; c-f; and pl).

The units c and c-f are very young alluvium, and are especially prone to severe liquefaction. The unit pl is dune sand, which is generally in uplands and is dry, but when wet during rainy seasons or when in lowlands this dune sand is very susceptible. Many Pleistocene deposits older than Holocene and Wisconsinan are also prone to problems. Older state map units susceptible are as follows: ec; hm; hb; hw; pe; gha; b; and b-o. Unit ec is generally a glacial lake deposit, and is most susceptible in low, wet areas near major streams such as the Illinois, Mississippi, Ohio, or Wabash Rivers. There are commonly loose sands (N about 5) at a depth of about 20 feet (6 m) in these lake sediments near the major streams which may be very susceptible to liquefaction problems. Very soft silts and clays, with N values of 2 or 3, are also relatively common. Units hm, gha, b, b-O, and pe all have extensive sand deposits laid down by flowing glacial meltwater, and may have sands of other origins. In general they are moderately dense (median N values of about 20) and subject to only moderate liquefaction-related problems at worst. Units hb and hw only rather locally contain sands or silts that can cause problems.

Much of the information used for interpretations is based on discussions and data provided by the following people:

Allen Goodfield, Illinois Department of Transportation, Springfield, Illinois.

Paul DuMontelle, Paul Heigold, Dennis Kolata, Myrna Killey, Don McKay, and John Kempton, Illinois State Geological Survey, Champaign, Illinois.

POTENTIAL FOR LIQUEFACTION IN INDIANA

Plate 3 shows areas in Indiana generally with moderate to high potential for liquefaction. Maps used to locate potentially liquefiable deposits are the Map of Indiana Showing Glacial Deposits, 1960, scale 1:1,000,000; Geologic Map of the 1° x 2° Vincennes Quadrangle And Parts of Adjoining Quadrangles, Indiana and Illinois, Showing Bedrock and Unconsolidated Deposits, 1970, scale 1:250,000; Geologic Map of the 1° x 2° Indianapolis Quadrangle, Indiana and Illinois, Showing Bedrock and Unconsolidated Deposits, 1979, scale 1:250,000; Geologic Map of the 1° x 2° Cincinnati Quadrangle, Indiana and Ohio, Showing Bedrock and Unconsolidated Deposits, 1972, scale 1:250,000. Deposits shown on plate 3 are described on the glacial deposits map as Upper Pleistocene materials. Included on plate 3 are lake sediments, dune sand, and valley train sediments. On the 1° x 2° sheets, the locations of these deposits are shown in greater detail; on these maps the units included are Recent sand and gravel (Qsa); Wisconsinan wind-deposited (dune) sand with some silt (Qsd); Illinoian and Wisconsinan glacial lake deposits (Qcl) and glacial valley-train and outwash (Qgv and Qgp); and older glaical lake deposits (Qsl). The unit Qsa is generally highly susceptible to liquefaction, because it commonly has sands that are quite loose and the water table is very shallow. Along major streams (such as White, Wabash, or Ohio Rivers) the upper 20 to 30 feet (6 to 9 m) of sediments have SPT N values ranging from 10 to 30, averaging about 15. The unit Qsd has very loose sands at many places, but the water table is generally too deep to cause problems except in low areas or during very wet seasons. Unit Qcl has some extremely soft (N equal to 0) non-plastic silts that are highly prone to liquefaction. These appear to be widespread and rather commonplace. Units Qgv and Qgp are generally exclusively sands, which are so dense that liquefaction would not be very troublesome except in the region of intensity X. Unit Qsl is probably only moderately susceptible in the worst places, in very broad poorly drained areas.

Much of the information used for interpretations is based on data and discussions provided by the following people:

Bill Sisliano, Indiana State Highway Commission, Indianapolis, Ind.

Henry Grey and John Hill, Indiana Geological Survey, Bloomington, Ind.

POTENTIAL FOR LIQUEFACTION IN KENTUCKY

Plate 4 shows areas in Kentucky generally with moderate to high potential for liquefaction. Maps used to locate potentially liquefiable deposits are the Generalized Geologic Map of Kentucky, 1979, scale 1:1,000,000 and the Geologic Map of Kentucky, 1981, scale 1:250,000. Material susceptible to liquefaction of the 1979 Generalized Geologic Map of Kentucky is described as alluvium. On the 1981 Geologic Map of Kentucky, materials susceptible are described as alluvial and lacustrine deposits, undivided (map unit Qa).

The lacustrine deposits are glacial lake sediments which are located primarily along tributaries to the Ohio or Mississippi Rivers. Much of the towns of Paducah and Owensboro are on these sediments. The beds commonly have some very soft clean silts highly to moderately susceptible to liquefaction in the uppermost 20 to 30 feet (6 to 9 m). At many places these silts are underlain by clean sands or silty sands with at least moderate susceptibility.

Near the Ohio and Mississippi Rivers, there are commonly up to 20 or 30 feet (6 to 9 m) of very loose or soft sediments which are very prone to liquefaction. These are typically underlain by more dense sands, but the sands would still be subject to widespread liquefaction, especially west of Paducah.

Much of the information used for interpretations is based on data and discussions provided by the following people:

Everett Gray and Ed Munson, Kentucky Department of Transportation, Frankfort, Ky.

O. Clarke Mann, Tennessee Earthquake Information Center, Memphis, Tenn.

POTENTIAL FOR LIQUEFACTION IN MISSISSIPPI

Plate 5 shows areas in Mississippi generally with moderate to high liquefaction potential. Maps used to locate potentially liquefiable deposits are the unpublished Quaternary geologic map for the State, scale 1:1,000,000, and the map Alluvial Geology of the Yazoo Basin, published by the U.S. Army Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi, 1967, scale 1:250,000. For the Yazoo Basin, much greater detailed data are in the collection of maps for the report Geologic Investigation of the Yazoo Basin, Lower Mississippi Valley (Kolb and others, 1968) published by the U.S. Army Waterway Experiment Station, Corps of Engineers; the maps are 15-minute quadrangles, scale 1:62,500.

In Mississippi, there are two distinctly different geologic-topographic settings where problems could arise: (1) in the alluvial lowlands of the Yazoo Basin, and (2) in alluvium along the larger streams draining the uplands, such as the Coldwater, Tallahatchie, Yocoma, Tuscumba, and Yalobusha Rivers.

The Yazoo Basin comprises the area of susceptible lowland sediments in the wide north-south oriented strip in the extreme western part of the state (see Plate 5). The basin contains almost everywhere more than 100 feet (30 m) of sand, which is locally overlain by either a fine-grained capping or very young alluvium laid down by streams presently in the basin. The only material of high susceptibility is the very young alluvium. In general very young alluvium is within a belt only a mile or two wide along the larger streams, and a narrower belt along smaller streams; maps showing locations of the very young alluvium are not available, so plate 5 necessarily includes large areas not susceptible to liquefaction. Susceptibility can only be evaluated by a site-specific investigation.

Deposits in the basin not susceptible to liquefaction are the geologic units (generally older than very young alluvium) described on the map Alluvial Geology of the Yazoo Basin as either backswamp or braided stream deposits; and, in addition, the fine-grained capping must exceed 20 feet (6 m) in the area of intensity IX, and 30 feet (9 m) in the area of intensity X. For the areas of intensity IX, there are large areas of backswamp or braided stream deposits with a fine-grained capping greater than 20 feet (6 m) which have been eliminated from plate 5.

Very young (Holocene) alluvium along larger streams of uplands is commonly moderately and locally highly susceptible to liquefaction. It is up to 20 feet (6 m) thick at many places, and generally thickens downstream. About the only places where problems would probably arise would be on the present-day flood plain and the first terrace above the flood plain (or above a lake-flooded area). Higher terraces are usually so well drained that problems would not develop.

Some streams valleys contain a layer of dense silt which apparently resulted from weathering of sedimentary silts (Grissinger and others, 1981; Grissinger and Murphey, 1983). This layer overlies clean sands at some places, and causes artesian pressures in the sands. It is very likely these sands are at least moderately prone to liquefaction.

Much of the information used for interpretations is based on discussions and data provided by the following people:

Roger Saucier, Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Miss.

Earl Grissinger and J. B. Murphey, U.S.D.A. Sedimentation Laboratory, U.S. Department of Agriculture, Oxford, Miss.

