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UA66/8/2 Earthquake Risk Assessment for Warren County, Kentucky

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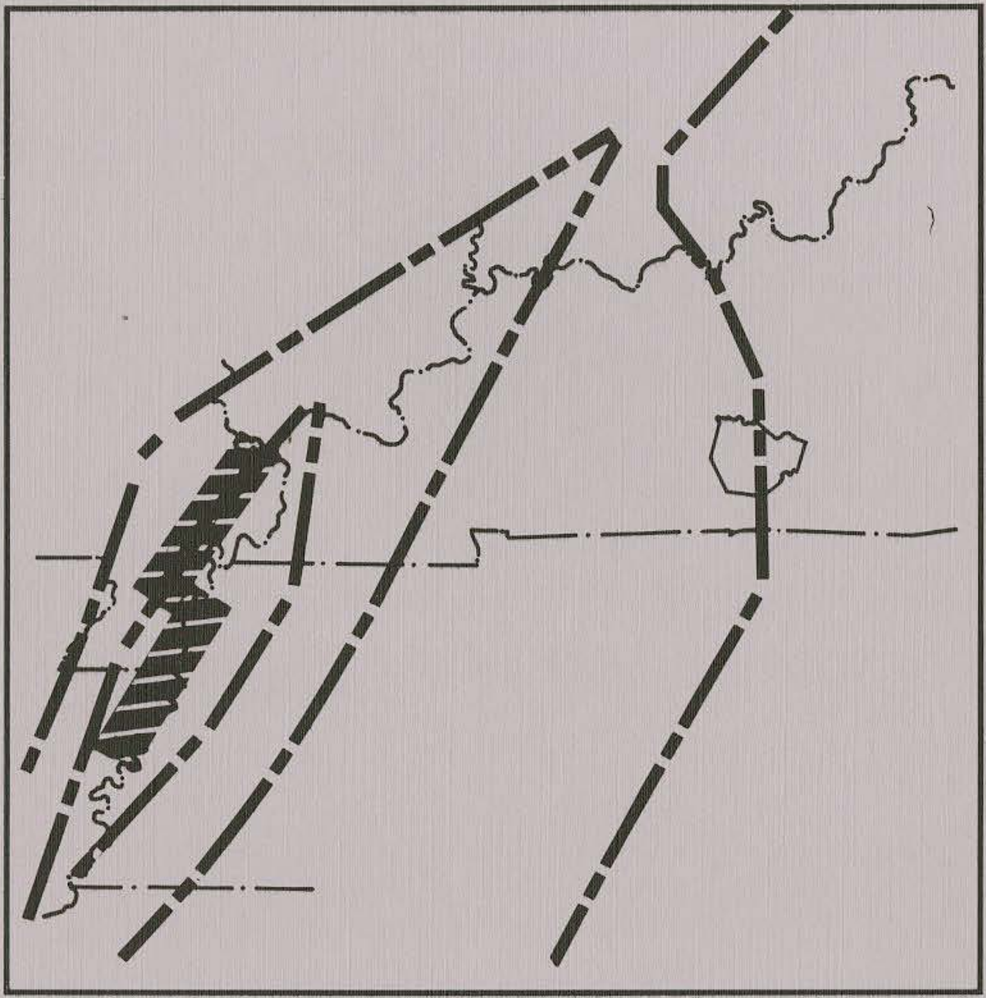

EARTHQUAKE ANALYSIS

WARREN COUNTY COMPREHENSIVE PLAN

TECHNICAL REPORT

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EARTHQUAKE RISK ASSESSMENT FOR WARREN COUNTY, KENTUCKY

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EARTHQUAKE RISK ASSESSMENT FOR WARREN COUNTY, KENTUCKY

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1989

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EXECUTIVE SUMMARY

The largest seismic event in U.S. history occurred along the New Madrid Rift Complex which parallels the Mississippi River along the boundaries of Kentucky, Missouri, Tennessee and Arkansas. Between December 16, 1811 and March 15, 1812, there were five great earthquakes with estimated magnitudes above 8.0 Richter, with one of these estimated at 8.8 Richter. Warren County, although 150 miles from the epicentral region, would suffer considerable damage from an 8.6 Richter earthquake.

