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Estimation of Earthquake Effects Associated with a Great Earthquake in the New Madrid Seismic Zone

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ABSTRACT

ESTIMATION OF EARTHQUAKE EFFECTS ASSOCIATED WITH A GREAT EARTHQUAKE IN THE NEW MADRID SEISMIC ZONE

Estimates have been made of the effects of a large $M_s = 8.6$, $I_o = XI$ earthquake hypothesed to occur anywhere in the New Madrid seismic zone. The estimates are based on the distributions of 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 map for a maximum intensity XI is believed to represent the upper level of shaking likely to occur. Specific intensity maps have been developed for six cities near the epicentral region taking into account the most likely distribution of site response in each city. Intensities found are: IX for Carbondale, IL; VIII and IX for Evansville, IN; VI and VIII for Little Rock, AR; IX and X for Memphis, TN; VIII, IX, and X for Paducah, KY; and VIII and X for Poplar Bluff, MO. On a regional scale, intensities are found to attenuate from the New Madrid seismic zone most rapidly to the west and southwest sides of the zone, most slowly to 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 documented but much more research is needed to define the liquefaction potential.

INTRODUCTION

The New Madrid seismic zone is the site of some of the largest historical earthquakes in the coterminous 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 neither expecting nor prepared for such a disaster. 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) the U.S. Geological Survey Professional Paper in 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 (unpub. data). 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, probability of occurrence, and location of an 1811-type earthquake, 2) to estimate the levels of damaging ground motion (in terms of Modified Mercalli intensities) throughout the Midwest resulting from this simulated earthquake, 3) to estimate the intensities at each of the six representative cities studied individually (see figure 1), 4) to assess the potential for geological effects such as liquefaction, flooding, and landslides, and 5) to find areas of lower intensities, both regional and in the six 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 attenuation of seismic energy in the midcontinent, which results in unusually large damage areas. This report does not include damage estimates, as did the earlier studies.

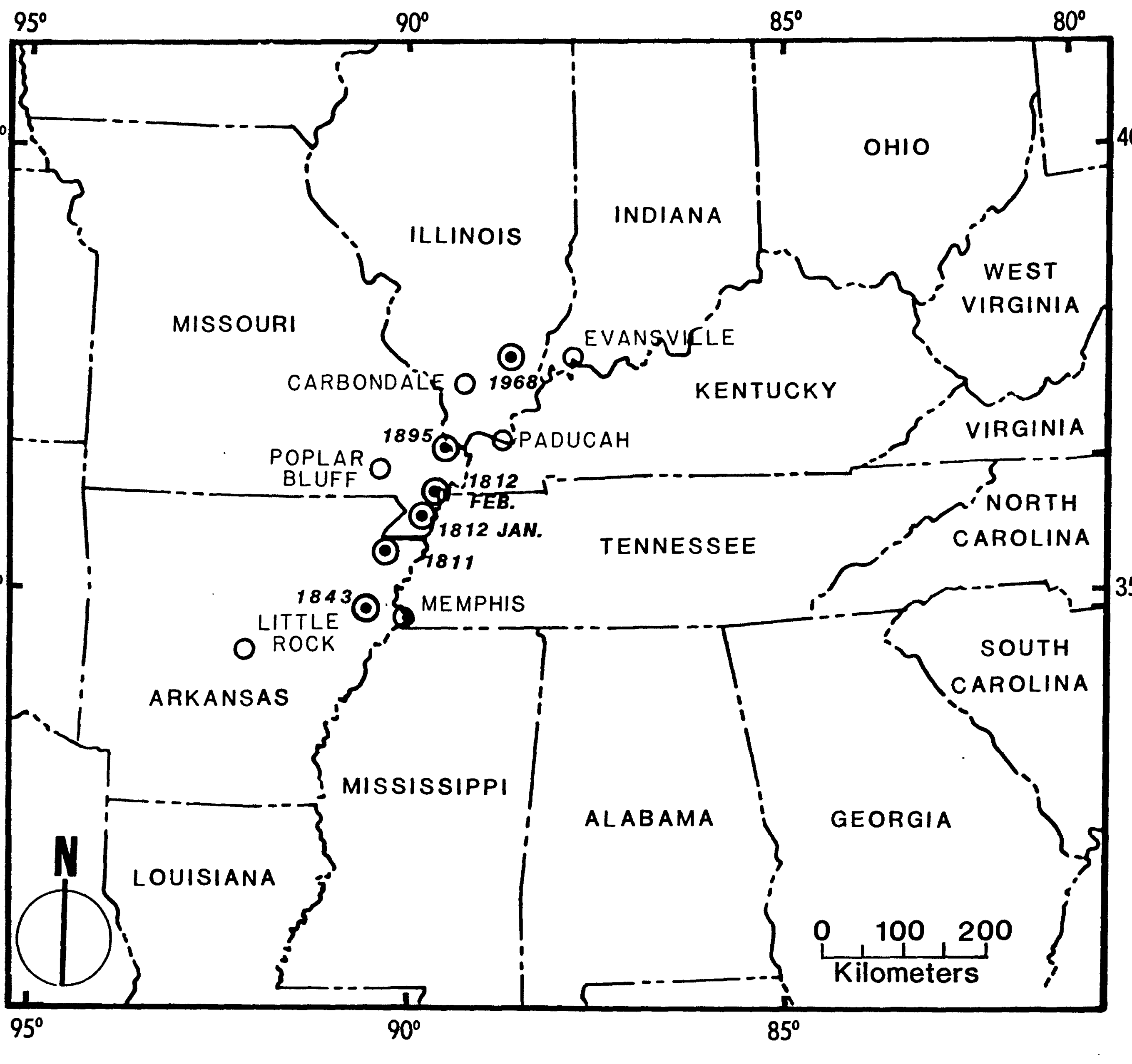

Figure 1.__Map showing the six cities evaluated in this report. Also shown (circles with dots) are localities of the epicenters of the large historical earthquakes discussed in this report.

LARGE HISTORICAL EARTHQUAKES

EARTHQUAKES OF 1811-1812

During the winter of 1811-1812 three great earthquakes occurred in the Mississippi Valley each having magnitude m_b* above 7.1 (see table 1 and figure 2). There have been no other earthquakes larger than these within the coterminous 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) over approximately 2,500,000 km^2, which includes the entire eastern United States (Nuttli, 1973). The area of

TABLE 1. RELATIVE SIZES OF THE 1811-1812 EARTHQUAKES. INTENSITY AND MAGNITUDE ESTIMATES FROM NUTTLI (1981). EPICENTER ESTIMATES FROM DAVID P. RUSS (PERSONAL COMMUNICATION)

	I_o	M_s	m_b	Epicenter Lat.	Epicenter Long.
1811 Dec 16	XI	8.6	7.2	35.8°N	90.3°W
1812 Jan 23	X-XI	8.4	7.1	36.2°N	89.8°W
1812 Feb 7	XI-XII	8.7	7.3	36.5°N	89.6°W

*"Magnitude" is a measure of the size of an earthquake, or of the total amount of energy released by the earthquake. Several different magnitudes may be calculated from the amplitudes of the seismic vibrations recorded by a seismograph. The two most common ones are m_b, derived from the body-wave vibrations, and M_s, derived from the surface-wave vibrations. In this report magnitudes will always be given as m_b; in addition, M_s will be given for the largest shocks. "Intensity" refers to the effects of an earthquake on people, structures, and ground. The intensity value is denoted by a Roman numeral in the Modified Mercalli Intensity Scale (see Appendix 1). The maximum intensity, I_o, is the most severe of these effects, and occurs, usually, near the instrumental epicenter. For old, pre-instrumental earthquakes, magnitudes are usually estimated from I_o, or from contoured maps of intensity data (isoseismal maps) using either the total felt area (largest isoseismal) or the attenuation or weakening of the intensities with distance.

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-VII level.

The maximum intensities of the three 1811-1812 earthquakes range from X to XII (see table 1). In the epicentral area of the first shock (December 16, 1811), 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 the Mississippi River north of Memphis. The roads between New Madrid and Arkansas were made impassible by the earthquake. The area of marked earth disturbances extended from Cairo to Memphis and from Crowley's Ridge to Chickasaw Bluffs.

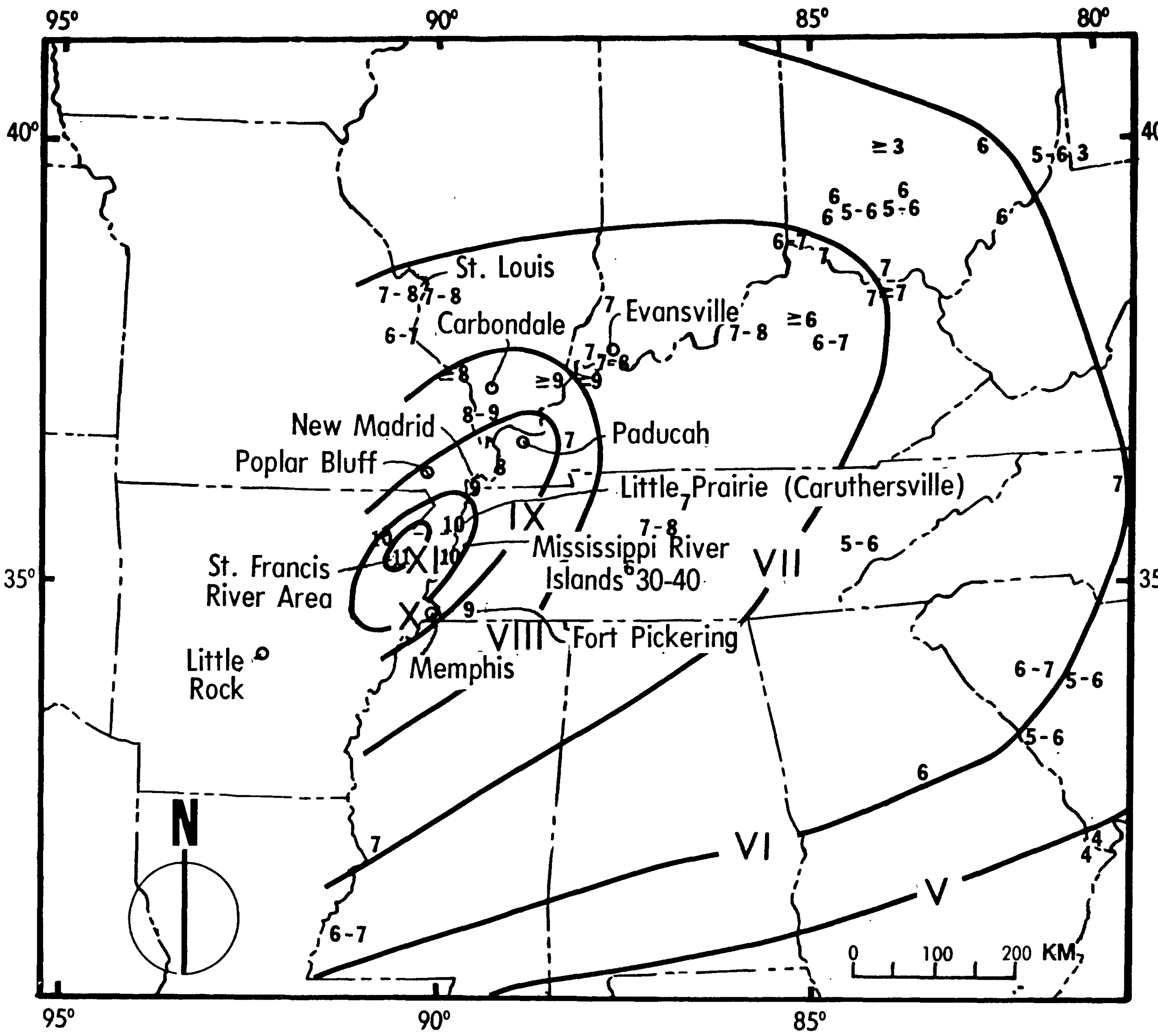

Figure 2. Isoseismal map of the December 16, 1811, earthquake, in northeast Arkansas (first major shock of the New Madrid series). After Nuttli (1981). Arabic numbers represent assigned Modified Mercalli intensities for individual locations; Roman numerals, the intensities for the isoseismals. Maximum intensity for this earthquake is XI. No information is available with which to complete the isoseismals on the west side. There are no assigned intensities for any of the six cities in this study except the IX at Fort Pickering near what is now Memphis. 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.