POTENTIAL FOR LIQUEFACTION IN MISSOURI

Plate 6 shows areas in Missouri generally with moderate to high liquefaction potential. Maps used to locate potentially liquefiable deposits are the Surficial Materials Map of Missouri, 1982, scale 1:1,000,000, and the 15-minute engineering geology maps, scale 1:62,500, in the U.S. Army Corps of Engineers reports Geologic Investigation of the St. Francis Basin (Saucier, 1964), and Geologic Investigation of the Western Lowlands Area, Lower Mississippi Valley (Smith and Saucier, 1971). Materials shown on plate 6 from the Missouri surficial materials map are alluvium described as unit A, B, or C. Alluvium unit A is generally very young alluvium, and it commonly has a high liquefaction potential, even in intensity IX M.M. Sediments equivalent to unit A are all those younger than braided stream terrace deposits in the Corps of Engineers report for Western Lowlands (Smith and Saucier, 1971).

Alluvium unit B is typically clay and silt-capped alluvium. Beneath the clay and silt cap, there is usually moderately dense clean sand. The cap ranges from 0 to about 25 feet (0 to 8 m) thick, and the clean sand ranges from 50 to 150 feet (15 to 45 m) thick. Unit B is highly susceptible to liquefaction in the region having intensity XI, and moderately to highly susceptible in intensity X. In the region of intensity IX, unit B is susceptible only in very localized places where the sands are unusually loose. Unit B is not susceptible to causing serious liquefaction-induced problems at places where the capping exceeds 20 feet (6 m) in the eastern half of the region of intensity IX, and where the capping exceeds 15 feet (4.7 m) in the western half. Unit B is equivalent to braided stream terrace deposits in the Corps of Engineer report.

Alluvium unit C has about the same engineering characteristics and susceptibility to liquefaction as unit B, except the fine-grained cap is much thinner or not present.

In a magnitude-8.6 (M_s) earthquake, liquefaction would be extremely common in intensities X and XI in units A, B, and C. Lateral spread landslides would be commonplace, many buildings and structures destroyed, and segments of the levees along the Mississippi River would probably collapse. Highways such as I-55 would almost certainly be impassable even to four-wheel-drive vehicles at many places, because of big open cracks, and because of liquefied sand and water being expelled from the cracks. This liquefied sand (that is, quicksand) would probably continue to flow from many cracks for several days after earthquake shaking stopped.

The Surficial Materials Map of Missouri also shows locations where loess near the Mississippi River is particularly thick. Where slopes are steep, and where the loess is particularly wet, landslides are likely in this map unit.

Much of the information used for interpretations is based on discussions and data provided by the following people:

John Whitfield and Tom Dean, Missouri Department of Natural Resources, Rolla, Missouri.

John Rockaway and Richard Stephenson, Missouri School of Mines, Rolla, Missouri.

Don Becke, Missouri Highway Department, Jefferson City, Missouri.

POTENTIAL FOR LIQUEFACTION IN TENNESSEE

Plate 7 shows areas in Tennessee generally with moderate to high liquefaction potential. Maps used to locate potentially liquefiable deposits are the Geologic Map of Tennessee, 1966, scale 1:250,000, and the 15-minute engineering geology maps, scale 1:62,500, in the U.S. Army Corps of Engineers report Geologic Investigation of the St. Francis Basin (Saucier, 1964). Material shown from the Tennessee geologic map is described as Quaternary alluvial deposits (Qal).

In the region of intensity IX, the alluvium on the present flood plains and lowest terraces is susceptible to widespread liquefaction and bank failures along streams. This alluvium is commonly 25 feet (8 m) thick, and contains loose sands and soft silts. Quite locally there are places where the higher terraces have up to 5 feet (1.7 m) of very loose sand or weak silt, which is reworked material laid on the terraces long after original formation of the terraces. Usually these reworked deposits are quite limited in areal extent. The liquefied area would be so restricted that it would probably affect only one column beneath a building, for example, but this could still cause serious structural damage.

In the regions of intensities X and XI, almost all deposits shown on plate 7 have a high liquefaction potential. In the event of an 1811-12 magnitude earthquake, there would be numerous lateral spreads which would destroy or severely damage many bridges, and leave large cracks in the ground from which liquefied sand would probably flow days after earthquake shaking stopped. This would make roads impassable at many places even to 4-wheel-drive vehicles. Many buildings would be destroyed. The levees along the Mississippi River would almost certainly fail at some places.

Much of the information used for interpretations is based on discussions and data provided by the following people:

O. Clarke Mann, Tennessee Earthquake Information Center, Memphis, Tennessee.

William Parks, U.S. Geological Survey, Memphis, Tennessee.

AERIAL RECONNAISSANCE STUDY OF AREAS THAT MAY HAVE SANDBLOWS CAUSED BY THE NEW MADRID EARTHQUAKES

by D. D. Dickey

INTRODUCTION

This paper summarizes results of a photo-reconnaissance study of part of the New Madrid earthquake region. The study area encompassed the wide expanse of lowlands west of Crowleys Ridge and east of the Paleozoic rocks of Ozark Mountains between the towns of Poplar Bluff, and Searcy (see figure 45); the Cache and Ohio River valleys in southern Illinois; and the Mississippi River lowlands from Cape Girardeau to St. Louis.

In previous studies, maps have been made showing the distribution of presumed 1811-12 sandblows in the alluvial lowlands east of Crowleys Ridge, Missouri and Arkansas, and west of the loess bluffs in Kentucky and Tennessee (Fuller, 1912; Heyl and McKeown, 1978; Saucier, 1977; Obermeier, 1984). Each of the investigators shows somewhat different distribution because of the different methods used for compilation, and because of varying criteria for minimum ground coverage. In the main, though, the maps are quite similar for regions with a high percent of the ground covered by sandblows.

Sandblows are small, dome-like accumulations predominantly of sand on the ground surface and those induced by the 1811-12 earthquakes in the geographic region between Crowleys Ridge and the Mississippi River are commonly 15 to 60 m (50 to 200 ft) in diameter and as much as 1 m (3 ft) high; they are formed by ground water, temporarily under artesian pressure as a consequence of the earthquake shaking, rapidly flowing to the surface, forming a fountain of sediment-laden water, and depositing a conical mound of transported sand and silt. Some authors refer to these features as sand boils rather than sandblows.

Field inspection is needed to confirm the features that appear to be sandblows on aerial photographs. That some sandblows probably occurred along parts of the Mississippi River floodstream upstream from Cape Girardeau is strongly indicated by the fact that correspondence from Father Urban, who was in charge of a Monastery at Cahokia, Illinois, territory in 1811-12, reported the effects of the New Madrid earthquakes there. His description of them included the earth opening up and sand and water being ejected. (McDermott, 1949).

Some of the features that appear to be sandblows may predate the 1811-1812 earthqakes, and be the result of earlier earthquakes. Field examination of some of them showed soil profiles which preclude them being as recent as 1811 (S. Obermeier, oral communication, 1985).

CRITERIA USED FOR IDENTIFYING SANDBLOWS ON AERIAL PHOTOGRAPHS

At many places it is not possible to distinguish between sandblows and other features on airphotos. Sandblows appear as small light-colored spots or patches on the aerial photography. Other types of features, Mima mounds and sand dunes, have similar appearances. Mima mounds are small (usually less