Johnson and Nava (1985) have estimated the probabilities for future, large earthquakes in the New Madrid seismic zone. They estimate that there is a 40-63% probability of 6.3 Richter event occurring by the year 2000 (within the next 10 years) and an 86-97% probability by the year 2035. A 6.3 Richter quake would certainly be felt in Warren County but probably would not cause any serious damage. Figure 6 of this report shows that on the Modified Mercalli Intensity Scale for a 6.7 Richter earthquake, Warren County lies on the boundary between Zone VI -STRONG (felt by all, indoors and outdoors, cracked plaster and overturned furniture) and VII-VERY STRONG (frightens all, general alarm, cracked chimneys, considerable damage in poorly built buildings—see Appendix).

Dr. Ron Seeger (1989), Professor of Geophysics, Western Kentucky University, estimates that in order to have any substantial damaging effect in Warren County, a major earthquake, greater than about 7.6 Richter would have to occur in the New Madrid seismic zone. He estimates the probability, using the Johnson and Nava (1985) data, of a 7.6 Richter quake to be about 4 to 6% by the year 2000 and 8 to 10% by 2035. Figure 7 of this report shows that for a 7.6 Richter earthquake, Warren County lies on the boundary between Zone VII-VERY STRONG (described above) and Zone VIII-DESTRUCTIVE (general fright approaching panic, changes in groundwater flow, wood structures damaged, falling of chimneys and towers—see Appendix).

Johnson and Nava (1985) estimate the probability of a great quake, equal to the 1811-1812 earthquakes, occurring in the New Madrid seismic zone to be less than 1% probability by the year 2000 and less than 4% by the year 2035. Figure 8 of this report shows that for an 8.6 Richter earthquake, Warren County lies on the boundary between Zone VIII DESTRUCTIVE (described above) and IX RUINOUS (panic general, cracked ground, damage in most all structures, pipes broken—see Appendix).

Earthquake prediction is still somewhat in its infancy as a science. Where good historic data and a sound understanding of the geologic forces responsible for earthquakes exist, general time predictions of recurrence intervals are possible. With historic records extending back into the 1500s and a good understanding of the geologic forces at work along plate boundaries, fairly good earthquake recurrance intervals and probabilities can be estimated along the San Andreas Fault in California. However, this is not the case along the New Madrid Fault. Areas of high seismic activity within crustal plates are rare and scientists are only beginning to understand this area. The best theory is that the rift complex, which is thought to have formed in late Precambrian to Cambrian time (1,500 to 500 million years ago), is currently experiencing compressive reactivation of some structural features. Johnson and Nava (1985) recognized that their probabilities are contingent on a number of factors which remain assumptions because of the lack of a geological or paleoseismological chronology of past New Madrid activity.

Alluvial soils along rivers can magnify earthquake damage but fortunately for Warren County, there are very few structures built upon alluvial soils. Since the faults in the northwest part of the county are believed to be inactive, karst features are believed to be the primary damage magnifiers.

Vibrating of the surface by blasting has induced the sinkhole collapse of regolith (soil) arches in other areas, causing the abandoning of a village in China (Waltham, 1989) and accounting for 4% of the sinkhole collapses in a study by Williams and Vineyard (1971) in Missouri. Earthquakes which occurred in 1962 in Yugoslavia caused the collapse of some bedrock cave roofs and caused the bottoms of many sinkholes to open (Milanovic, 1981).

There are cantilevered cave roofs in many locations under Warren County which appear to be unstable. It is possible that a large earthquake might induce the collapse of some of these. It would be a mistake, however, to assume that homes built above known bedrock caves are at greater seismic risk. The cave system under the county is extremely complicated and even small caves often have some very large rooms which have been created by roof collapses. Unless bedrock borings have been made, it would be incorrect to assume that any home upon the sinkhole plain of Warren County is not above a cave.