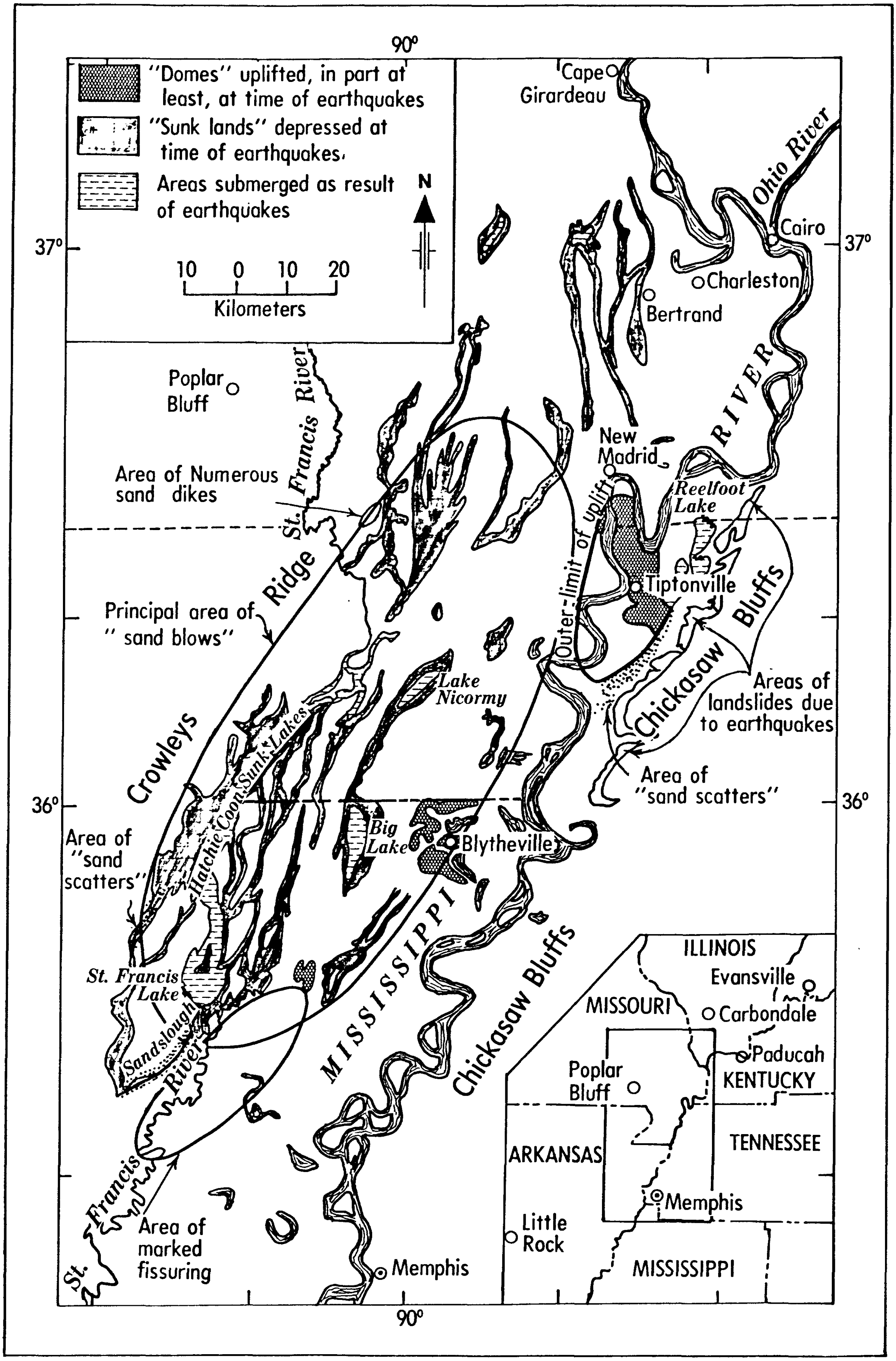

Figure 3. Map of the ground effects of the New Madrid district. After Fuller (1912).

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 three main shocks, there were numerous aftershocks, fifteen of them quite strong (table 2). All 18 of the above shocks were strong enough to be felt at Washington, D.C., and awaken sleepers when 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, 1913 p. 33).

TABLE 2. AFTERSHOCKS OF THE 1811-1812 NEW MADRID EARTHQUAKES. NUMBERS AND M_S MAGNITUDES ARE FROM NUTTLI (1981). CONVERSION TO m_b FROM A FIGURE IN NUTTLI (1982).

M_S	m_b	Number
≥ 8	≥ 6.8	3
7-8	6.3-6.8	5
6-7	5.8-6.3	10

There is little available information on the 1811-1812 series for the six cities in this study. Using Nuttli's (1981) map of the 1811 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; and Poplar Bluff, the IX area. Nuttli (1973) assigned a IX at Fort Pickering, near what is now Memphis.

The isoseismals for the 1811 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 for west of the Mississippi River. Even less is known about the distribution of effects of the two 1812 shocks in the sequence; Nuttli (1973) lists only 13 locations having assigned intensities for each of these earthquakes and does not attempt to make an isoseismal map from them. In order to estimate what the distribution of intensities for such large shocks might have been, another source of intensity information is necessary.

OTHER LARGE EARTHQUAKES

Significant information is available for three other central U.S. shocks, which are all smaller than the three 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 HOPPER AND ALGERMISSEN (1980 AND UNPUB. DATA), COFFMAN AND CLOUD (1970), AND NUTTLI (1981).

	I_o	m_b	Epicenter
1843 Jan 5	VIII	6.0	Near Memphis, Tennessee
1895 Oct 31	IX	6.2	Charleston, Missouri
1968 Nov 9	VII	5.5	South-central Illinois

The two largest of these earthquakes, those in 1843 and 1895, were chosen as the basis for the simulated earthquake developed in this study. They occurred near the south and north ends of the New Madrid seismic zone, respectively. Since it is assumed that the simulated earthquake in this study might occur anywhere in the New Madrid seismic zone, the locations of these two shocks are ideal for the simulation. 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 simulation. The 1968 earthquake, although smaller than the 1843 and 1895 shocks, and located north of the New Madrid seismic zone, is also discussed here because of its excellent data set, including assigned intensities at all six of the cities considered in this report.

The information available for each of the six 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 when that information exists. Since there are no records from any of these cities in 1811-1812 (most of the cities didn't yet exist, except for Fort Pickering near Memphis), the isoseismal area within which a city lies is noted instead of an intensity value assigned on the basis of actual earthquake effects. Intensities near the 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.

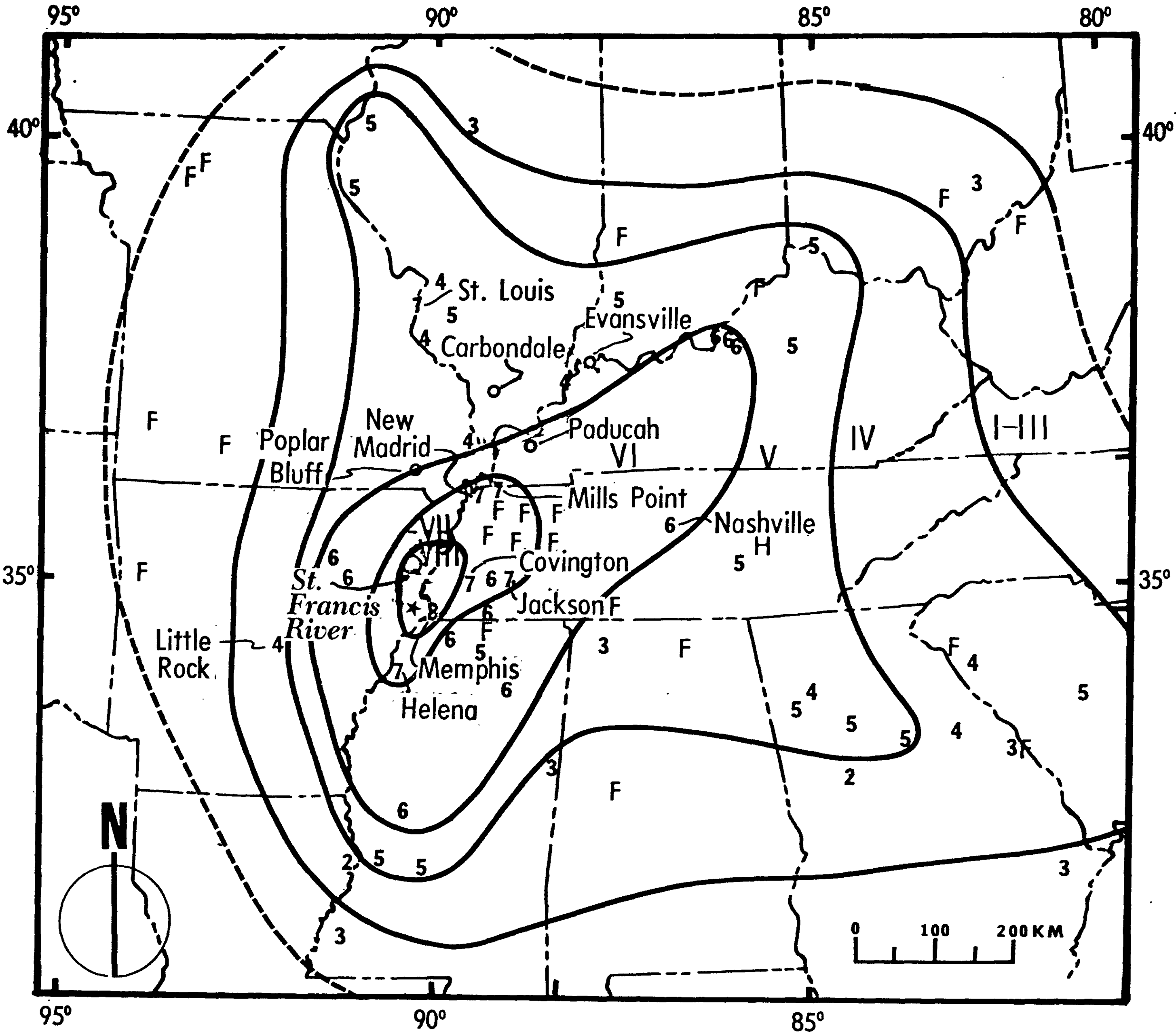

Figure 4.__Isoseismal map of the January 5, 1843, earthquake near Memphis, Tennessee. After Hopper and Algermissen (unpub. data). Arabic numbers represent assigned Modified Mercalli intensities for individual locations; F, H, and O are used for Felt, Heavy, and Liquefaction, respectively. Star is at the epicenter. Of the six cities in this study there are assigned intensities for two: IV at Little Rock and VIII at Memphis. 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.

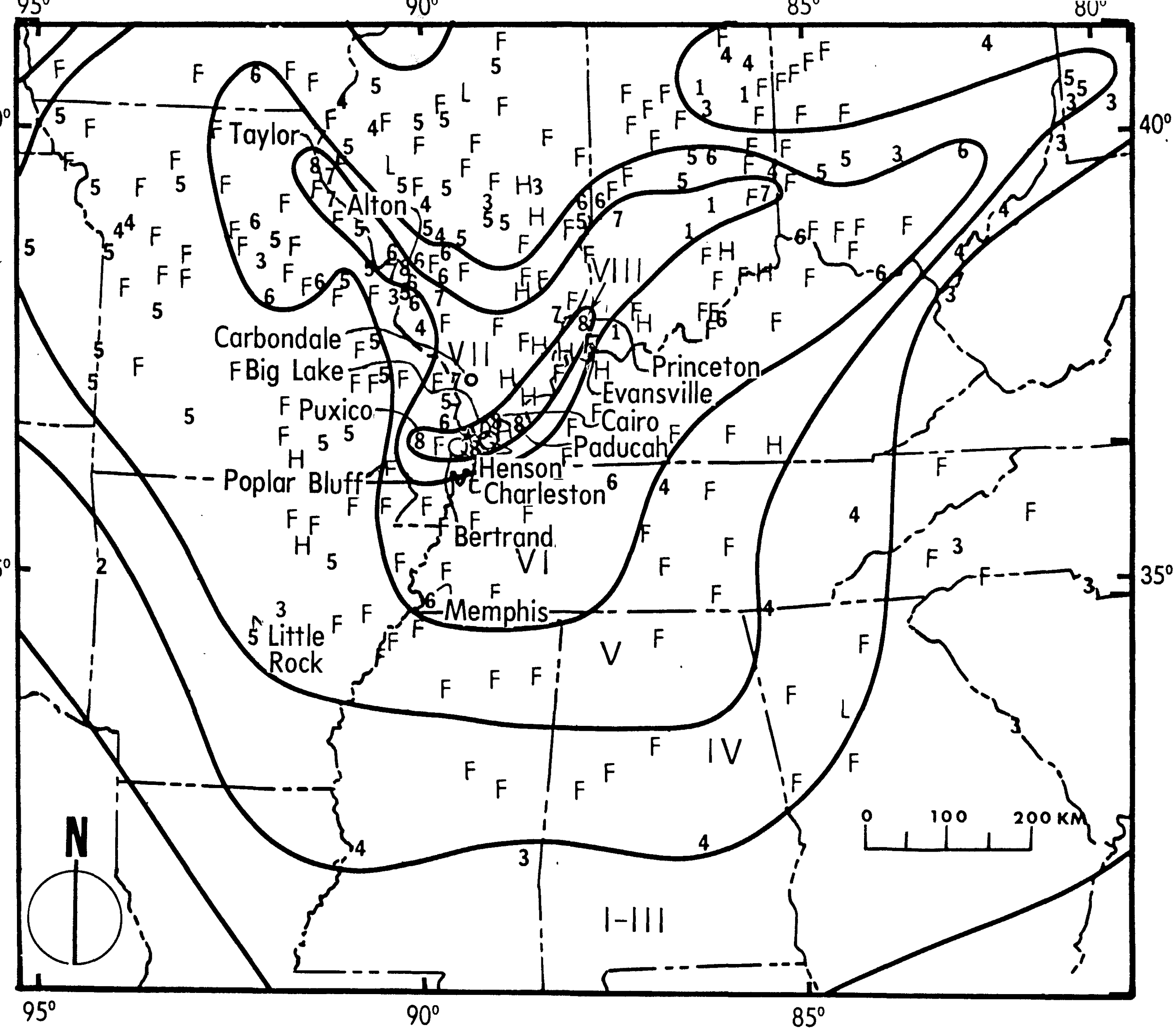

Figure 5. Isoseismal map of the October 31, 1895, earthquake near Charleston, Missouri. After Hopper and Algermissen (1980). Arabic numbers represent assigned Modified Mercalli intensities for individual locations; F, H, L, and Q are used for Felt, Heavy, Light, and Liquefaction, respectively. Star is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