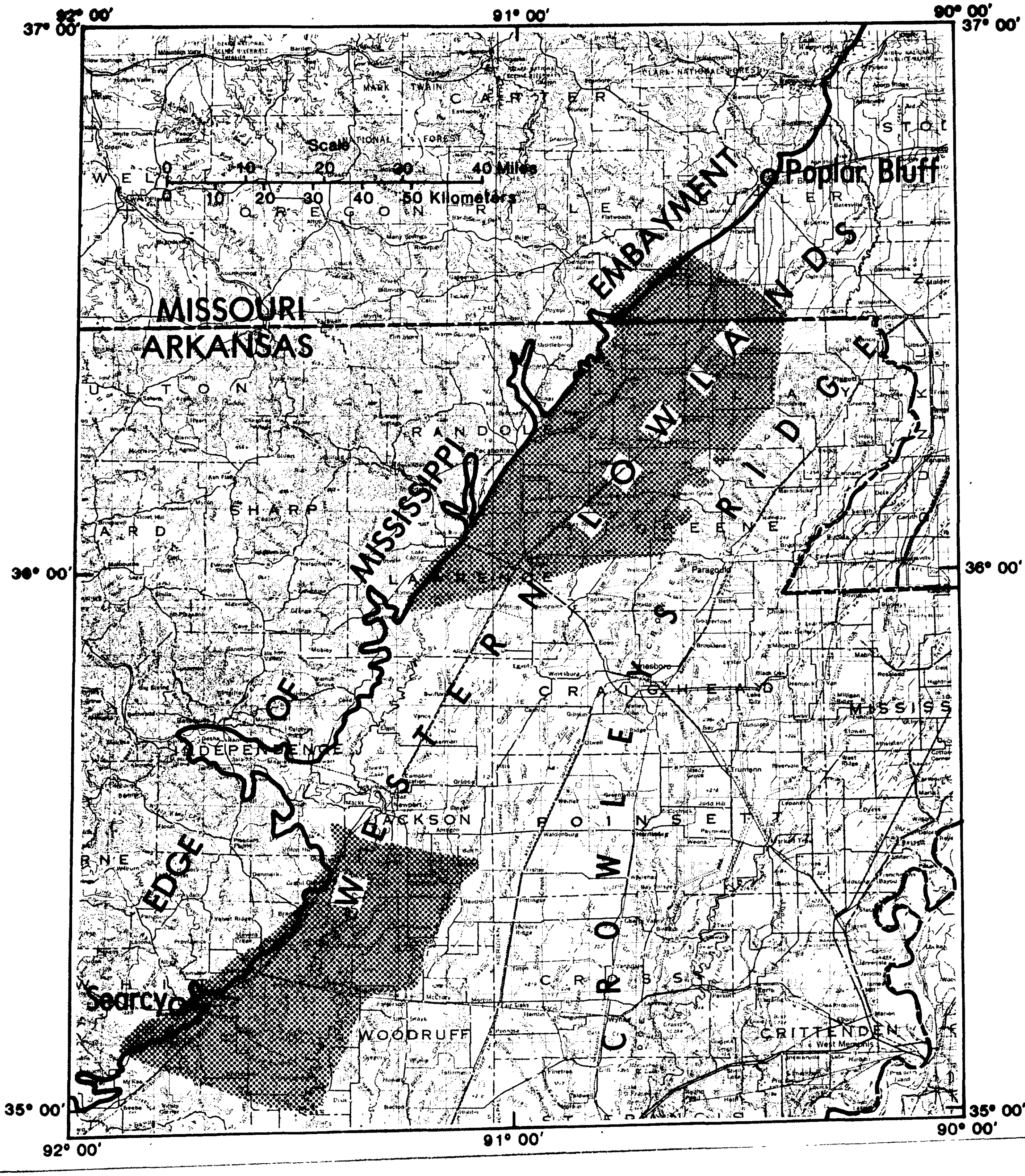


Figure 45.--Areas in Western Lowlands of Arkansas and Missouri where sandblows (stippled pattern) are interpreted from study of aerial photographs. Areas in Western Lowlands without pattern may contain sandblows but suitable aerial photographs were not available for interpretation.

than 100 feet in diameter) and are a few feet high. Where they occur in the alluvium of the Mississippi Valley, they are lighter in color than the surrounding alluvium and vegetation on them is commonly stunted. The origin of Mima mounds is unknown. An attempt was made to differentiate sandblows from Mima mounds on the aerial photographs, but because there was no opportunity to examine these features in the field, the attempt may not have been very successful. Generally, larger, more irregular forms were mapped as sandblows and smaller, more circular forms of uniform size were mapped as Mima mounds.

Sandbars in abandoned stream channels may also have a light appearance similar to that of sandblows and Mima mounds. They characteristically have long linear, gently arcuate shapes. Sandblows may be present in areas of sandbars and may be mistaken for sandbars, and vice-versa.

TIME OF PHOTOGRAPHY PROBLEM

Photography taken when ground is bare is most useful for mapping sandblows or other features that appear as tonal changes on photographs. Most of the area of interest is farmed, and crops obscure the visability of sandblows. Sandblows are certainly present in wooded areas at many places, but invisible on the photographs. Mapped boundaries (figure 45) may be highly inaccurate in many areas because of the vegetation problem.

RELATION OF SANDBLOWS TO SOIL TYPES

The U.S. Department of Agriculture Soil Conservation Service has published maps and reports of soil surveys of many counties in the study area. These reports contain aerial photographs of the counties with soil unit boundaries overprinted. I examined the reports for Craighead, Independence, Jackson, and Lawrence Counties, Ark. (Ferguson, 1979; Ferguson and others, 1982; Gore, 1974; Gore and others, 1978). Sandblows appear to be abundant in some areas in these counties, being most abundant on soils classified as fine sandy loam. Where most abundant, the area of sandblows is greater than the area between sandblows and therefore is a determining factor in classifying the soil as "fine sandy". Sandblows appear to be abundant on some other soil types, with silt loam being the next most common host environment for them.

PHOTOGRAPHY AVAILABLE

AMS (Army Map Service) photography at about 1:80,000 scale was used where available, because scale is best for reconnaissance. The area covered, however, is patchy.

U.S. Geological Survey photography at a scale of about 1:40,000 is good, but areas covered are also patchy.

ASCS (Agriculture Soil Conservation Service) photography at a scale of about 1:20,000 is available for much of the area of this project. It was used very little because time was not available to examine the very large number of photographs needed to cover the study area.

PHOTOGRAPHY EXAMINED

Cache River area (not shown on figure 45)

378807 HAP 81 series photographs

Dated:	4-23-82
Photographs:	230-6 to 230-9 230-63 to 230-66 230-72 to 230-76
Summary:	Possible sandblows on photographs 8, 64, 73, 74

Western Lowlands from north of Corning to south of Walnut Ridge, Ark.

VV FS M AMS series photographs

Dated:	9-9-49, photographs 511 to 525 11-5-49, photographs 2914 to 2928 9-1-49, photographs 391 to 406 photographs 363 to 378 9-23-49, photographs 1141 to 1157 photographs 1158 to 1167
Summary:	Probable sandblow appearing features and Mima mounds are abundant on photographs 1160-1162, 1148-1151, 369-370, 394-396, 2917-2918, 522-525.

Western Lowlands (eastern part) near Jonesboro, Ark.

GS-VDMJ series photographs

Dated:	4-9-74
Photographs:	1-108 to 1-114 1-101 to 1-107 1-83 to 1-90
Summary:	Probable sandblows on photographs 1-108. Many more sandblows may be present but obscured by early crops. The possibility of sandblows in the western lowlands southwest of Jonesboro, Ark. (fig. 45), is particularly suspect.

Western Lowlands (western part) from south of Newport to DesArc, Ark.

VV FS M AMS series photographs

Dated: 9/1/49, photographs 308-316
10-12-49, photographs 1755-1765
9-9-49, photographs 527-538
8-31-49, photographs 209-222
8-11-49, photographs 54-62
7-19-49, photographs 1-9

Summary: Probable sandblows abundant and visible even on photos taken in summer.

Western Lowlands, northeast corner of Poplar Bluff 2° quadrangle

GS-VEVD series photographs

Dated: 4-5-80

Photographs: 3-147 to 3-152
3-95 to 3-99

Summary: Probable sandblows abundant to common on photographs 3-149 to 3-152. They may be common or abundant other places but not recognized because of extent of crops at time of photographs (April). These photographs overlap with 29017 and 29023 series photographs. The area northwest of Fisk has abundant, plainly visible Mima mounds or sandblows on photograph 29023 17364, dated 10-20-73, but they are not apparent on these April photographs.

Western Lowlands east of Poplar Bluff, Mo.

A40 29023 series photographs

Dated: 10-20-73

Photographs: 173-59 to 173-65
173-77 to 173-85

Summary: Probable Mima mounds abundant north of Missouri Pacific Railroad. Sandblows abundant south of Missouri Pacific Railroad and common north of it.

Western Lowlands (southeast corner Rolla 2° quadrangle and southwest corner Paducah 2° quadrangle.

A40 29017 series photographs

Dated: 10-10-74

Photographs: 174-1 to 174-4
174-38 to 174-45
174-89 to 174-91

Summary: Probable Mima mounds abundant and sandblows common in area close to Lowlands-pre Tertiary boundary. Sandblows common to abundant southeast of this area.

CONCLUSIONS

By Margaret G. Hopper

The largest earthquake chosen for simulation in this study is an I_o = XI Modified Mercalli, m_b = 7.2, M_s = 8.6 shock anywhere along the New Madrid seismic zone. In no other location in the Midwest is such a large earthquake deemed likely. Its potential regional distribution of Modified Mercalli effects is shown in figure 14. Note that the map in figure 14 does not represent a single earthquake, but rather a composite of earthquakes along the New Madrid seismic zone. Thus the intensity at any given site is the maximum expected, but higher than that which would likely occur if the epicenter happened to be at the end of the seismic zone farthest from the site. The zone, for example, of intensity X M.M., would probably be shorter for a single shock. However, in 1811-1812 there were four major shocks and hundreds of aftershocks, many of them large enough to cause damage, especially in structures already damaged by the first main shock. The 1811-1812 shocks are thought to have begun at the southern end of the seismic zone and moved toward the northern end with each successive major earthquake from December 16 to February 7 (see table 1 and figure 1). Thus it is possible that all the areas of figure 14 would be exposed to the heavy damages more or less contemporaneously.