It is probable that there are hundreds of thousands of regolith (soil) arches above voids in the bedrock under Warren County. A large earthquake would probably induce the collapse of some of these existing arches. However, the great majority of these are believed to be in or near the bottoms of our numerous bowl-shaped sinkholes and therefore, within the sinkhole flood plain for a one-hundred year probability, three-hour storm event. Therefore, our existing storm water management plan which prohibits the building of structures within the sinkhole flood plain provides an excellent land use plan for preventing the building of structures in areas which are the most likely to have a sinkhole collapse either during a flood or during an earthquake. Therefore, an earthquake land use plan already exists for Warren County.

Other areas that are particularly at risk of collapse or subsidence are areas where bedrock caves have already collapsed. These are areas of broken rock with sediment, water and air separating the boulders. These areas are believed to be at high risk of sinkhole collapse or subsidence due to increased packing caused by erosion by cave streams during floods or vibration during large earthquakes. Some of these areas are obvious as deep, steep-walled sinkholes but microgravity investigations combined with exploratory drilling have revealed extensive areas both in the city and county which do not have a surface expression. These areas need to be found and identified. Structures should not be built on these potentially unstable sites.

Because of the cutter-and-pinnacle bedrock surface in the karst areas of Warren County, it is possible that differential compaction could be accellerated during large earthquakes and this could damage foundations. Most differential compaction is likely to occur in sinkhole bottoms which have collapsed in the past and then were filled with trash, old cars, appliances, tree stumps, rocks, etc. Again, these areas usually occur within the sinkhole flood plain and the existing storm water management plan should prevent structures from being built upon most of these areas. Unfortunately, even though it is against a county ordinance to fill sinkholes, and against the state law to dispose of waste without a permit, many sinkholes have been filled, and structures have been built upon these filled sinkholes.

Warren County is faced with a serious dilemma in terns of how to plan for a large earthquake which will occur in the New Madrid seismic zone. Some time in the future, a great quake, as large as the ones during the winter of 1811-1812, is going to occur. If it happens in the near future it will result in major damage in Warren County. Should the county therefore launch a crash program to prepare for a great quake? Yes, if there is reason to believe it is going to happen in the near future but that does not appear to be the case.

Some day Warren County is going to have a 1000 year probability flood and there is a 10% probability that it will happen in the next 100 years and a 1% chance that it will happen in the next 10 years. Should the county prepare for it? A reasonable planning decision was made in 1976 that the county will plan for a 100 year probability, 3-hour rain event for storm water management purposes. Planning for a 100 year storm, which has a 1% probability of occurring each year, will not only eliminate flood losses during 100 year and lesser storms, but it will greatly reduce flood losses when a 1000 year flood does occur.

A similar planning decision is needed in preparing for an earthquake. The probability for an 8.6 Richter quake in the near future appears to be small and the cost of preparing for a great quake would be very high. However, the probability for a major quake of 7.6 Richter is higher (it may or may not be 4 to 6% in the next 10 years but it has a much higher probability than an 8.6 Richter quake). Planning for a 7.6 Richter quake is far superior to doing nothing and even when the 8.6 Richter quake does occur, damages will be considerably less than they would have been without any earthquake planning. However, there are certain strategic buildings, such as hospitals, fire departments, police stations, etc., where it may be necessary to plan for a higher magnitude earthquake.

Homes and buildings in Warren County should have earthquake and sinkhole collapse insurance. Most homeowners probably do not realize that there is a potential for earthquake damage in Warren County. Many homeowners probably also believe that their homeowners insurance policy covers their home in the event of earthquake or sinkhole collapse damage. It does not unless they have paid extra for earthquake protection. Most homeowners do not have and cannot get sinkhole collapse insurance from their present insurance company. Only one or two companies presently provide both earthquake and sinkhole collapse insurance under an "earth movement" rider to their homeowners policy. The state of Florida requires all insurance companies doing business in Florida to provide sinkhole collapse protection. Kentucky should do the same. If necessary, Warren County should require that all insurance companies provide this protection.

The cost of adding earthquake (and sinkhole collapse) insurance to one's homeowners policy varies with the insurance company and the value of the home but it is usually not very expensive. (If it is, then the consumer should consider changing his insurance company).