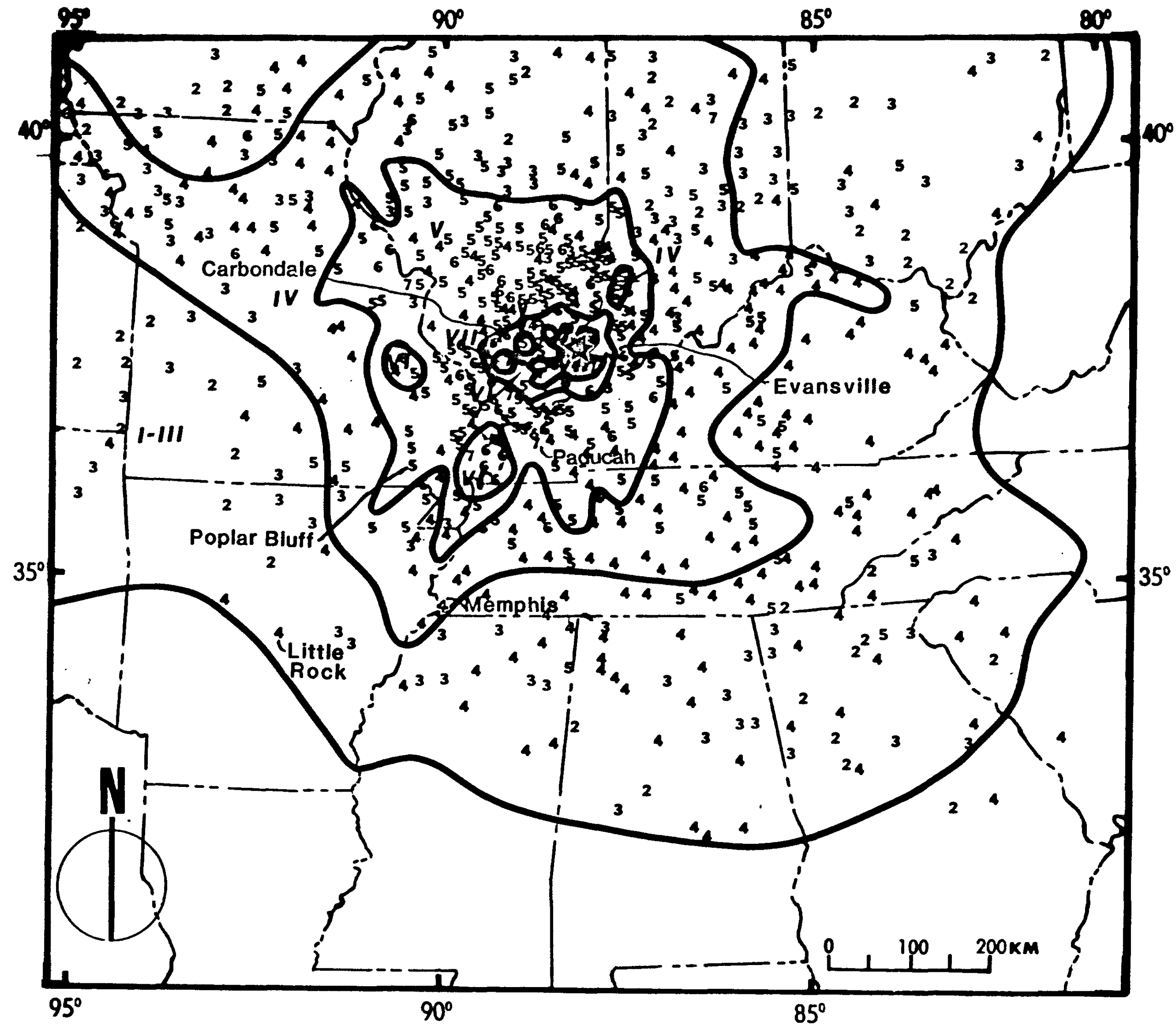

Figure 6. Isoseismal map of the November 9, 1968, earthquake in south-central Illinois. After Gordon and others (1970). Arabic numbers represent assigned Modified Mercalli intensities for individual locations. Star is at the epicenter. Assigned intensities at the six cities in this study are: VI at Carbondale,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

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. INTENSITIES AT NEARBY LOCATIONS ARE NOTED WHERE RELEVANT. THERE IS INSUFFICIENT INFORMATION TO CONTOUR ISOSEISMALS FOR THE 1812 EARTHQUAKES, SO THE CITIES' ISOSEISMAL AREAS ARE UNKNOWN FOR THOSE SHOCKS. LATITUDE (°W) AND LONGITUDE (°N) ARE SHOWN BELOW EACH DATE AND EACH CITY AND EACH EARTHQUAKE DATE.

DATE AND EPI-CEN-TER	CARBON-DALE IL 37.7° 89.2°	EVANS-VILLE IN 38.0° 87.6°	LITTLE ROCK AR 34.7° 92.3°	MEMPHIS TN 35.1° 90.1°	PADUCAH KY 37.1° 88.6°	POPLAR BLUFF MO 36.8° 90.4°
1811 Dec. 16 35.8° 90.3°	238km In VIII AREA.	336km in VII AREA OFF MAP.	212km in VII AREA?	80km IX at FORT PICKER-ING	205km in IX AREA	104km in IX AREA
1812 Jan. 23 36.2° 89.8°	178km	280km	274km	120km	145km	87km
1812 Feb. 07 36.5° 89.6°	142km	241km	311km	160km	102km	82km
1843 Jan. 05 35.2° 90.5°	307km in V AREA	402km in V AREA	170km IV	32km VIII	269km in VI AREA	179km in VI AREA
1895 Oct. 31 37.0° 89.4°	81km in VII AREA	192km FELT. in VII AREA	362km V	223km VI	81km VIII	94km FELT. in V AREA
1968 Nov. 09 38.0° 88.5°	69km VI	81km VI	498km I-IV	350km I-IV	105km VI	218km V

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 six cities studied in this report are discussed below. More detailed information can be found in Appendices 2-7 at the end of this report.

January 5, 1843

The 1843 earthquake (figure 4) is the third largest historical earthquake (or series) in the central Mississippi valley. Only the 1811-1812 and the 1895 earthquakes were larger. Moreover, it is the closest of the large Mississippi valley earthquakes to the epicenter of the 1811 earthquake. More intensity data are available for 1843, and therefore its isoseismals show 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 (Hopper and Algermissen, unpub. data). 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 Hopper and Algermissen (unpub. data), for the 1843 earthquake for each of the six 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 avalable 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.

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 "O", 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 4 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 six 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.

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 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 six 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.

SEISMICITY OF THE NEW MADRID SEISMIC ZONE

Large earthquakes of the New Madrid seismic zone are shown in figure 7. It includes the three 1811-1812 earthquakes with Io $\geq$ XI M.M., the 1843 and 1895 earthquakes with Io's of VIII and IX respectively, and all other shocks with Io $\geq$ VI-VII. Intensities $\leq$VI are indicated by small circles.

There are numerous smaller earthquakes in the study region in addition to the three 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 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.

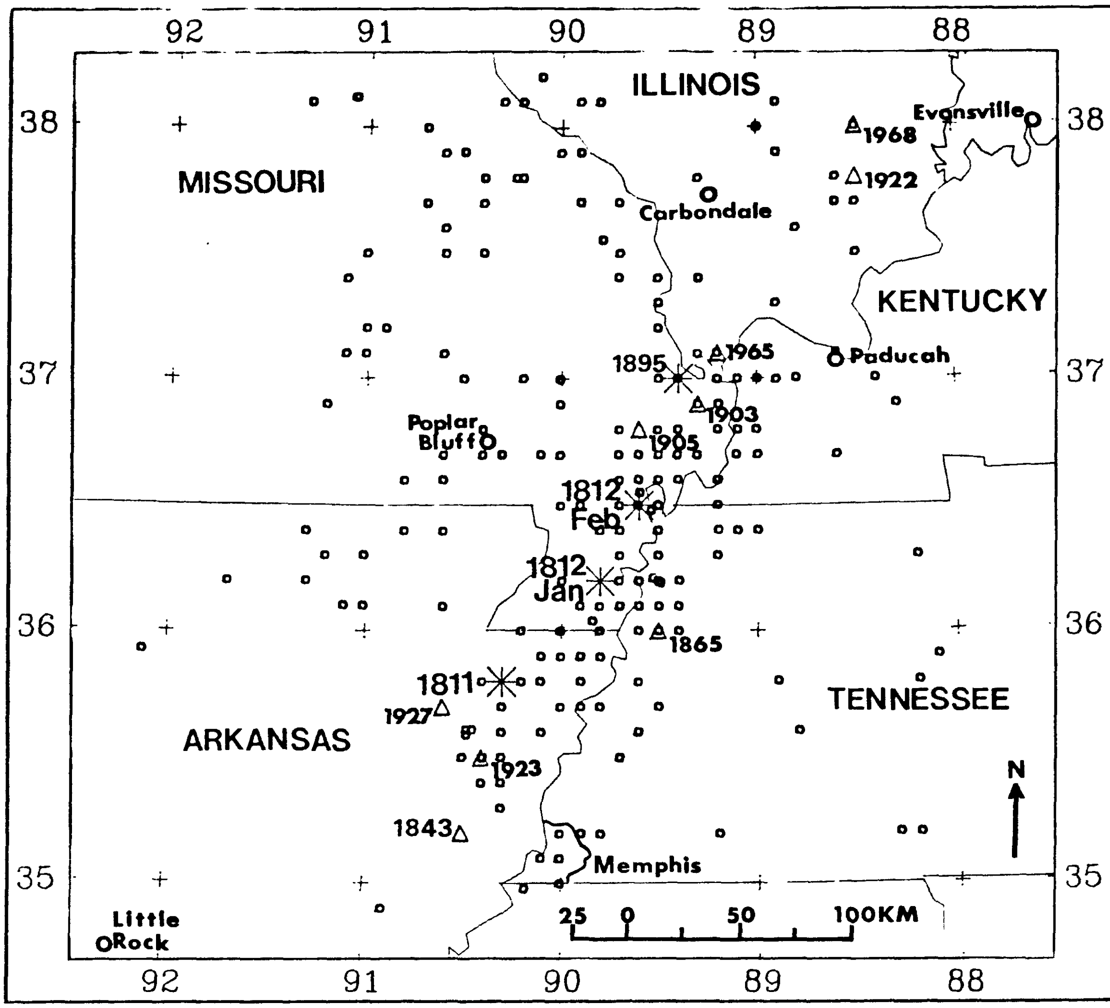

Figure 7. Historical seismicity of the New Madrid seismic zone and surrounding areas, 1800-1982. Plotted from Algermissen and Askew, unpublished listings. Epicenters for intensities IX and above are indicated by astericks; VI-VII, VII, and VIII by triangles; and VI and below by small circles. Epicenters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

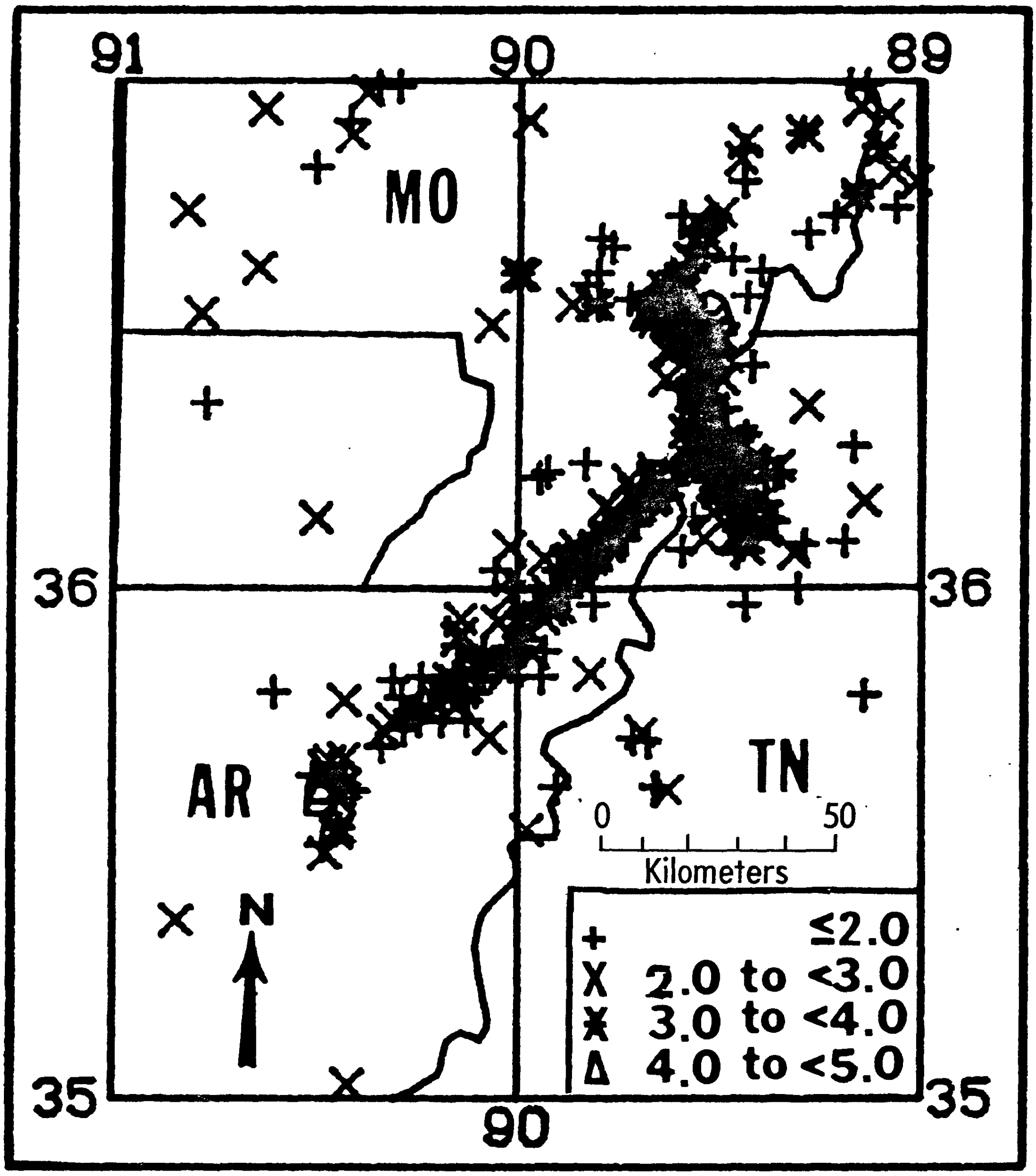

Figure 8.__Microseismicity of the New Madrid seismic zone, 1974-1981. Plotted from tape obtained from Robert B. Herrmann of Saint Louis University.