At the time of the largest shock or shocks, there would be geological effects such as liquefaction, flooding, and landsliding. Liquefaction and flooding are particularly a problem in the low-lying alluvial areas along the major watercourses. Landslides are most likely on the bluffs along these same watercourses, but also can occur on hills with susceptible geologic conditions anywhere.

Possible areas of intensities lower than those in nearby regions can be picked out on figure 14. The closest such area to the epicentral region is in south-central Arkansas. In general, the intensities tend to attenuate most rapidly on the southwest side of the New Madrid seismic zone. Within any county, areas of lower intensity than suggested on figure 14 can be found. The simulated intensities are for the worst conditions prevalent in a county. Intensity may be as much as several intensity levels lower in less susceptible areas of a county. Planners wishing to avoid the more high-risk areas should consult a local geologist and follow the examples provided by the separate studies of the seven cities in this report.

The seven cities studied represent a range in population and industrial development, but all are near the epicentral region and are likely to experience intensities of VIII or greater in the event of an M_s = 8.6 earthquake. Development of the city intensity maps for M_s = 8.6, (figures 20, 23, 26, 29, 32, 35, and 38) assumes the epicenter to be at the nearest point of the New Madrid seismic zone to each city. Actual level of intensity is determined from the regional map, figure 14, but within a city, distribution of effects and range of intensities is determined solely by local geologic conditions. A city with fairly uniform geologic conditions, such as Carbondale, is assigned a single intensity value (IX for the M_s = 8.6 shock) throughout the town. A city like Poplar Bluff, with a radical difference in the geologic conditions below and above the bluff, is assigned two intensity values (X and VIII) with a difference of two intensity levels. Results for the other cities for the hypothetical M_s = 8.6 earthquake are: Evansville, IX and VIII; Little Rock, VIII and VI; Memphis, X and IX; Paducah, X, IX, and VIII; and Saint Louis, IX, VIII, and VII.

Far more likely to occur than an M_s = 8.6, I_o = XI earthquake are the two smaller-magnitude shocks considered in this study. An I_o = X shock in the New Madrid seismic zone has a return period of 200 years (last one in 1811) and I_o = IX, 80 years (last one in 1895) (Algermissen, 1972). These may be compared to 500 years for the I_o = XI earthquake studied. The potential regional distributions for these two smaller shocks are shown in figures 15 and 16. As with figure 14, these maps are composites of the intensities produced by many earthquakes of magnitude 7.6 (figure 15) and magnitude 6.7 (figure 16) with epicenters all along the length of the New Madrid seismic zone.

Both of these shocks (M_s = 7.6 and 6.7) are capable of generating intensities high enough to cause geological effects such as liquefaction, flooding and landsliding. These effects will be most prevalent in the areas of intensity IX and above on figures 15 and 16.

Intensity maps for the seven cities studied are shown for the M_s = 7.6 earthquake (figures 21, 24, 27, 30, 33, 36, and 39) and for the M_s = 6.7 earthquake (figures 22, 25, 28, 31, 34, 37, and 40). Intensities found in the seven cities for the M_s = 7.6 earthquake are: Carbondale, VIII; Evansville, VIII and VII; Little Rock, VII and V; Memphis, IX and VIII; Paducah, IX, VIII, and VII; Poplar Bluff, IX and VII; and Saint Louis, VIII, VII, and VI. Intensities found for the same places for the M_s = 6.7 earthquake are one intensity unit lower than shown above for M_s = 7.6.

Long-period effects from any of the three earthquakes studied are expected to cause isolated instances of damage in susceptible locations at large epicentral distances. For example, Chicago, in the intensity-VII area of figure 14, may have some damage to tall buildings due to the period of the seismic waves at that distance being at or near the resonant period of the buildings. Much smaller earthquakes in or near the New Madrid seismic zone have been felt in tall buildings in Chicago.

APPENDIX 1

MODIFIED MERCALLI INTENSITY SCALE OF 1931
(From Wood and Neumann, 1931)

I

Not felt--or, except rarely under especially favorable circumstances.

Under certain conditions, at and outside the boundary of the area in which a great shock is felt:

I R.F.[1]

- sometimes birds, animals, reported uneasy or disturbed;
- sometimes dizziness or nausea experienced;
- sometimes trees, structures, liquids, bodies of water, may sway--doors may swing, very slowly.

II

Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons.

Also, as in grade I, but often more noticeably:

I to II R.F.

- sometimes hanging objects may swing, especially when delicately suspended;
- sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly;
- sometimes birds, animals, reported uneasy or disturbed;
- sometimes dizziness or nausea experienced.

III

Felt indoors by several, motion usually rapid vibration.

III R.F.

Sometimes not recognized to be an earthquake at first.

Duration estimated in some cases.

Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away.

Hanging objects may swing slightly.

Movements may be appreciable on upper levels of tall structures.

Rocked standing motor cars slightly.

[1] Indicates corresponding degree of intensity in the Rossi-Forel scale, an intensity scale widely used in the United States before the publication of the Modified Mercalli Scale in 1931. Intensity scales used in other parts of the world are discussed in Barosh (1969). An amplified version of the Modified Mercalli scale is given by Richter (1958).

IV

Felt indoors by many, outdoors by few.
Awakened few, especially light sleepers.
Frightened no one, unless apprehensive from previous experience.
Vibration like that due to passing of heavy, or heavily loaded trucks.

IV to V R.F.

Sensation like heavy body striking building, or falling of heavy objects inside.
Rattling of dishes, windows, doors; glassware and crockery clink and clash.
Creaking of walls, frame, especially in the upper range of this grade.
Hanging objects swung, in numerous instances.
Disturbed liquids in open vessels slightly.
Rocked standing motor cars noticeably.

V

Felt indoors by practically all, outdoors by many or most; outdoors direction estimated.
Awakened many, or most.
Frightened few--slight excitement, a few ran outdoors.
Buildings trembled throughout.
Broke dishes, glassware, to some extent.

V to VI R.F.

Cracked windows--in some cases, but not generally.
Overturned vases, small or unstable objects, in many instances with occasional fall.
Hanging objects, doors, swing generally or considerably.
Knocked pictures against walls, or swung them out of place.
Opened, or closed, doors, shutters, abruptly.
Pendulum clocks stopped, started, or ran fast, or slow.
Moved small objects, furnishings, the latter to slight extent.
Spilled liquids in small amounts from well-filled open containers.
Trees, bushes, shaken slightly.

VI

Felt by all, indoors and outdoors.

Frightened many, excitement general, some alarm, many ran outdoors.

Awakened all.

VI Persons made to move unsteadily.

to Trees, bushes, shaken slightly to moderately.

VII Liquid set in strong motion.

R.F. Small bells rang--church, chapel, school, etc.

Damage slight in poorly built buildings.

Fall of plaster in small amount.

Cracked plaster somewhat, especially fine cracks chimneys in some instances.

Broke dishes, glassware, in considerable quantity, also some windows.

Fall of knick-knacks, books, pictures.

Overturned furniture in many instances.

Moved furnishings of moderately heavy kind.

VII

Frightened all--general alarm, all ran outdoors.

Some, or many, found it difficult to stand.

Noticed by persons driving motor cars.

Trees and bushes shaken moderately to strongly.

Waves on ponds, lakes, and running water.

Water turbid from mud stirred up.

Incaving to some extent of sand or gravel stream banks.

Rang large church bells, etc.

Suspended objects made to quiver.

VIII-- Damage negligible in buildings of good design and

R.F. construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc.

Cracked chimneys to considerable extent, walls to some extent.

Fall of plaster in considerable to large amount, also some stucco.

Broke numerous windows, furniture to some extent.

Shook down loosened brickwork and tiles.

Broke weak chimneys at the roof-line (sometimes damaging roofs).

Fall of cornices from towers and high buildings.

Dislodged bricks and stones.

Overturned heavy furniture, with damage from breaking.

Damage considerable to concrete irrigation ditches.

VIII

Fright general--alarm approaches panic.
  Disturbed persons driving motor cars.
  Trees shaken strongly--branches, trunks, broken off, especially palm trees.
  Ejected sand and mud in small amounts.
  Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters.

VIII+ to IX- R.F.

Damage slight in structures (brick) built especially to withstand earthquakes.
  Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling.
  Fall of walls.
  Cracked, broke, solid stone walls seriously.
    Wet ground to some extent, also ground on steep slopes.
  Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers.
  Moved conspicuously, overturned, very heavy furniture.