The building code for Warren County should be upgraded to conform with the new and revised earthquake regulations in the Uniform Building Code (1988), published by the International Conference of Building Officials. Warren County is in Seismic Zone 1 with Zone 4 being the highest and Zone 0 being the lowest.

Foundation investigations for multi-storied buildings and other strategic buildings should require not only soil borings but bedrock borings as well. New buildings should not be built above cave rooms with unstable cantilevered domes or above areas of broken rock where caves have collapsed. Where possible, these buildings should have their foundations built upon solid bedrock in order to prevent differential compaction problems associated with cutter-and-pinnacle bedrock surfaces.

The present storm water management plan prevents the building of structures within the one hundred year probability, three-hour storm, sinkhole flood plain. Since these areas are also the most vulnerable areas for sinkhole collapse and differential compaction, Warren County already has an earthquake land use plan. However, areas of broken rocks resulting from cave collapses should be identified and structures prohibited from these potentially unstable areas.

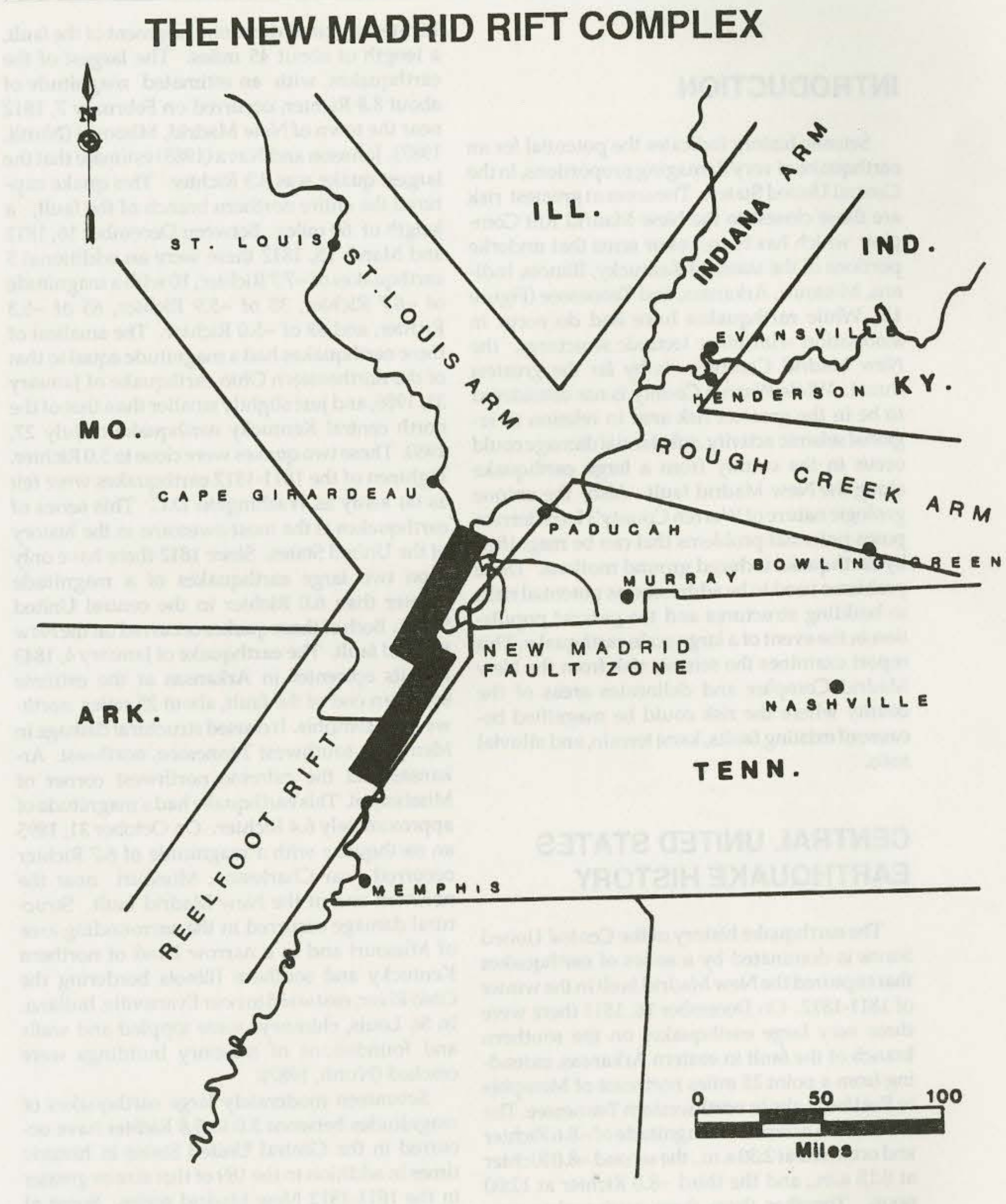
INTRODUCTION

Seismic history indicates the potential for an earthquake of very damaging proportions, in the Central United States. The areas at greatest risk are those closest to the New Madrid Rift Complex which has branches or arms that underlie portions of the states of Kentucky, Illinois, Indiana, Missouri, Arkansas, and Tennessee (Figure 1). While earthquakes have and do occur in association with other tectonic structures, the New Madrid Complex is by far the greatest threat. While Warren County is not considered to be in the greatest risk area in relation to regional seismic activity, substantial damage could occur in the county from a large earthquake along the New Madrid fault. Also, the unique geologic nature of Warren County's karst terrain poses potential problems that can be magnified by earthquake induced ground motions. These problems need to be addressed as potential risks to building structures and the general population in the event of a large scale earthquake. This report examines the seismic risk from the New Madrid Complex and delineates areas of the county where the risk could be magnified because of existing faults, karst terrain, and alluvial soils.

CENTRAL UNITED STATES EARTHQUAKE HISTORY