ESTIMATION OF MAGNITUDE AND PROBABILITY OF OCCURRENCE OF LARGE DAMAGING EARTHQUAKES IN THE MISSISSIPPI VALLEY

MAXIMUM MAGNITUDE EARTHQUAKES

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 $m_b \sim$ 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 three 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 has 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

Source	Magnitude or Maximum MM Intensity	Estimated Recurrence (years)	Method Used
Nuttli (1974)	7.0 - 7.4 (m_b)	510	Maximum likelihood
	7.0 - 7.4 (m_b)	710	Weighted least squares
Algermissen (1973)	XI ($m_b \sim 7.2$)	500	Least squares (1811-1812 events included)
McClain and Myers (1970)	X	175	
Mann and Howe (1973)	7.7 (M_s) X	600-700	
Algermissen (1972)	XI ($m_b \sim 7.2$)	500-600	Extreme value analysis

ESTIMATION OF DAMAGING GROUND MOTION IN TERMS OF MODIFIED MERCALLI INTENSITIES

The ground shaking (reported in Modified Mercalli 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 it is assumed to be a magnitude m_b = 7.2, Io = XI M.M. earthquake located in the New Madrid seismic zone. This agrees with the size of the December, 1811, earthquake as estimated by Nuttli (1981).

Variations in intensity patterns of three large regional earthquakes are used to develop a composite regional intensity map for a large earthquake that might occur anywhere along the zone. The method used and the resulting map (figure 9) are discussed in the next section. From this regional intensity map, projected intensities at each of the six cities in this study have been determined.

Seismic zonation at the scale of an individual city 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 section on site geology deals with these conditions for each of the six cities studied.

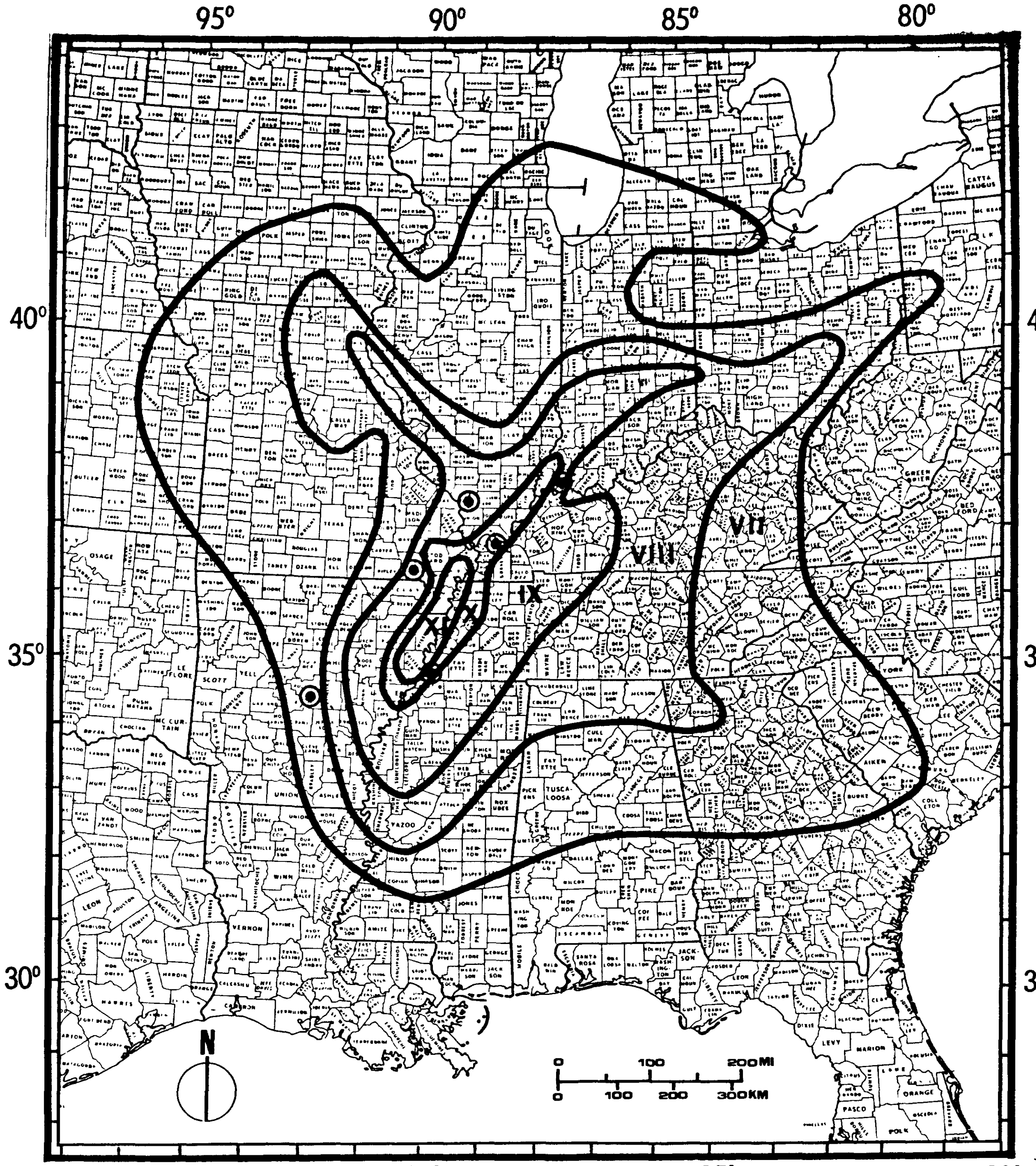

Figure 9. Hypothetical regional intensity map for an 1811-size earthquake having an epicenter anywhere along the New Madrid seismic zone (the zone of intense microseismicity in figure 8). Dots show the locatons of the six cities in this study. The contours on this map are used to assign the county intensities shown in figure 16.

Finally, the projected regional intensity at each city and the individual site conditions are combined to develop intensity maps for each of the six cities. These are shown in figures 10-15. The figures are discussed in the section on city maps.

In addition to the above, special attention is 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 are discussed.

SEISMIC INTENSITIES

Causes of intensity pattern variations

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 mechanism; 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 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

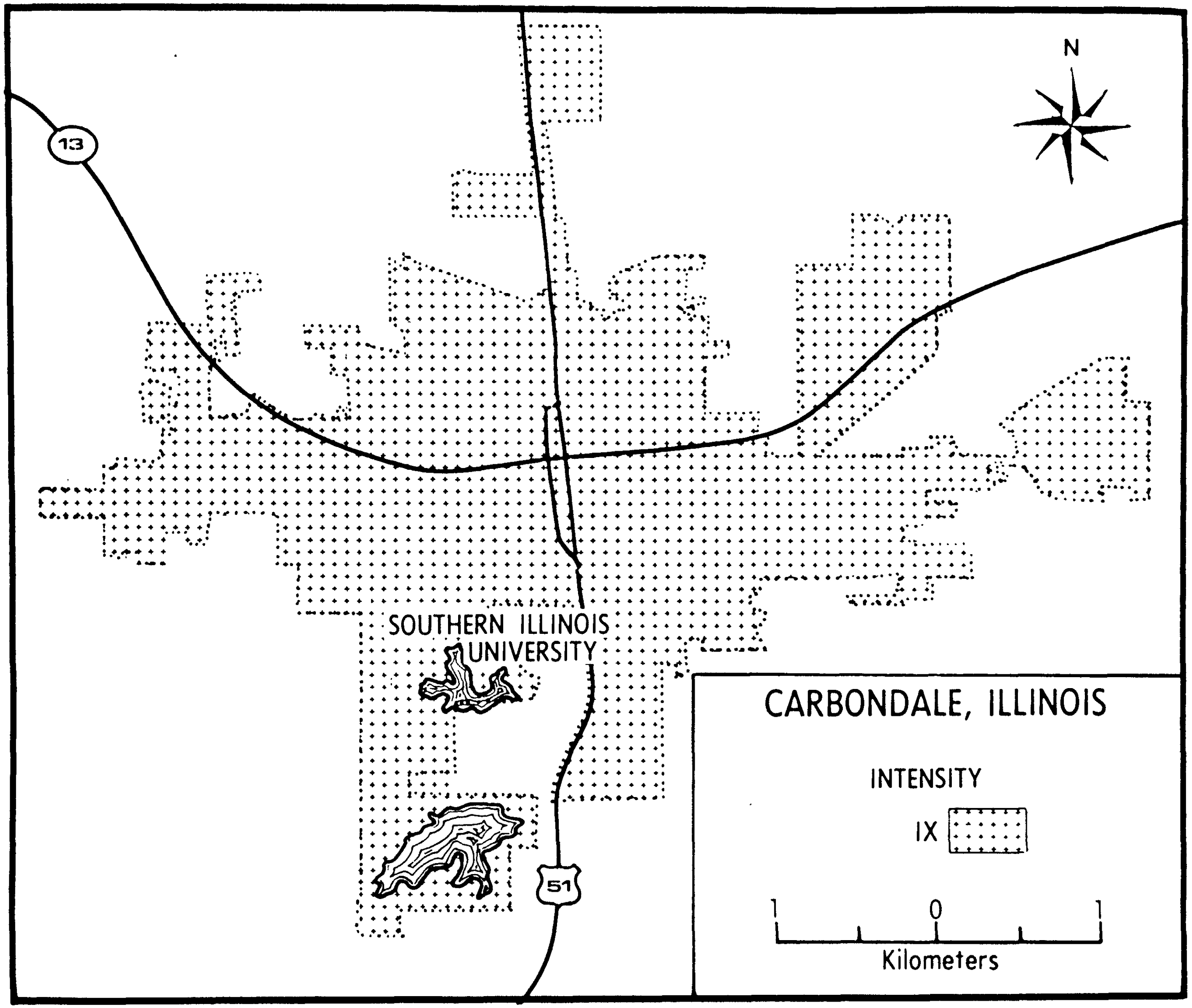

Figure 10.__Hypothetical intensity map for Carbondale, Illinois. For an earthquake near the north end of the New Madrid seismic zone, the intensity for Carbondale is IX for the entire city. For an earthquake near the south end of the New Madrid seismic zone, the intensity at Carbondale would be lower.

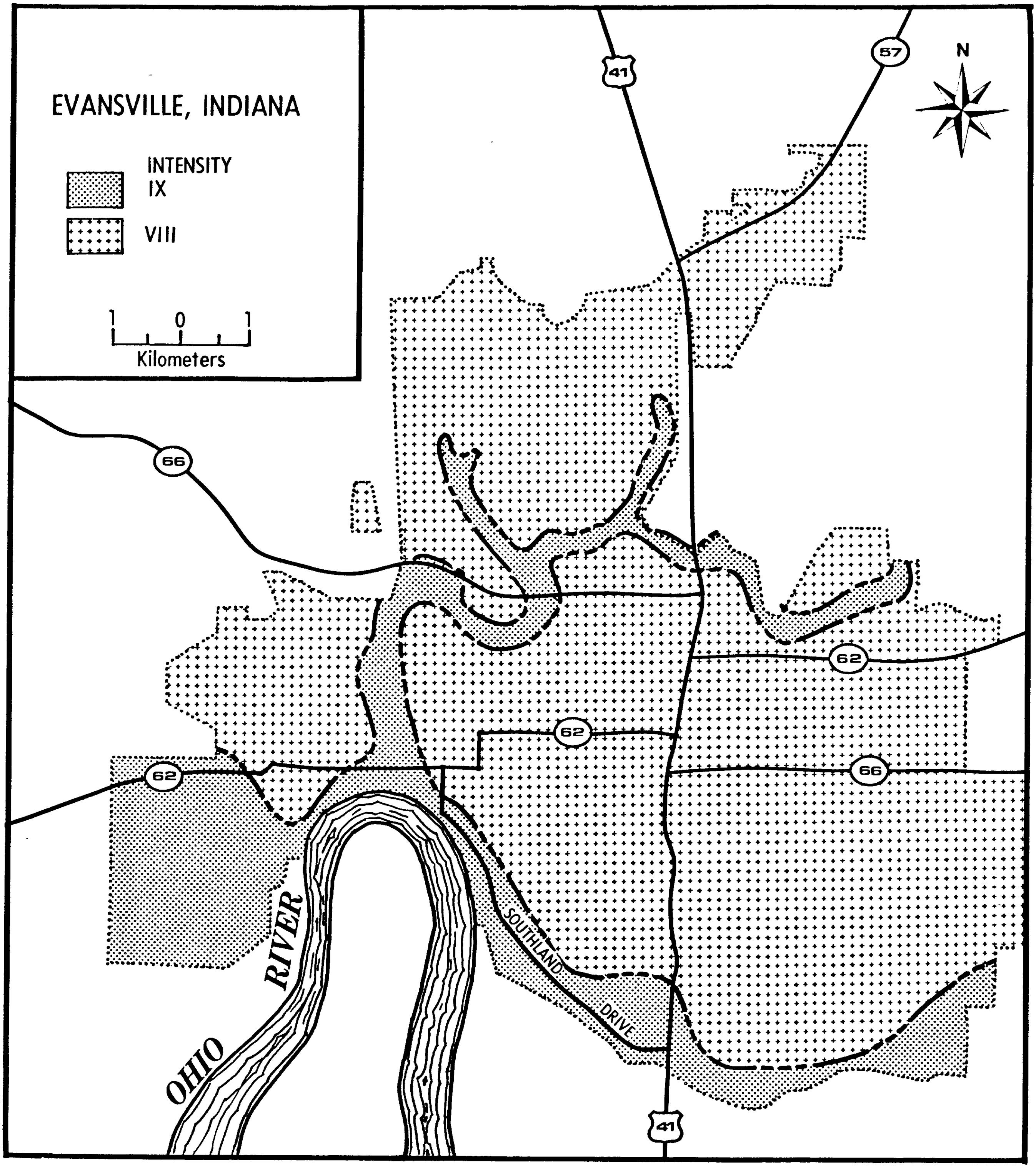

Figure 11. Hypothetical intensity map for Evansville, Indiana. For an earthquake near the north end of the New Madrid seismic zone, intensities projected for Evansville are: IX along the Ohio River flood plain and its tributary and VIII for the lacustrine sediments of the rest of the city. For an earthquake near the south end of the New Madrid seismic zone, the intensity at Evansville would be lower.