IX

Panic general.
Cracked ground conspicuously.
Damage considerable in (masonry) structures built especially to withstand earthquakes:

IX+ R.F.

  threw out of plumb some wood-frame houses built especially to withstand earthquakes;
  great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames;
  serious to reservoirs; underground pipes sometimes broken.

X

Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks.

Landslides considerable from river banks and steep coasts.

Shifted sand and mud horizontally on beaches and flat land.

X Changed level of water in wells.

R.F. Threw water on banks of canals, lakes, rivers, etc.

Damage serious to dams, dikes, embankments.

Severe to well-built wooden structures and bridges, some destroyed.

Developed dangerous cracks in excellent brick walls.

Destroyed most masonry and frame structures, also their foundations.

Bent railroad rails slightly.

Tore apart, or crushed endwise, pipe lines buried in earth.

Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI

Disturbances in ground many and widespread, varying with ground material.

Broad fissures, earth slumps, and land slips in soft, wet ground.

Ejected water in large amount charged with sand and mud.

Caused sea-waves ("tidal" waves) of significant magnitude.

Damage severe to wood-frame structures, especially near shock centers.

Great to dams, dikes, embankments, often for long distances.

Few, if any (masonry), structures remained standing.

Destroyed large well-built bridges by the wrecking of supporting piers, or pillars.

Affected yielding wooden bridges less.

Bent railroad rails greatly, and thrust them endwise.

Put pipe lines buried in earth completely out of service.

XII

Damage total--practically all works of construction damaged greatly or destroyed.

Disturbances in ground great and varied, numerous shearing cracks.

Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive.

Wrenched loose, tore off, large rock masses.

Fault slips in firm rock, with notable horizontal and vertical offset displacements.

Water channels, surface and underground, disturbed and modified greatly.

Dammed lakes, produced waterfalls, deflected rivers, etc.

Waves seen on ground surfaces (actually seen, probably, in some cases).

Distorted lines of sight and level.

APPENDIX 2

EFFECTS OF THE 1811-12, 1843, 1895, AND 1968 EARTHQUAKES AT CARBONDALE, ILLINOIS

1811 December 16 2:15 a.m. (238 km from Carbondale)

No information on Carbondale. Within 100 km of Carbondale Street and Nuttli's (1984) intensity map for this shock shows that intensities were assigned to two locations: VII-VIII 40 km southeast of Carbondale, and VII 40 km southwest of Carbondale on the Mississippi River. Carbondale is within the VIII area on Nuttli's (1981) isoseismal map.

1811 December 16, 8:15 a.m. (202 km from Carbondale)

No information on Carbondale. No intensities assigned to any location within 100 km of Carbondale on Street and Nuttli's (1984) intensity map for this shock. Within 200 km of Carbondale are locations assigned V, VI-VII, VII, VII, VII-VIII, VIII, and XI.

1812 January 23 (178 km from Carbondale)

No information on Carbondale. Street and Nuttli's (1984) intensity map for this earthquake shows one location having an assigned intensity within 100 km of Carbondale: VII-VIII 40 km southwest of Carbondale.

1812 February 7 (142 km from Carbondale)

No information on Carbondale. Street and Nuttli's (1984) intensity map for this shock shows one location having an assigned intensity within 100 km of Carbondale: VIII 40 km southwest of Carbondale.

1843 January 5 (307 km from Carbondale)

No information on Carbondale. Carbondale lies within the intensity-V area on the isoseismal map of Hopper and Algermissen (unpub. data, 1983). Within a 100-km radius of Carbondale are two intensity-IV locations.

1895 October 31 (81 km from Carbondale)

No information on Carbondale. Within a 60-km radius of Carbondale are two VII's, one V, one Felt and one Heavy on Hopper and Algermissen' (1980) isoseismal map. Carbondale lies within the VII isoseismal.

1968 November 9 (69 km from Carbondale)

From United States Earthquakes, 1968 (Coffman and Cloud, 1970): "Carbondale.--Felt by all and frightened many. Putty cracked around picture windows of trailer. North-south crack in cement walk. Some oil tanks overturned, all oriented with long axis north-south. Small objects fell to the west. Television shifted slightly. Water in fish tank was splashed out on the west side. Trailer's blocks sank into mud on the northwest corner and had to be releveled after quake. Walking was difficult. Damage slight." They assigned intensity VI.

APPENDIX 3

EFFECTS OF THE 1811-12, 1843, 1895, AND 1968 EARTHQUAKES AT EVANSVILLE, INDIANA

1811 December 16, 2:15 a.m. (336 km from Evansville)

No information on Evansville. Within 100 km of Evansville Street (1982) and Street and Nuttli (1984) show: VIII at the approximate location of Evansville; VII-VIII 80 km north of Evansville, VI-VII 90 km south of Evansville, VI 70 km south of Evansville, VI 45 km southeast of Evansville, and VII 20 km south of Evansville. Street (1982) also lists an VIII at Uniontown, Ky., 40 km southwest of Evansville; Nuttli (1981) shows $\geq$IX at approximately this location. Evansville is within the VII isoseismal on Nuttli's (1981) map.

1811 December 16, 8:15 a.m. (305 km from Evansville)

No information on Evansville. Street and Nuttli's (1984) intensity map for this shock shows an VIII at the approximate location of Evansville, and a VII directly across the river.

1812 January 23 (280 km from Evansville)

No information on Evansville. Street and Nuttli (1984) show one location having an assigned intensity within 100 km of Evansville: VII 80 km north of Evansville.

1812 February 7 (241 km from Evansville)

No information on Evansville. Two locations having assigned intensities are shown within 100 km of Evansville on Street and Nuttli's (1984) intensity map for this shock: VII 80 km north of Evansville, and VI 50 km south of Evansville. They also assign VIII to Louisville, Ky., 160 km east of Evansville on the Mississippi River.

1843 January 5 (402 km from Evansville)

No information on Evansville. Evansville lies within the intensity-V area on the isoseismal map of Hopper and Algermissen (unpub. data). Within a 100-km radius of Evansville there are one intensity-V and one intensity-IV location.

1895 October 31 (192 km from Evansville)

Marvin (1895) records the earthquake as felt at Evansville. Within a 60-km radius of Evansville there are one VIII, two VII's, three heavy's, and one felt on Hopper and Algermissen's (1980) map. Evansville lies within the VII isoseismal and near the edge of the VIII isoseismal on that map.

1968 November 9 (81 km from Evansville)

From United States Earthquakes, 1968 (Coffman and Cloud, 1970): "Evansville (Federal Building).--Felt by all. Two ornament columns on building dislodged. About 4 square feet [0.4 m^2] of plaster fell from third floor ceiling. Small objects fell. Loud earth noises. Damage slight. Press reported a chimney fell on old house, and that plaster cracked and broke throughout the city. Bricks loosened on an old church building, and wall threatened to collapse." They assigned intensity VI.

APPENDIX 4

EFFECTS OF THE 1811-12, 1843, 1895, AND 1968 EARTHQUAKES AT LITTLE ROCK, ARKANSAS

1811 December 16, 2:15 a.m. (212 km from Little Rock)

No information on Little Rock. The closest location having an assigned intensity is a VII-VIII near the mouth of the Arkansas River, approximately 130 km southeast of Little Rock, on Street and Nuttli's (1984) intensity map for this shock. Little Rock is off the edge of Nuttli's (1981) isoseismal map for the 1811 earthquake, but extension of his isoseismals would probably place it in the VII or VIII area.

1811 December 16, 8:15 a.m. (247 km from Little Rock)

No information on Little Rock. Street and Nuttli's (1984) intensity map for this shock shows no locations having assigned intensities within 200 km of Little Rock.

1812 January 23 (274 km from Little Rock)

No information on Little Rock. Street and Nuttli's (1984) intensity map for this shock shows no locations having assigned intensities within 200 km of Little Rock.

1812 February 7 (311 km from Little Rock)

No information on Little Rock. Street and Nuttli's (1984) intensity map for this shock shows no locations having assigned intensities within 200 km of Little Rock.

1843 January 5 (170 km from Little Rock)

An intensity IV is assigned at Little Rock by Hopper and Algermissen (unpub. data). From the Arkansas State Gazette, Little Rock, Ark., January 11, 1843: "Earthquake. - On the fourth instant about half past eight o'clock, P.M., a quaking of the earth was very sensibly felt here, attended by the rattling of windows, glasses, and cupboards, and the creaking of our wooden houses....The shaking of the earth in this instance seemed to indicate a vibratory motion from N.E. to S.W., and continued for about the space of one minute."