The earthquake history of the Central United States is dominated by a series of earthquakes that ruptured the New Madrid fault in the winter of 1811-1812. On December 16, 1811 there were three very large earthquakes on the southern branch of the fault in eastern Arkansas, extending from a point 25 miles northeast of Memphis to Reelfoot Lake in northwestern Tennessee. The first had an estimated magnitude of ~8.6 Richter and occurred at 2:30 a.m., the second ~8.0 Richter at 8:15 a.m., and the third ~8.0 Richter at 12:00 noon. Together these three earthquakes ruptured the entire southern segment of the fault, a length of about 90 miles. On January 23, 1812 an earthquake with an estimated magnitude of ~8.4 Richter ruptured the central segment of the fault, a length of about 45 miles. The largest of the earthquakes, with an estimated magnitude of about 8.8 Richter, occurred on February 7, 1812 near the town of New Madrid, Missouri (Nuttli, 1987). Johnson and Nava (1985) estimate that the largest quake was 8.3 Richter. This quake ruptured the entire northern branch of the fault, a length of 60 miles. Between December 16, 1811 and March 15, 1812 there were an additional 5 earthquakes of ~7.7 Richter, 10 with a magnitude of ~6.7 Richter, 35 of ~5.9 Richter, 65 of ~5.3 Richter, and 89 of ~5.0 Richter. The smallest of these earthquakes had a magnitude equal to that of the northeastern Ohio earthquake of January 31, 1986, and just slightly smaller than that of the north central Kentucky earthquake of July 27, 1980. These two quakes were close to 5.0 Richter. Eighteen of the 1811-1812 earthquakes were felt as far away as Washington D.C. This series of earthquakes is the most awesome in the history of the United States. Since 1812 there have only been two large earthquakes of a magnitude greater than 6.0 Richter in the central United States. Both of these quakes occurred on the New Madrid fault. The earthquake of January 4, 1843 had its epicenter in Arkansas at the extreme southern end of the fault, about 25 miles northwest of Memphis. It caused structural damage in Memphis, southwest Tennessee, northeast Arkansas and the extreme northwest corner of Mississippi. This earthquake had a magnitude of approximately 6.4 Richter. On October 31, 1895 an earthquake with a magnitude of 6.7 Richter occurred near Charleston, Missouri near the northern end of the New Madrid fault. Structural damage occurred in the surrounding area of Missouri and in a narrow band of northern Kentucky and southern Illinois bordering the Ohio River, eastward to near Evansville, Indiana. In St. Louis, chimneys were toppled and walls and foundations of masonry buildings were cracked (Nuttli, 1987).