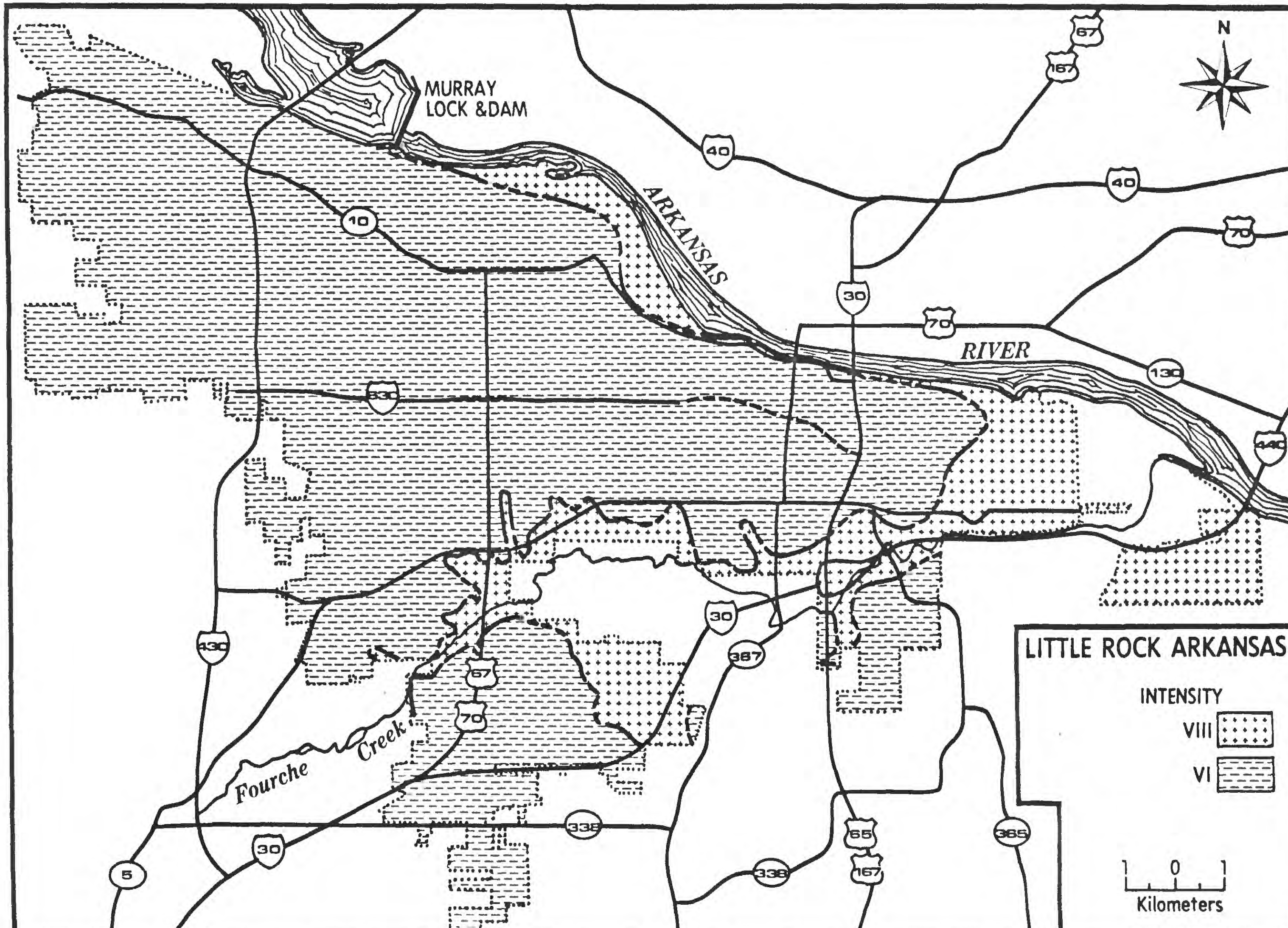

Figure 12. Hypothetical intensity map for Little Rock, Arkansas. For an earthquake near the south end of the New Madrid seismic zone, intensities projected for Little Rock are: VIII on the river alluvium, but only VI on the sandstones, shales, and limestones of the hills. For an earthquake near the north end of the New Madrid seismic zone, the intensities at Little Rock would be lower.

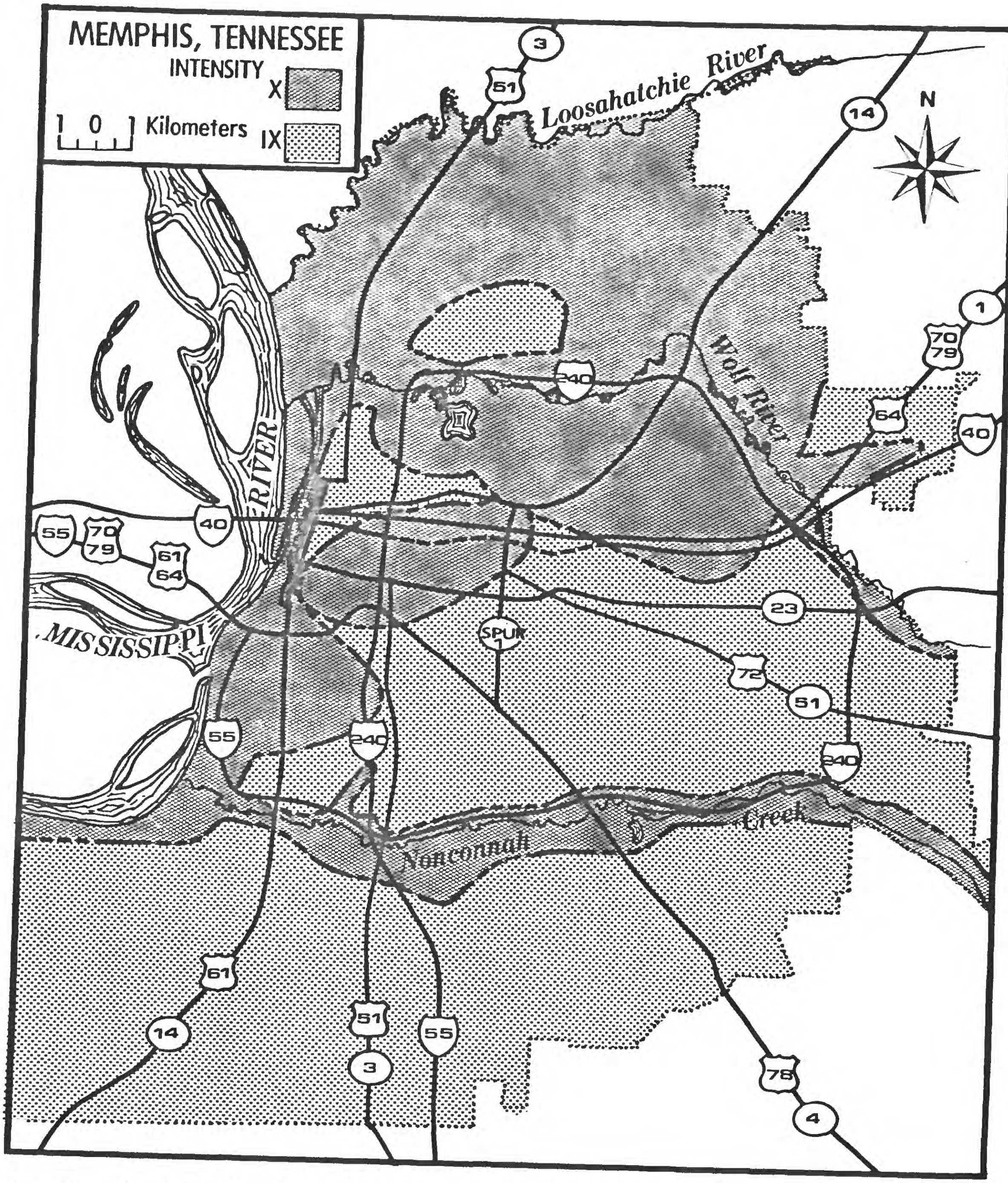

Figure 13.__Hypothetical intensity map for Memphis, Tennessee. For an earthquake near the south end of the New Madrid seismic zone, intensities projected for Memphis are: X in the alluvial valleys and in the areas found by Sharma and Kovacs (1980) to have high amplification factors (figure 20) or to be susceptible to liquefaction (figure 19), and IX in the rest of the city. For an earthquake near the north end of the New Madrid seismic zone, the intensities at Memphis would be lower.

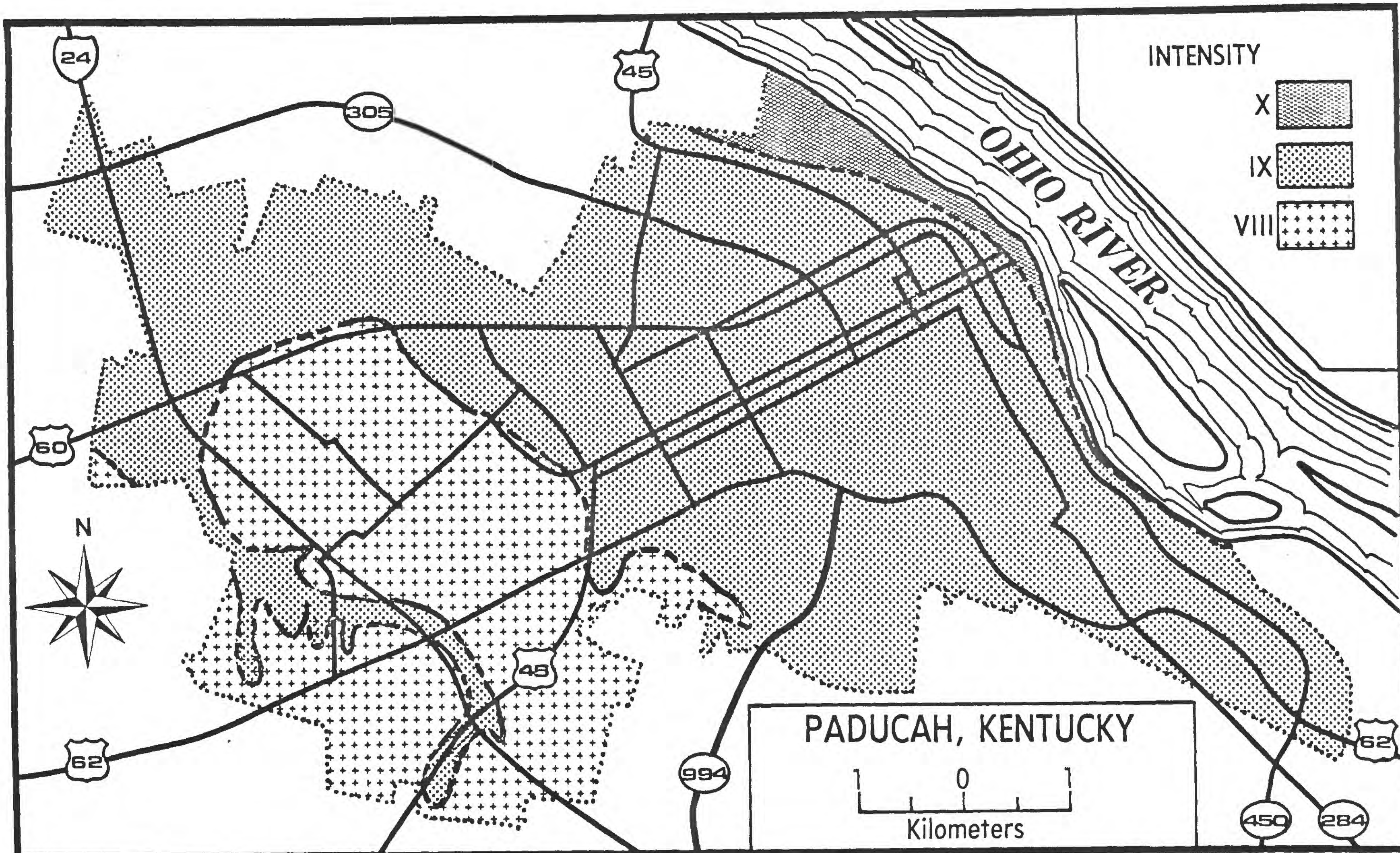

Figure 14.__Hypothetical intensity map for Paducah, Kentucky. For an earthquake near the north end of the New Madrid seismic zone, intensities projected for Paducah are: X on the river alluvium, IX on the lacustrine deposits underlying most of the city, and VIII in the hills southwest of the city. For an earthquake near the south end of the New Madrid seismic zone, the intensities at Paducah would be lower.