1895 October 31 (362 km from Little Rock)

Intensity V is assigned at Little Rock by Hopper and Algermissen (1980). From Marvin (1895): "Distinct earthquake, the vibrations being east and west and lasting about one minute, occurred at 6:15 a.m. Shock was also felt at Forrest City, Helena, Brinkley, and several other points in eastern Arkansas."

1968 November 9 (498 km from Little Rock)

United States Earthquakes, 1968 (Coffman and Cloud, 1970) assigns intensity I-IV at Little Rock.

APPENDIX 5

EFFECTS OF THE 1811-12, 1843, 1895, AND 1968 EARTHQUAKES AT MEMPHIS, TENNESSEE

1811 December 16, 2:15 a.m. (80 km from Memphis)
Street (1981) quotes The American Statesman, Lexington, Ky., March 3, 1812: "At Fort Pickering, the block house, which is almost a solid mass of hewn timber, trembled like an aspen leaf."

Nuttli (1973 and 1981) gives IX at Fort Pickering near Memphis. Street (1982) notes insufficient information, and Street and Nuttli (1984) show VIII there. There are no other assigned intensities within 100 km of Memphis on Street and Nuttli's (1984) intensity map. Memphis is within the IX area on Nuttli's (1981) isoseismal map for this shock.

1811 December 16, 8:15 a.m. (100 km from Memphis)
No information on Memphis. Street and Nuttli's (1984) intensity map for this shock shows no locations having assigned intensities within 100 km of Memphis.

1812 January 23 (120 km from Memphis)
No information on Memphis. Street and Nuttli's (1984) intensity map for this shock shows no locations having assigned intensities within 200 km of Memphis.

1812 February 7 (160 km from Memphis)
No information on Memphis. Street and Nuttli's (1984) intensity map for this earthquake shows no locations having assigned intensities within 100 km of Memphis.

1843 January 5 (32 km from Memphis)
Intensity VIII assigned by Hopper and Algermissen, unpub. data.

From The Daily Picayune, New Orleans, La, January 10, 1843: "Courier reports of Memphis newspaper--hundreds run into streets, in fear houses would tumble down. No damage done, unless it be to crockery ware. The vibrations of the earth lasted in all two minutes and were accompanied by a heavy rumbling sound."

From The Weekly Picayune, New Orleans, La., January 16, 1843: "The Memphis papers of the 5th instant give the particulars of one of the greatest earthquakes which has occurred there since 1811. The paroxysm commenced about twenty minutes before 9 o'clock, on the evening of the 4th instant, and lasted about half a minute during which time, says the Enquirer, 'the firm-set earth did reel to and fro as a drunken man,' so violently indeed as to make hundreds run into the streets from fear that the houses they were in were about to tumble down. No damage, however, was done, unless it be to crockery-ware, which we should think it likely have suffered some where placed loosely on shelves. The vibrations of the earth might have lasted in all nearly two minutes, and were accompanied by a heavy rumbling sound as if some seventeen hundred and fifty heavy loaded wagons had been driving briskly along the street.

There was quite a rush at the theatre, and indeed everywhere else, to get out of doors, and the shrieks of females were heard in different quarters of the town. The Editor of the Enquirer closes his account of the earthquake with, We shall not be surprised to hear of considerable damage being done at Mills Point, New Madrid, etc.'"

From The Memphis Appeal, Memphis, Tenn., January 13, 1843: "...It was preceded and accompanied with a rumbling sound, as of rumbling thunder. Opinions are various as to that period of duration--some supposing half a minute, and some as much as two minutes--but all agree that it was a rather alarming affair, and by far the severest since 1811. But little damage has been done to buildings. The coping of some chimneys has been removed, and we have heard of the prostration of a cotton shed."

From The American Eagle, Memphis, Tenn., January 6, 1843: "At about half past 8 o'clock yesterday evening our City was visited by one of those awful throes of Nature, so convulsive and terrible, as to spread almost universal alarm over the city. The firmest buildings trembled and cracked, and the earth reeled and rocked under a most terrific excitement...

We were in our office at the moment, in the second story of a new block of brick buildings. The commencement of the jarring we conceived to proceed from the violent undertaking of some person to shake open a door beneath us. But in a moment afterwards, the agitation seized the brick walls surrounding us, shaking and reeling them, to such an extent, as to knock down particles of brick and plaster, jarring the roof and whole building so as to impress us with the fear of the building's falling. Sensible of the appalling cause of the agitation, we hastily fled into the street for safety....In the street was still a violent rocking of the earth, and a rattling and rumbling noise. People fled into the streets, and cries, and lamentations of many horror-stricken men and women were heard to fill the air.

The shock lasted about two minutes, and reached its most agitation period at the end of the first half minute, when it gradually died away in a dismal rumbling sound, apparently moving to the south-east, and proceeded from the north-west...

The tops of several chimneys were shaken down, the bricks falling inside, and with the reeling of the houses and quaking of the earth, frightfully alarming the inhabitants. A great many brick walls are seriously cracked and sunk, windows broken, and a cotton shed, naturally crazy, fell down shortly after the shock. At our auction houses, which were filled with people, so alarming and precipitate was the rush into the street that many people were crushed and trampled upon by the affrightened crowd."

From Heinrich (1941): "Destructive at Memphis, Tennessee, where chimneys fell and brick walls cracked. One building reputedly collapsed."

1895 October 31 (223 km from Memphis)
Intensity VI assigned by Hopper and Algermissen (1980).

From The Telegraph Herald, Dubuque, Iowa, November 1, 1895: "Memphis, Tenn., Oct. 31.--A violent earthquake shook Memphis Thursday morning at 5:08. The shock lasted not over a minute. It was preceded by a roar."

From The Saint Louis Post-Dispatch, Saint Louis, Mo., October 31, 1895: "MEMPHIS, Tenn., Oct. 31.--A heavy shock of earthquake was felt here this morning at 5:08. The vibration was from east to west. Houses rocked and people were almost spilled out of bed. The shock lasted about a minute, and was preceded by a rumbling sound."

From Heinrich (1941): "Several chimneys were reported thrown down in the suburbs of Memphis, Tennessee."

From Marvin (1895): "An earthquake shock of considerable severity was felt in this city this morning shortly after 6 o'clock. A careful comparison of time by a number of competent observers shows that the vibrations from the first shock ceased at 6 hr. 07 min. 30 sec. a.m., having lasted about thirty seconds. A secondary shock or vibration was observed at 6 hr. 14 min. 00sec. by a number of reliable observers, though not by all. There was no damage done in this city, except to two chimneys in the suburbs, which were shaken down."

From Moneymaker (1954): "At...Memphis, Tennessee, several chimneys were thrown down."

1968 November 9 (350 km from Memphis)
United States Earthquakes, 1968 (Coffman and Cloud, 1970) assigns intensity I-IV at Memphis.

APPENDIX 6

EFFECTS OF THE 1811-12, 1843, 1895, AND 1968 EARTHQUAKES AT PADUCAH, KENTUCKY

1811 December 16, 2:15 a.m. (205 km from Paducah)

Street (1981) quotes Dudley (1858): "About four miles above Paducah, on the Ohio river, on the Illinois side, on a post-oak flat, a large circular basin was formed, more than one hundred feet in diameter, by the sinking of the earth, how deep no one can tell, as the tall stately post-oaks sank below the tops of the tallest trees. The sink filled with water, and continues so to this time."

No other information about Paducah. Street and Nuttli's (1984) intensity map shows two locations having assigned intensities within 100 km of Paducah: X 95 km southwest of Paducah, and VII-VIII 8 km northwest of Paducah. Street (1982) also lists VIII for Dorena, Mo., 75 km southwest of Paducah. On Nuttli's (1981) isoseismal map, Paducah is within the intensity-IX area.

1811 December 16, 8:15 a.m. (170 km from Paducah)

No information on Paducah. Street and Nuttli's (1984) intensity map for this shock shows only one location having an assigned intensity within 100 km of Paducah: V 100 km east of Paducah.

1812 January 23 (145 km from Paducah)

No information on Paducah. Street and Nuttli's (1984) intensity map for this shock shows no locations having assigned intensities within 100 km of Paducah.

1812 February 7 (102 km from Paducah)

No information on Paducah. Street and Nuttli's (1984) intensity map for this shock shows no locations having assigned intensities within 100 km of Paducah. However, two VI's an VIII, and an XI are assigned to places less than 150 km from Paducah.

1843 January 5 (269 km from Paducah)

No information on Paducah. On Hopper and Algermissen's (unpub. data) isoseismal map there are two VII's, two IV's, and three felt's within a 100-km radius of Paducah; none of these points is within 75 km of Paducah.

1895 October 31 (81 km from Paducah)
Intensity VIII assigned by Hopper and Algermissen (1980).

From The Saint Louis Post-Dispatch, Saint Louis, Mo., October 31, 1895: "PADUCAH, Ky., Oct. 31.--At 5:10 o'clock this morning a severe shock of earthquake was felt all over town. Houses swayed to and fro, a number of chimneys fell and several walls were cracked."

1968 November 9 (105 km from Paducah)
From United States Earthquakes, 1968 (Coffman and Cloud, 1970): "Paducah.--Few bricks fell from chimneys (press)." They assigned intensity VI.

APPENDIX 7

EFFECTS OF THE 1811-12, 1843, 1895, AND 1968 EARTHQUAKES AT POPLAR BLUFF, MISSOURI

1811 December 16 2:15 a.m. (104 km from Poplar Bluff)

No information on Poplar Bluff. Street and Nuttli (1984) show three locations having assigned intensities within 100 km of Poplar Bluff: X 80 km east of Poplar Bluff, XI 90 km southeast of Poplar Bluff, and VII 95 km north of Poplar Bluff. Poplar Bluff is near the outer edge of the intensity-IX area on Nuttli's (1981) isoseismal map.

1811 December 16, 8:15 a.m. (90 km from Poplar Bluff)

No information on Poplar Bluff. Street and Nuttli's (1984) intensity map for this shock shows only one location having an assigned intensity within 100 km of Poplar Bluff: XI 50 km southeast of Poplar Bluff.

1812 January 23 (87 km from Poplar Bluff)

No information on Poplar Bluff. Street and Nuttli's (1984) intensity map for this shock shows one location having an assigned intensity within 100 km of Poplar Bluff: VII-VIII 95 km north of Poplar Bluff.

1812 February 7 (82 km from Poplar Bluff)

No information on Poplar Bluff. Street and Nuttli's (1984) intensity map for this shock shows two locations having assigned intensities within 100 km of Poplar Bluff: XI about 70 km east of Poplar Bluff and VIII 95 km north of Poplar Bluff.

1843 January 5 (179 km from Poplar Bluff)

No information on Poplar Bluff. On Hopper and Algermissen's (unpub. data) isoseismal map there are one VII (at New Madrid) and one IV within a 100-km radius of Poplar Bluff. Both points are on the Mississippi River and are over 75 km away from Poplar Bluff. Poplar Bluff is on the edge of the VI isoseismal.

1895 October 31 (94 km from Poplar Bluff)

Poplar Bluff lies within the intensity-VI isoseismal, and near the edge of the VII isoseismal on Hopper and Algermissen's (1980) map for the 1895 earthquake. Within a 30-km radius of Poplar Bluff are intensities of VIII and V. Poplar Bluff itself is assigned Felt.

From Heinrich (1941): "At Poplar Bluff the movement was described as rocking and seemed to be east-west. A noise 'like a cyclone' preceded the shock."

1968 November 9 (218 km from Poplar Bluff)

United States Earthquakes, 1968 (Coffman and Cloud, 1970) assigned intensity V at Poplar Bluff.

APPENDIX 8

EFFECTS OF THE 1811-1812, 1843, 1895, AND 1968 EARTHQUAKES AT SAINT LOUIS, MISSOURI

1811 December 16, 2:15 a.m. (317 km from Saint Louis)
Street and Nuttli (1984) show intensity VII at Saint Louis on their intensity map for this shock.

Street (1981) quotes from The Louisiana Gazette, Saint Louis, Mo., December 21, 1911:

Earthquake

On Monday morning last, about a quarter past two, St. Louis and the surrounding country, was visited by one of the most violent shocks of earthquake that has been recorded since the discovery of our country.

As we were all wrapt in sleep, each tells his story in his own way. I will also relate my simple tale.

At the period above mentioned. I was roused from sleep by the clamor of windows, doors and furniture in tremulous motion, with a distant rumbling noise, resembling a number of carriages passing over pavement - in a few seconds the motion and subterraneous thunder increased more and more: believing the noise to proceed from N. or N.W. and expecting the earth to be relieved by a volcanic eruption, I went out of doors & looked for the dreadful phenomenon. The agitation had now reached its utmost violence. I entered the house to snatch my family from its expected ruins, but before I could put my design in execution the shock had ceased, having lasted about one and three fourth minutes. The sky was obscured by a thick hazy fog, without a breath of air. Fahrenheit thermometer might have stood at this time at about 35 or 40°.

At forty seven minutes past two, another shock was felt without any rumbling noise and much less violent than the first, it lasted near two minutes.

At thirty four minutes past three, a third shock nearly as tremulous as the first, but without as much noise, it lasted about fifty seconds, a slight trembling continued at intervals for some time after.

A little after day light, a fourth shock was felt, but with less violence than any of the others, it lasted nearly one minute.

About 8 o'clock, a fifth shock was felt; this was almost as violent as the first, accompanied with the usual noise, it lasted about half a minute: this morning was very hazy and unusually warm for the season, the houses and fences appeared covered with a white frost, but on examination it was found to be vapour, not possessing the chilling cold of frost: indeed the moon was enshrouded in awful gloom.

At half past eleven, a slight shock was felt, and about the same hour on Tuesday last, a smart shock was felt - several gentlemen declare, they felt shocks at other intervals.

No lives have been lost, nor has [sic] the houses sustained much injury, a few chimneys have been thrown down, and a few stone houses split.

In noticing extraordinary events, perhaps no attendant circumstances should be deemed unimportant: This is one of that character, a faithful record of appearances in such cases as these, may form data for science. Viewing the subject in this way, it may not be amiss to notice the reports of those who have explored the extensive plains and mountains of the West.

On the margin of several of our rivers pumice and other volcanic matter is found. At the base of some of the highest of the black mountains, stone covers the earth, bearing marks of the violent action of fire. Within -0 [sic] miles of the great Osage village on the head waters of their river, and 1-0 [sic] miles from this town, it is said that a volcano had ceased to burn for the last three years, and it is thought to have now broke out in some quarter of our country. Upon the whole, this has been an uncommon year; the early melting of snow to the north raised the Mississippi to an unusual height. The continued rains in the summer and the subsequent hot weather, and consequent sickness amongst the inhabitants, rendered that period somewhat distressing. - Autumn, to this time, has been unusually mild, and health pervades the land in every quarter.

Since writing the above, several slight shocks were sensibly felt, to the number ten or twelve.

Editor

1811 December 16, 8:15 a.m. (290 km from Saint Louis)
Street and Nuttli (1984) show intensity VI-VII at Saint Louis on their intensity map for this shock. See also, the account above from the Louisiana Gazette.

1812 January 23 (275 km from Saint Louis)
No information on Saint Louis. Street and Nuttli's (1984) intensity map shows no data within 100 km of Saint Louis.

1812 February 7 (245 km from Saint Louis)
Intensity VIII assigned by Street and Nuttli (1984).

Street (1981) quotes from The Louisiana Gazette, Saint Louis, Mo., February 8, 1812: "On Thursday morning last, between 2 & 3 o'clock, we experienced the most severe shock of earthquake that we have yet felt, many houses are injured, and several chimneys thrown down; few hours pass without feeling slight vibrations of the earth. Should we ever obtain another mail, we shall be attentive in recording the progress in every quarter."

1843 January 5 (390 km from Saint Louis)
Intensity VII assigned to Saint Louis (Hopper and Algermissen, unpub. data).

From the Missouri Reporter, Saint Louis, Mo., January 5, 1843: "Earthquake felt N to S."

From the Missouri Reporter, Saint Louis, Mo., January 12, 1843, which quotes the Cincinnati Gazette: "Lasted 3 to 4 minutes and shook free looking-glasses, etc., in an extraordinary manner."

From the Daily Missouri Republican, Saint Louis, Mo., January 6, 1843: "A SHOCK OF AN EARTHQUAKE - On Wednesday evening about 9 o'clock, the citizens of Saint Louis were thrown into considerable trepidation by a shock of an earthquake. The shock was nearly a minute in duration, and so severe as to make the timbers in some houses crack, and generally the glass in each of the windows, and glasses upon the sideboards jingle and rattle, and the chairs and tables rock and shake. Persons who were in third and fourth stories felt it most sensibly, and in many instances fled from their rooms; it was, however, sensibly felt by persons in other apartments. It was accompanied by a rumbling noise, like the rolling of a heavy carriage over the pavement. We have various statements as to the direction of the vibration but those in the best position to observe, and coolest at the time, say it was from West to East. It was the severest shock felt in the city for several years, and is the second felt in about three months."