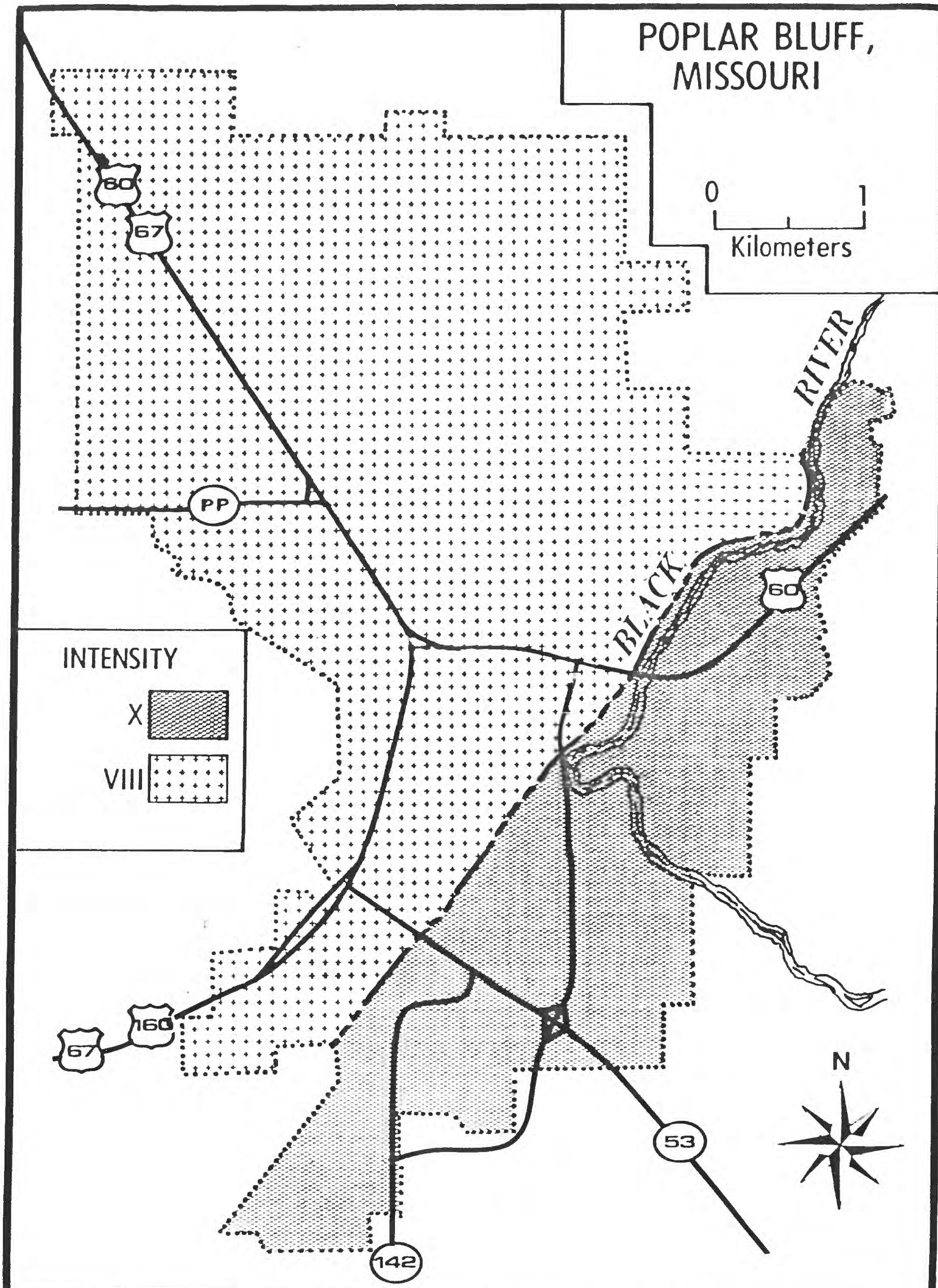

Figure 15. Hypothetical intensity map for Poplar Bluff, Missouri. For an earthquake near the north end of the New Madrid seismic zone, intensities projected for Poplar Bluff are: X on the Mississippi flood plain southeast of the city, but only VIII on the uplands to the northwest. For an earthquake near the south end of the New Madrid seismic zone, the intensities at Poplar Bluff would be lower.

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 IV area there are 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 9) developed in this study.

Hypothetical regional isoseismal map

The 1843 and 1895 isoseismal maps have been used as the basis of the hypothetical regional map 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 level of an 1811-size earthquake; the 1895 earthquake is raised two intensity levels from a low maximum intensity of IX to XI. The maximum intensity of the 1843 shock has been raised 2.5 levels from mid-VIII to XI. The results are two 1811 type maps, one for the northern end of the New Madrid seismic zone and one for the southern end, 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 (figure 9).

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 I_o are assumed to be parallel to similar graphs for earthquakes of higher I_o. 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 9. 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 an earthquake located near the center of the seismic zone to be used as a third basis for the hypothetical regional map has only a small effect on the outer contours. By the same reasoning, if only one 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 9, 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 map in figure 16 shows the same information as figure 9, but has been generalized to show the predominant intensity in each affected county. In figure 16, a particular county has been judged to be either within or outside a particular intensity area. As with contouring intensty 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. This map 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 intensity shown on figure 16. If, for example, the county of interest is on the north side of the area of figure 16, and the earthquake which actually occurs on the north end of the New Madrid seismic zone, some parts of the county are expected to experience the intensities shown on figure 16. 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 figure 16 will probably be at least one intensity unit lower than shown, and vice versa. Discussion of the application of figure 16 to specific locations follows the next section.

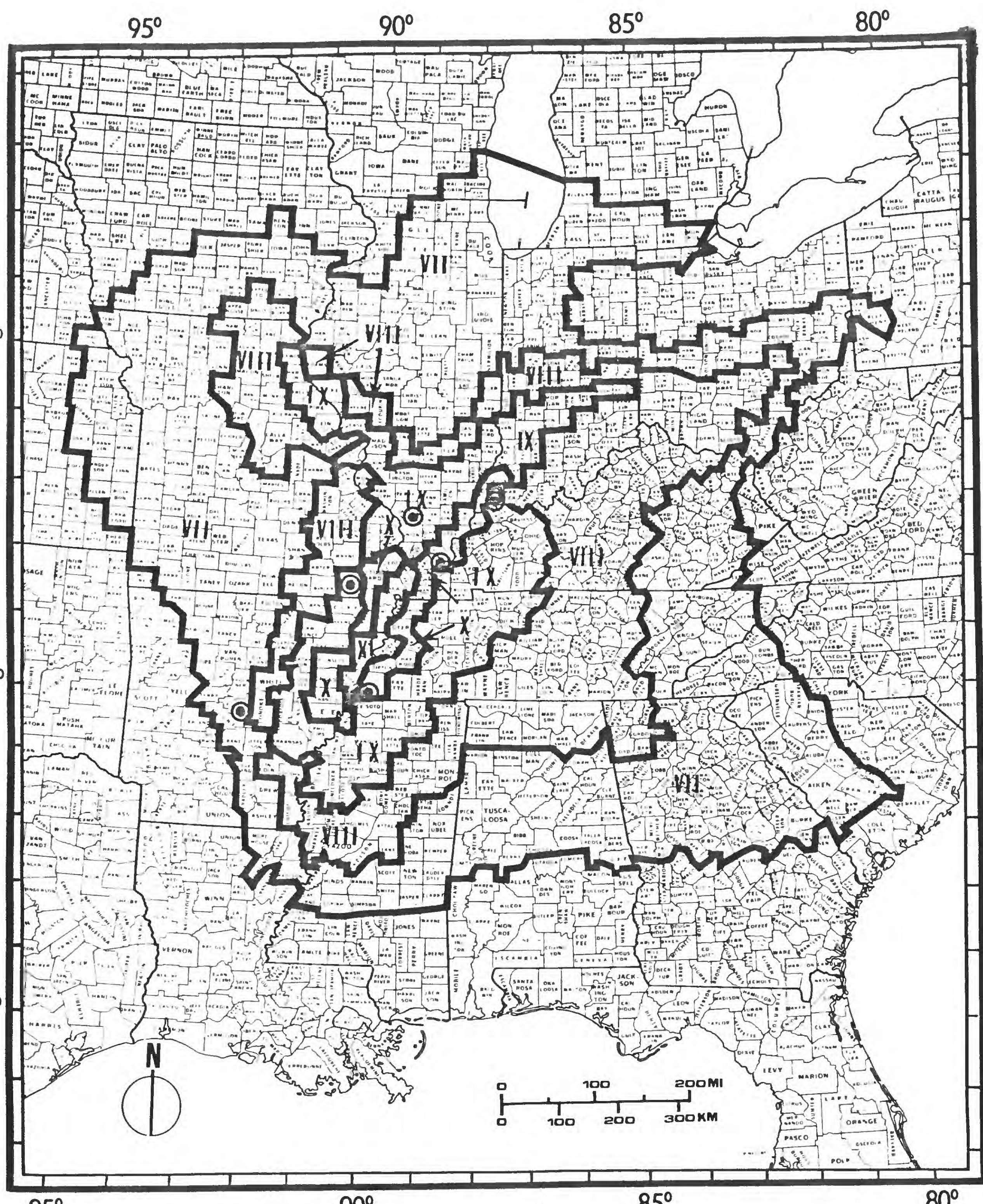

Figure 16.__Hypothetical regional intensity map by county. Assumes an 1811-size earthquake having an epicenter anywhere along the New Madrid seismic zone. Dots show the locations of the six cities in this study.

Liquefaction and landsliding

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 1 m, often with severe tilting. One apartment building tilted 80 degrees from the vertical but remained structurally intact. 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 (unpub. data). The potential for liquefaction may well exist beyond the Saint Francis basin, however. More work needs to be done in this region by examination of areal photographs to find the farthest extent of previous liquefaction evidence.

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 all six of the cities studied in this report are within this distance range of some segment of the New Madrid seismic zone, the potential for liquefaction must be assumed to exist in all of them that are underlain by liquefiable sediments. In each case, this is the area shown as the highest intensity on figures 11-15. Carbondale (fig. 10), 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.

STUDIES OF SIX CITIES

Maps of the six cities studied individually are shown in figures 10-15. The intensity in general in the area of a city can be determined from the map of hypothetical regional intensities, figure 16. But to zone a city in greater detail it is necessary to have some knowledge of the local geologic conitions. For this purpose, field investigations were made for each of the six 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 1811-size 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 earthquake occurred near the south end of the zone, Memphis would in fact experience the IX's and X's shown in figure 16, but Evansville, which is north of the zone, and which is projected in figure 11 and figure 16 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 three 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 10-15 take into account both the regional map intensity (figure 16) and the local geologic conditions at each city. The regional map gives the highest common intensity 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, figure 10) has so little significant geologic variation as to be assigned only one intensity throughout, IX. Paducah (figure 14), on the other hand, has conditions likely to produce most severe damage along the river and sucessively 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. Poplar Bluff and Little Rock (figures 15 and 12) 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 from X in the Mississippi River alluvial plain to VIII on the uplands. Finally, geologic conditions at Evansville and Memphis suggest a difference of one intensity level.

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

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, 1974). 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:

1) Landslides. Landslides in response to strong earthquakes are unlikely.

2) Liquefaction. The liquefaction potential is low.

Hypothetical intensity map for Carbondale:

The highest projected intensity at Carbondale is IX M.M. from the regional map (figure 16). This intensity would occur for an 1811-size earthquake anywhere near the north end of the New Madrid seismic zone. Carbondale would experience only intensity VIII for an 1811-size earthquake near the south 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 an earthquake of the size studied in this report is 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 M.M. intensity value, IX. Again note that this is the highest projected intensity, and that every building in Carbondale is not expected to be damaged at the intensity-IX level. Some buildings may not be damaged at all. Rather, the predominant part of the most important damage will be at this level.

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, 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:

1) 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.

2) 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 map for Evansville:

Intensities projected at Evansville are VIII and IX M.M., for an earthquake near the north end of the New Madrid seismic zone (figure 16). An earthquake near the south end of the seismic zone would produce only VII and VIII at Evansville. 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 an earthquake 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 11 as VIII.

Little Rock, Arkansas

Physiographic description:

Little Rock is situated on the border between the Ouachita province and the Mississippi Alluvial Plain (Fenneman, 1938). Most of the city is located south of the Arkansas River, west of the Mississippi Alluvial Plain, and north of Fourche Creek in the subdued Ouachita Mountains. Within the city area these mountains have a maximum total difference in 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 the city is 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 the city 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.

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, Bickner, and Festervand, 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. 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 non-plastic, 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, 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 artificial 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:

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

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

Hypothetical intensity map for Little Rock:

Intensity VII M.M. is projected at Little Rock on the regional map (figure 16) for an epicenter near the south end of the New Madrid 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).

At Little Rock the hypothetical intensities change from VIII for river and stream alluvium to VI for the neighboring sandstone, shale, and limestone hills of the rest of the city. Landslides are unlikely for most of the city, but a few small landslides might occur along some of the steeper bluffs. There is a moderate potential for liquefaction in the flood plain deposits (area shown as VIII in figure 12), although no geologic evidence of previous liquefaction in the area has been found.

Memphis, Tennessee

Physiographic description:

Memphis is 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 city 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 17. Both are from M & H Engineering and Memphis State University (1974).

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 a 1-2m. 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	0-16	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 and gravels 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.

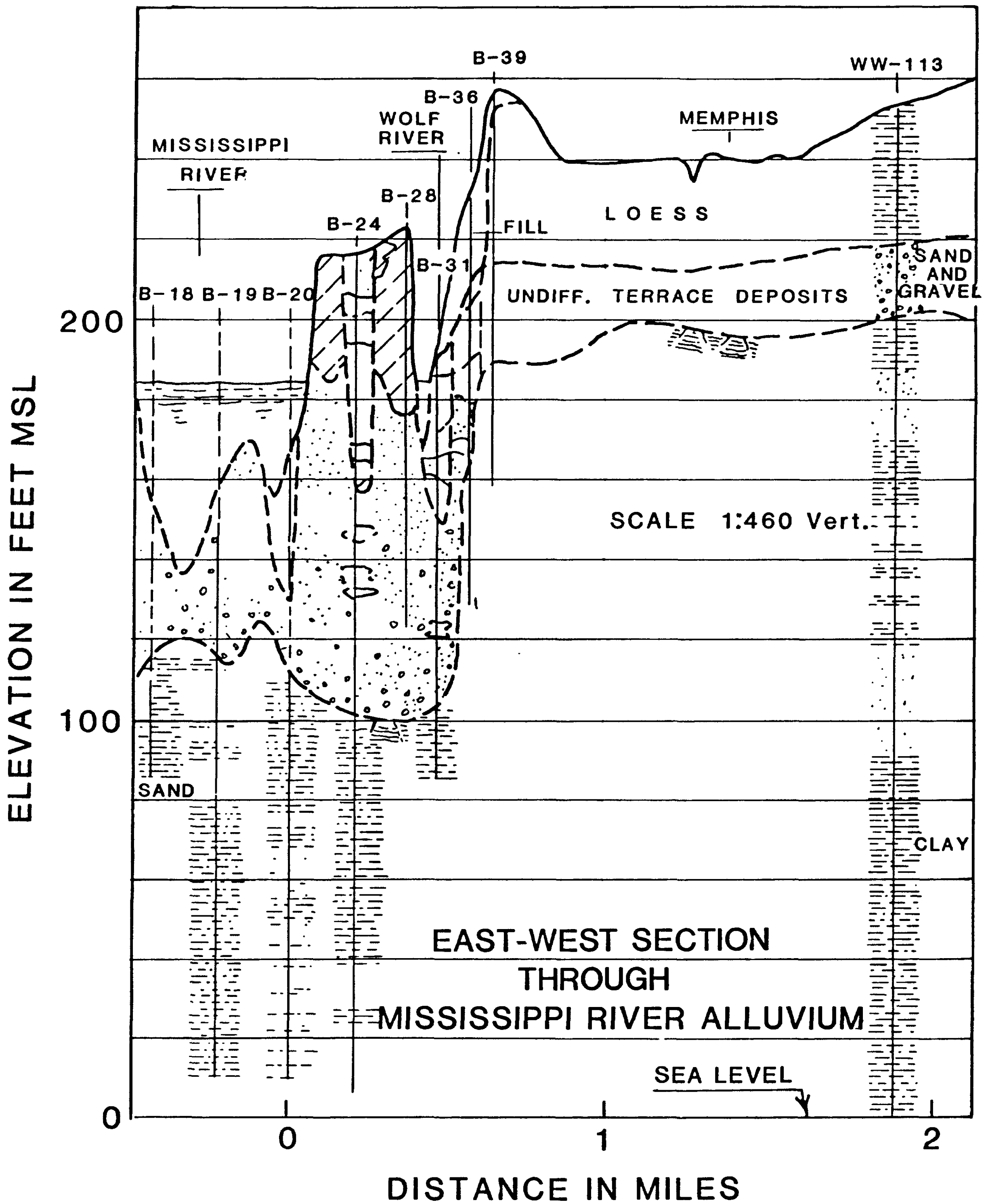

Figure 17. East-west geologic cross section beneath Memphis, Tennessee. After Sharma and Kovacs (1980), who quote M. & H. Engineering and Memphis State University (1974).

Physical property tests and other information:

The general locations for boreholes from which Sharma and Kovacs (1980) collected data are shown in figure 18. To protect confidentiality of the sources, exact locations of bore holes are omitted. By calculating relative 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 19).

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, 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. Information useful in reaching a conclusion about the possibility of the occurrence of horizontal block glide landslides is meager and inconclusive.

Potential for landslides, liquefaction, and other geologic effects:

1) 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. The occurrence of horizontal block glide landslides cannot be ruled out entirely.

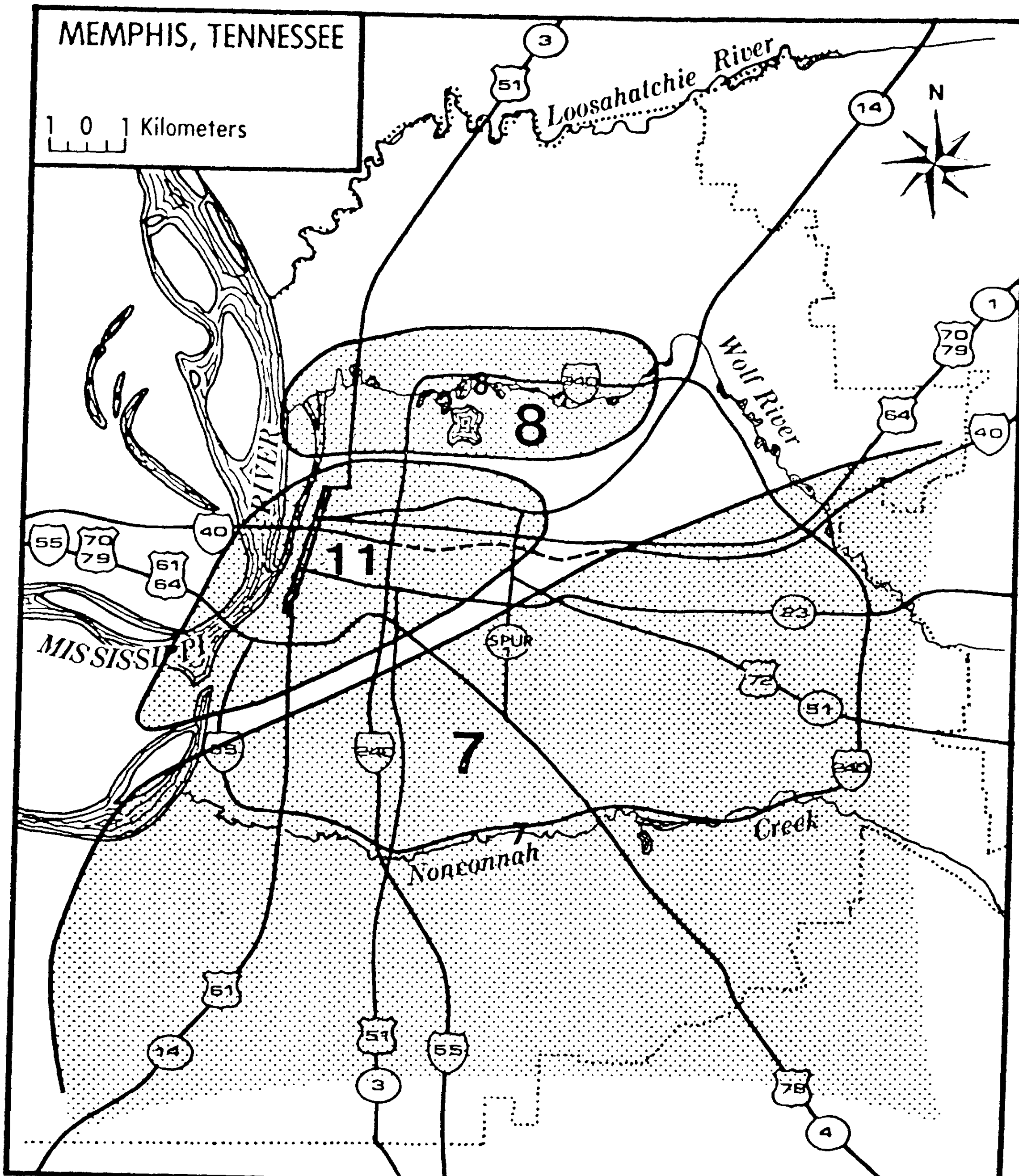

Figure 18. Map of Memphis, Tennessee. After Sharma and Kovacs (1980). Figures within shaded areas indicate the number of sites investigated for Sharma and Kovacs' study within each shaded area.

2) Liquefaction. Areas of potential liquefaction within the city of Memphis are shown in figure 19, (from Sharma and Kovacs, 1980). The liquefaction potential is probably high for the area underlain by Mississippi River flood plain deposits.

Hypothetical intensity map for Memphis:

The highest projected intensities at Memphis are IX-X M.M. from the regional map (figure 16). These intensities would occur in the event of the assumed 1811-size earthquake at the south end of the New Madrid seismic zone. If the 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 earthquake at the 1843 epicenter (on which the southern part of the hypothetical map is based), just 32 km away (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.

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

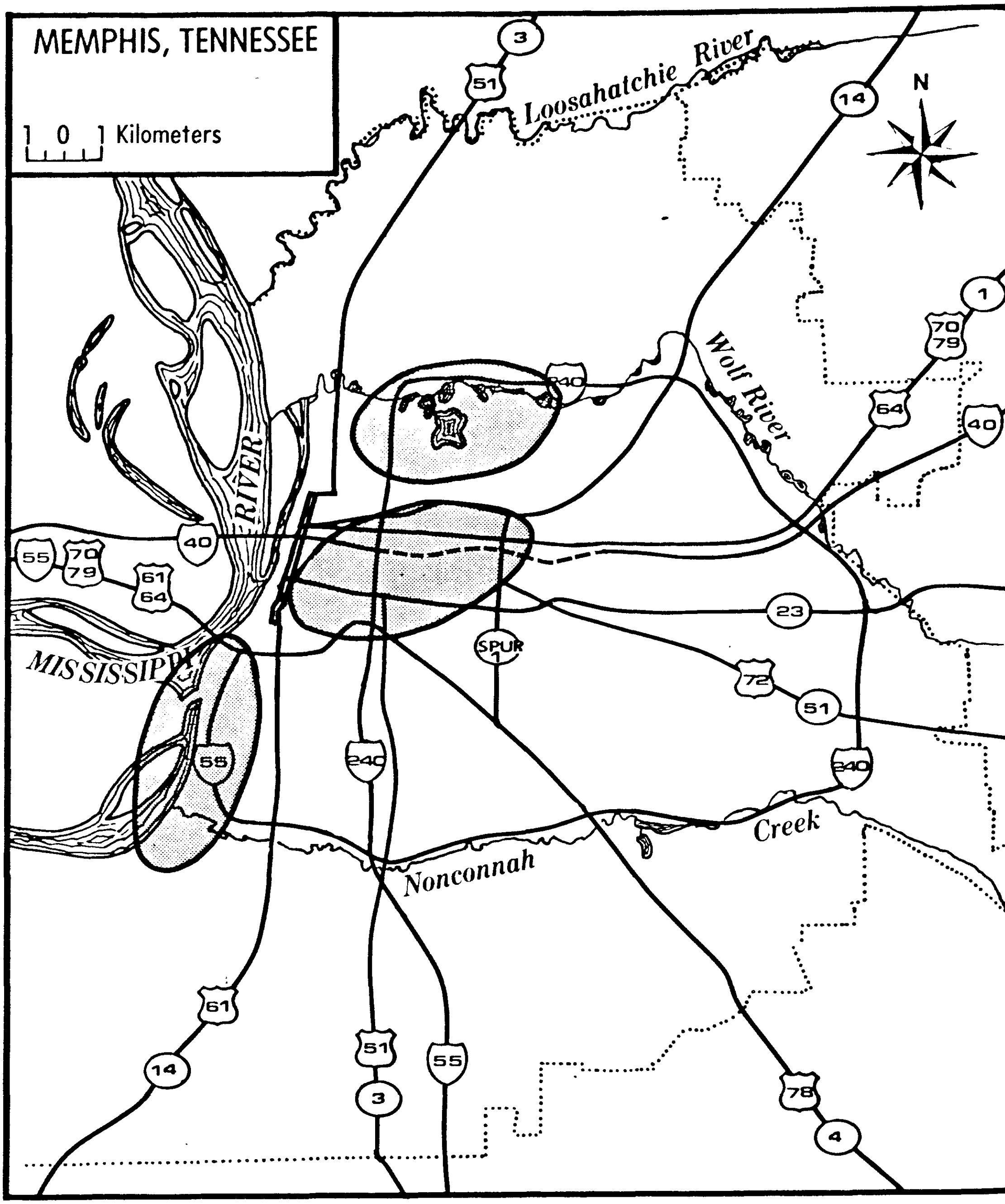

Figure 19. Map of Memphis, Tennessee. After Sharma and Kovacs (1980). Shaded areas indicate zones where soils may be susceptible to liquefaction for earthquakes with Modified Mercalli intensity greater than VII.