From Moneymaker (1954), "Persons standing or walking found it difficult to stand upright in St. Louis, Missouri, and Louisville, Kentucky."

From Coffman, von Hake, and Stover (1982), "At St. Louis, Mo., people were frightened; one chimney fell."

From Heinrich (1941): "At St. Louis the intensity was reported as sufficient to knock people down."

From a letter from W. C. Love to his wife who was visiting in Terre Haute, Indiana; letter dated 15 January 1843: "The earthquake shook us 'considerably'--I was on Horse-back & supposed that my Horse had started & stumbled--I have heard of no damage, in Town, except to Mauro's chimney & the chimney of the Session-House of Ballard's church." [No location is given for the writer of the letter. St. Louis was assumed because of the account of the session-house chimney, reported also in the press. See Peoria Register account below.]

From <u>The Peoria Register and North-western Gazetter</u>, Peoria, Ill., January 13, 1843: "An earthquake continuing for a minute and over was felt in this city about nine o'clock last night. The tremulous motion was uncommonly severe--and from its long duration, created a great deal of alarm. Many persons ran out of the 2d Presbyterian and Unitarian Churches. The consternation is reported as having been very great. Several ladies in the first named church manifested signs of extreme terror and some burst into tears. Part of the chimney of the session house of the first Presbyterian

Church...[line blank]...rubbish, sliding from a neighboring roof, was driven through a window into the room. There was a meeting going on at the time.

It is not recollected that since the great New Madrid earthquakes, the city has been visited by shocks so severe and prolonged as those last night. It is thought that the motion was from south to north. Such shocks were frequent just before the ravages of the New Madrid earthquakes."

1895 October 31 (198 km from Saint Louis)
Intensity VI was assigned by Hopper and Algermissen (1980).

From the Daily News, Denver, Colo., November 1, 1895: "The Most Severe Felt Since the Year 1811. ST. LOUIS, Oct. 31.--At 5:12 a.m. several severe earthquake shocks were distinctly felt here. The vibrations were from east to west and each shock continued several seconds. The operators in the Western Union telegraph office became alarmed and several rushed from the building. The shocks were not accompanied by any rumbling noise. Clocks were stopped and windows rattled, but no serious damage has as yet been reported.

In the west end of the city the people, it is reported by the telephone company, rushed in alarm from their homes, and returned only after having become numb with cold.

Up to 10 a.m. no dmage had been reported beyond the toppling of a few old chimneys, a general swaying of beds and the rattling of furniture and other loose things. The shock was the severest ever felt here and lasted fully two minutes. The weather bureau reports the vibrations were from east to west...

Prof. F. E. Nipher of the Washington university, who has taken a deep interest in the study of earthquakes, said to an Associated press representative to-day:

"To the best of my knowledge this is the most severe earthquake in this locality since the New Madrid earthquake in southwest [sic] Missouri in 1811. As far as I can determine now the direction of this vibration was from north to south, or probably from northeast to southwest.

Prof. Prichard of the Washington university thinks nearly the correct time of the shock was 5:7:25, and that it lasted about one minute and forty-five seconds."

From the Telegraph Herald, Dubuque, Iowa, November 1, 1895: "St. Louis, Oct. 31.--At 5:12 Thursday morning a distinct earthquake shock was felt here. Buildings trembled and people ran excitedly into the street. The shock lasted three minutes."

From Marvin (1895): "A slight shock of earthquake was felt at 6.10 a.m., lasting about fifteen seconds. The direction of vibration was from east to west. No damage of consequence reported."

From the Post Dispatch, Saint Louis, Mo., October 31, 1895: "An Earthquake Shakes the City--Violent Seismic Disturbance Lasting Nearly a Minute--Felt Throughout the City--Houses Rocked, Windows Rattled and Brick chimneys Tumbled to the Ground--St. Louis was awakened this morning by the liveliest earthquake that has been felt here in many years.

There were no casualties and the damage to property consisted of the destruction of a few chimneys and the demolition of a few tottering walls. The German Lutheran Church, on Eighth and Walnut streets, got about the worst treatment. It will probably have to be torn down, as the walls are badly cracked.

The shock or shocks, for there appears to have been two of them, were sufficiently violent, however, to arouse everybody who was asleep and to alarm those who were awake. There were panics in the hotels and the all-night resorts, and at the Western Union Telegraph office the operators stampeded.

The time of the disturbance was 5:10, and it lasted at least 45 seconds. Some alleged experts on such phenomena insist that it was twice as long. Opinions vary as to the duration of the vibrations. The Weather Bureau officials say it was from east to west, but a great many citizens claim it was from north to south. Others hold to a diagonal, northwest to southeast theory, and still others contend that the movement was from southwest to northeast.

The first shock was a short and slight one. It was followed by a heavy rumbling, as described by old soldiers as similar to the sound of artillery passing over a paved road. Then came a heavy trembling that endured for more than thirty seconds and did the damage to property.

The shocks were felt in every quarter of the city and in St. Louis County and in numerous adjoining towns.

The shock was also felt on the division of the Toledo, St. Louis & Kansas City Railway from St. Louis to Frankfort, Ind., a distance of 245 miles.

The venerable brick church of the Holy Ghost, German Lutheran, southwest corner of Eighth and Walnut streets, was badly shaken and cracked. A chimney at its northeast corner was thrown down, and the cornice work along the Walnut street side near Eighth, was crumbled and cracked in a number of places. The massive front section which forms the vestibule and choir seems to be wholly detached at the top from the body of the building, which has left a crack an inch or more wide some thirty feet down, alongside a spout leading down from the eaves. The Walnut street pavement is strewn with broken bricks and morter thrown down by the shock.

A daughter of the pastor, Rev. Ch. F. Stark, showed a Post-Dispatch reporter the inside of the church. Several cracks on both sides of the choir ceiling are visible, and the building is evidently damaged very seriously at the Eighth street end--the front. The Holy Ghost congregation is building a new church in the West End, and this structure, put up in 1834, is soon to be given over to business uses.

Mrs. Anna Horrocks, living two doors from the Holy Ghost, on Walnut, said to the reporter that the shock was very sharp and severe, ringing the door bell and creating the idea of burglars, murderers and all kinds of awful things. She heard the cracking of the church walls distinctly.

Fourth District patrolmen report that the shocks were plainly felt in that part of the city and nearly every one was awakened, many rushing out of their homes in their night garments. No damage was reported.

The shock caused considerable alarm in the Third District and the people fled in fear from the ricketty tenements along Seventh, Eighth and Carr and Biddie streets. No damage was reported, although the old buildings were given a lively shaking up."

[There is another 30 inches of fine print in this article about the reactions of people in Saint Louis to the earthquake from which the following is extracted.]

"Ran pellmell down the stairs...when the night clerk's composure and merriment over their alarm stopped the stampede."

"Hotel Manager...said he never felt the shock, but the...guests...were all aroused from sound slumber and nearly scared to death. The bells began to ring with such violence that the dayboard is now out of order. Bells in the rooms wouldn't work well, and guests ran out in the halls in their night clothing to ring the hall bells."

"Bartender was roused...by glasses rattling and falling over."

"The water pitchers in the rooms rattled as if they had the ague and chandeliers shook violently."

"A guest on the third floor was shaken out of bed."

"A panic was created at the Western Union office...Twenty men were on duty on the third floor...The big clock on the south wall...fell to the floor. The switchboards...swayed to and fro. If it had continued the least bit longer I am satisfied that the building would have collapsed, said Mr. Henry. The building moved three or four inches. It was easy to see that with the naked eye."

"A queer streak of light stretched over the sky just before the shock."

"I saw a chimney on a three-story building...topple over."

"A pyramid of tomato cans tumbled over."

"The shocks were choppy."

"A distinct shock, which felt much like the rocking of a cradle...A lot of things in my garret fell down."

"I got up with a club to look for the man under the bed."

"The big show windows all cracked loudly, and I was so sure that some of them were broken that I lighted matches to examine them."

"I heard a lot of tinware shaking, and at once realized that it was an earthquake."

"Every dog on earth seemed to be barking at once."

"The chimney and portions of the top walls of the residence...collapsed and fell while the earth was vibrating."

1968 November 9 (162 km from Saint Louis)

From United States Earthquakes, 1968 (Coffman and Cloud, 1970): "St. Louis.--Press reported: Several injured by falling debris. Walls cracked, chimneys fell, and windows broke. A 15- by 20-foot section of southwest wall at Mid-American Metal Company collapsed. Civil War Museum at Jefferson Barracks closed due to a large crack opening in museum wall, causing bricks and plaster to fall. Many objects crashed to floors." They assigned intensity VII.

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