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 earthquake assumed for this study. A particularly critical area for landslides is the east bank of the Mississippi River from about I-55 to about I-40 (figure 13) (M & H Engineering and Memphis State University). 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 at Memphis intensity IX, 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 18), they computed selective amplification factors for various parts of Memphis (figure 20). 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 20, 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 19, and the number of boreholes from which they obtained their input data in figure 18. 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 map, figure 13. The slightly higher intensity on the alluvium can be seen in the areas of X along the Mississippi, Loosahatchie, and Wolf Rivers and Nonconnah Creek. Some of these areas correspond to the areas of high amplification (shown in figure 20) on the north and west sides of the city. Two of the three areas of potential liquefaction (shown in figure 19) are also included in the high amplification areas, but the central one from figure 19 can be distinguished as a separate area of potential X in figure 13. 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.

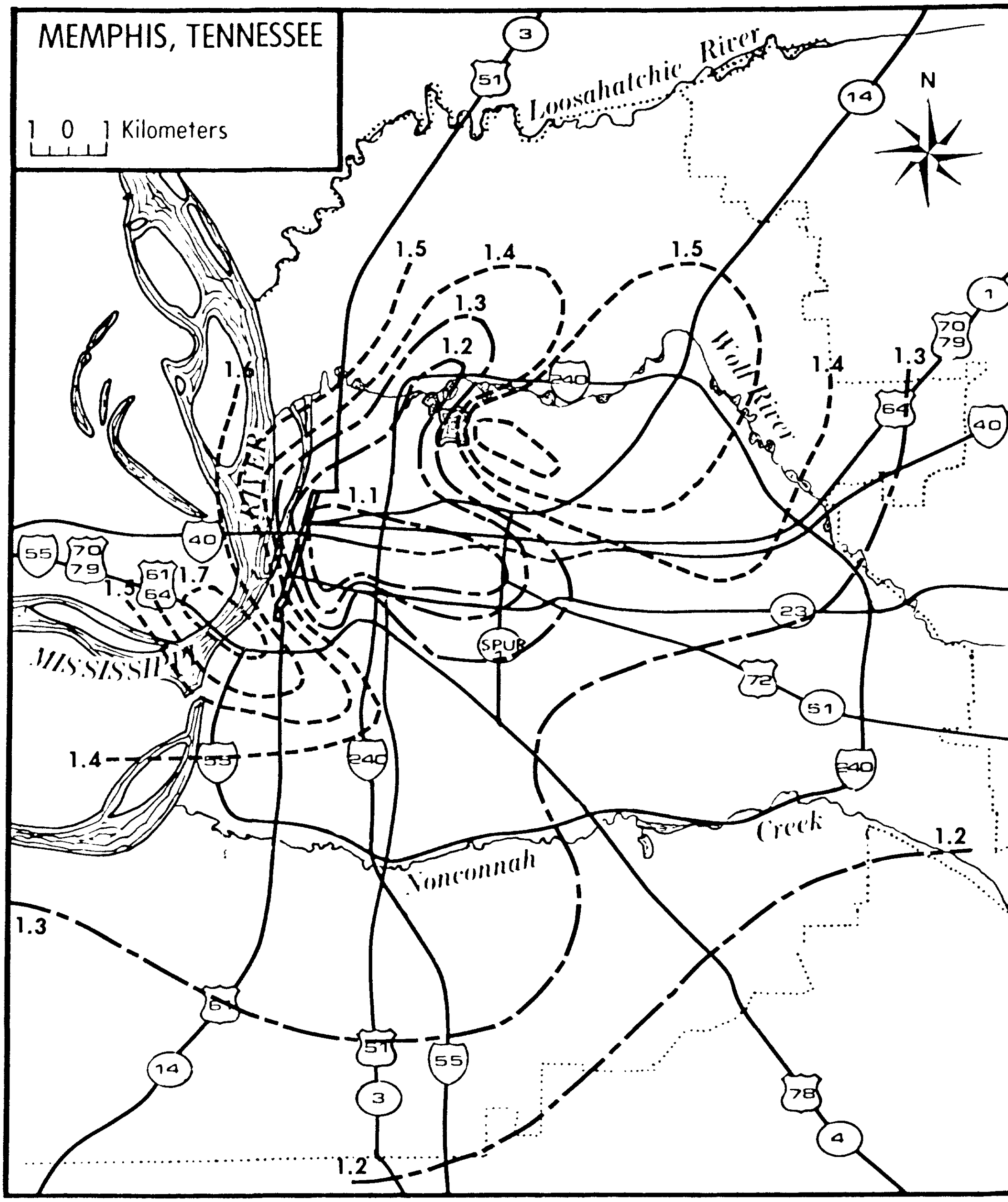

Figure 20.__Map of Memphis, Tennessee. After Sharma and Kovacs (1980). Contours are for amplification factors above assumed bedrock acceleration of 18% g at Memphis from a magnitude m_b=7.0 earthquake 50 km away from Memphis in the New Madrid seismic zone.

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:

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

2) 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 map at Paducah:

The highest projected intensities at Paducah are VIII-X M.M. from the regional map (figure 16). This range of intensities would occur for an 1811-size earthquake near the northern end of the New Madrid seismic zone. The range would be somewhat lower for an epicenter farther south. 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 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.

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 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 bore hole at the Veterans Administration Hospital is typical of several others located in the city west of Black River (Smith, Sam, 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) (Malloy, Dan, 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:

1) 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.

2) 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 map for Poplar Bluff:

From the regional map (figure 16) 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 (VII-IX). 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. 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 domintates the northern part of the regional map (figure 16), 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.

AREAS OF PROJECTED MINIMAL DAMAGE

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 map, figure 16--for example, the area of of intensity VII in south-central Missouri. It may be seen by inspection of figure 16 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 or low.

It is assumed that, for disaster planning purposes an area of intensity VIII (structural damage) would not be considered an area of minimal damage even if relatively low compared to nearby areas of IX or greater. Moreover, areas of intensity VII (architectural damage) and VI (threshold of any type of damage) are areas of minimal damage even if they are not relatively low. Thus the areas of minimal damage are those areas shown as VII, VI, and ≤VI in figure 16 and on the maps of the six 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 figure 16 is 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 intensity shown on figure 16 for his county is a guide to the highest level of intensity projected to be prevalent in some part of his county. Every point in the county will not experience this intensity; some places within the county will be lower, even in the part of the county where this guide intensity occurs often.

2) The guide intensity itself will be lower for an epicenter at the farthest part of the New Madrid seismic zone from his county.

3) The same guide intensity 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 rises. This is discussed more fully in the section on predomiant periods below.

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 sited 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.

PREDOMINANT PERIODS

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. Two topics of particular importance for 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 twelth floor of a 16-story building at M.I.T. 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 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 (Nuttli, 1979). The anomalously low attenuation of these waves in the central U.S. 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, too can be triggered in susceptible places at large epicentral distances from a great earthquake. Seiches and oscillations in surface water may occur out to hundreds of kilometers from the epicenter.

CONCLUSIONS

An earthquake the size of the 1811 shock, in spite of the long recurrence time, must be considered an event which might reasonably be expected to occur in the New Madrid seismic zone. In no other location in the Midwest is such a large earthquake deemed likely. Therefore, the earthquake chosen for simulation in this study is an I_o = XI, m_b = 7.2 shock anywhere along the New Madrid seismic zone. Its potential regional distribution of Modified Mercalli effects is shown in figure 16. Note that the map in figure 16 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 far end of the seismic zone 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 three 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 16 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 16. 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 16 can be found. The simulated intensites 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 six cities in this report.

The six 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. Development of the city intensity maps, figures 10-15, 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 16, 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) 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 are: Evansville, IX and VIII; Little Rock, VIII and VI; Memphis, X and IX; and Paducah, X, IX, and VIII.

Long-period effects from such an earthquake 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 16, 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*

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	sometimes birds, animals, reported uneasy or disturbed;
R.F.**	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	sometimes hanging objects may swing, especially when delicately
to	suspended;
II	sometimes trees, structures, liquids, bodies of water, may sway,
R.F.	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.
Sometimes not recognized to be an earthquake at first.
Duration estimated in some cases.

III	Vibration like that due to passing of light, or lightly loaded trucks, or
R.F.	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.

*Wood, H. O., and Neumann, F., 1931, Modified Mercalli Intensity Scale of 1931, Bulletin Seismological Society of America, v. 21, pp. 277-283.

**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 Sensation like heavy body striking building, or falling of heavy objects
to inside.
V Rattling of dishes, windows, doors; glassware and crockery clink
R.F. 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.
Building trembled throughout.
Broke dishes, glassware, to some extent.
V Cracked windows-in some cases, but not generally.
to Overturned vases, small or unstable objects, in many instances,
VI with occasional fall.
R.F. Hanging objects, doors, swing generally or considerable.
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- R.F. Damage negligible in buildings of good design and 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.
Damage slight in structures (brick) built especially to withstand earthquakes.

VIII+ to IX- R.F. 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 R.F. Changed level of water in wells.
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.
Threw objects upward in the air.

APPENDIX 2

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

1811 December 16 (238 km from Carbondale)

No information on Carbondale. The nearest points for which there is information are Cape Girardeau, 40 km away from Carbondale, on the Mississippi River and a $\geq$IX 90 km away on the Ohio River. Carbondale is within the VIII isoseismal (Nuttli, 1981).

1812 January 23 (178 km from Carbondale)

No information on Carbondale. The only intensity information in the Midwest is two points: an VIII at Cape Girardeau and a IX at New Madrid (Nuttli, 1973).

1812 February 7 (142 km from Carbondale)

No information on Carbondale. Nuttli (1973) assigned IX at Cape Girardeau, 40 km from Carbondale and 103 km from the epicenter. He also assigned VIII-IX at Saint Louis and IX at Cahokia, each about 140 km from Carbondale and 250 km from the epicenter.

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 (336 km from Evansville)

No information on Evansville. It is within the intensity- VII isoseismal on Nuttli's (1981) map and there is a VII location very nearby (within less than 20 km of Evansville). Across the Ohio River on the Kentucky side are a VII-VIII location at 25 km from Evansville, and a $\geq$IX at 30 km.

1812 January 23 (280 km from Evansville)

No information on Evansville. The only intensity information in the Midwest is two points: an VIII at Cape Girardeau and a IX at New Madrid (Nuttli, 1973).

1812 February 7 (241 km from Evansville)

No information on Evansville. The nearest location having intensity information is the IX at Cape Girardeau (Nuttli, 1973), 180 km from Evansville, and much closer to the epicenter at 103 km. At approximately the same epicentral distance as Evansville are the IX at Cahokia and the VIII-IX at Saint Louis, about 240 km from Evansville and 250 km from the epicenter.

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 (212 km from Little Rock)

No information on Little Rock. Little Rock is off the west edge of the area 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.

1812 January 23 (274 km from Little Rock)

No information on Little Rock. The only intensity information in the Midwest is two points: an VIII at Cape Girardeau and a IX at New Madrid (Nuttli, 1973).

1812 February 7 (311 km from Little Rock)

No information on Little Rock. No intensity information within a 300-km radius of Little Rock. No information south or west of the epicenter except the V at New Orleans (Nuttli, 1973), over 700 km from the epicenter. Saint Louis at 251 km epicentral distance is an VIII-IX.

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, AR, 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 (80 km from Memphis)

Intensity IX at Fort Pickering, TN, near Memphis (Nuttli, 1973). Memphis is within the intensity-IX area on Nuttli's 1981 isoseismal map. The next nearest location having intensity information is between Mississippi River islands 30 and 40, which Nuttli assigned X; their location is 70 km north of Memphis along the river and 45 km from the epicenter.

1812 January 23 (120 km from Memphis)

No information on Memphis. The nearest intensity information, IX (Nuttli, 1973), is from New Madrid, MO, 180 km from Memphis and 59 km from the epicenter.

1812 February 7 (160 km from Memphis)

No information on Memphis. The nearest intensity information, X-XI (Nuttli, 1973), is from New Madrid, MO, 180 km from Memphis and 21 km from the epicenter.

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, TN, 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, TN, 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, IA, 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 (205 km from Paducah)

No information on Paducah. Nuttli's (1981) map shows it in the intensity-IX area with an intensity VII assigned to a location within 40 km of Paducah.

1812 January 23 (145 km from Paducah)

No information on Paducah. The only intensity information in the Midwest is two points: an VIII at Cape Girardeau and a IX at New Madrid (Nuttli, 1973).

1812 February 7 (102 km from Paducah)

No information on Paducah. The nearest location having intensity information is the X-XI at New Madrid (Nuttli, 1973) only 21 epicentral distance as Paducah is the IX at Cape Girardeau, 90 km from Paducah and 103 km from the epicenter.

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 (104 km from Poplar Bluff)

No information on Poplar Bluff. Nuttli's (1981) map shows it near the outer edge of the intensity-IX area, but there are no locations with assigned intensity values within an 80-km radius of Poplar Bluff; nearby intensity values include X at Little Prairie (Caruthersville), 90 km from Poplar Bluff; X at 85 km; IX at New Madrid at 80 km; and VIII-IX at Cape Girardeau at 110 km. These locations are all along the Mississippi River. The only locations near Poplar Bluff that are not on the river and that have assigned intensities are a X and an XI in northeastern Arkansas at 95 and 120 km from Poplar Bluff and closer to the epicenter. The XI is on the Saint Francis River.

1812 January 23 (87 km from Poplar Bluff)

No information on Poplar Bluff. The only intensity information in the Midwest is two points: an VIII at Cape Girardeau and a IX at New Madrid (Nuttli, 1973).

1812 February 7 (82 km from Poplar Bluff)

No information on Poplar Bluff. The nearest locations having intensity information are the X-XI at New Madrid (Nuttli, 1973), 80 km from Poplar Bluff and 21 km from the epicenter, and the IX at Cape Girardeau 110 km from Poplar Bluff and 103 km from the epicenter.

1843 January 5 (179 km from Poplar Bluff)

No information of 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) assigns intensity V at Poplar Bluff.

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