Seventeen moderately large earthquakes of magnitudes between 5.0 to 5.8 Richter have occurred in the Central United States in historic times in addition to the 189 of that size or greater in the 1811-1812 New Madrid series. Some of these were in the Wabash Valley, a region where focal depths are often about 13 miles deep, suggesting the potential of a very large earthquake there. Two were in the Illinois Basin of



Source: Nuttli, (1987).

southern Illinois and one occurred in northern Illinois. Two earthquakes occurred in northwestern Ohio, near the town of Anna, and are noteworthy for occurring at a shallow depth of about 3 miles, which possibly limits the maximum earthquake magnitude in this region to around 5.0 Richter. This is believed to be true also of the 1980 quake in northcentral Kentucky and the 1986 quake in northeastern Ohio (Nuttli, 1987). One earthquake occurred in the St. Francois uplift region northwest of the New Madrid fault and two occurred in the Quachita-Wichita Mountains zone. These areas are believed to have the potential for large quakes. Two of the historical earthquakes were associated with the Nemaha Uplift, and one quake was associated with the Colorado Lineament zone. Figure 2 is a map showing the location and intensity of some of the largest historical earthquakes. Of the eight source zones shown in Figure 2, shallow focal depths with magnitudes not greater than about 5.5 Richter are likely to occur from the Cincinnati Arch and the Colorado Lineament. Great earthquakes have occurred along the New Madrid fault and very large ones may occur along the Wabash Valley fault, both of these regions of earthquake activity occur due to crustal rifting. The remaining source zones appear to have the potential for producing large earthquakes of between 6.5 to 7.0 Richter at the maximum. (Nuttli, 1987).

The 1811-1812 mainshocks produced massive ground deformation over a wide area. Sand craters and sandblows occurred in the Mississippi River flood plain from south of St. Louis to the mouth of the Arkansas River, in the Ohio River Valley from Cairo, Illinois to southwestern Indiana, and in the St. Francis River Valley of Arkansas. Liquefaction and landslides affected an area of about 6,000 square miles in east Missouri, western Tennessee and northeastern Arkansas. Vertical uplift and subsidence of 10 to 20 feet were reported in the epicentral areas, as well as deep and long rifts in the soil that were so wide that they could not be jumped across on horseback. At St. Louis, at least 175 miles away from the mainshock epicenters, 2 to 3 feet thick stone foundations of houses were split by the ground shaking and chimneys fell. Similar damage occurred at Louisville, at about the same distance from the epicenters. Low density population and simple log cabin structures accounted for the relatively small loss of life and property. Areas of southeast Missouri were so ravaged by the earthquakes that the United States Congress passed the first Disaster Relief Act in 1815, giving new land to the settlers of the area (Nuttli, 1987). The only other central United States earthquake known to have caused notable ground failure was the Charleston, Missouri event of October 31, 1895. A new lake was formed and sandblows were reported in an area of about 6 miles radius of the epicenter. Building damage was extensive at Charleston, Missouri, and hundreds of chimneys were shaken down in nearby Cairo, Illinois. The November earthquake of 1968 which had an epicenter near Golden Gate, Illinois, and a magnitude of 5.8 Richter did not cause ground failure but did cause some structural damage to foundations and stone facades in southern Illinois and parts of Western Kentucky (Nuttli, 1987).

THE NEW MADRID RIFT COMPLEX

There has been considerable speculation by scientists as to when the New Madrid Rift Complex will unleash another 1811-1812 magnitude earthquake. The average citizen in Kentucky knows very little about the true nature and risks associated with living in this area. A 7.0+ Richter quake from the New Madrid Fault could have disasterous effects on Western Kentucky.

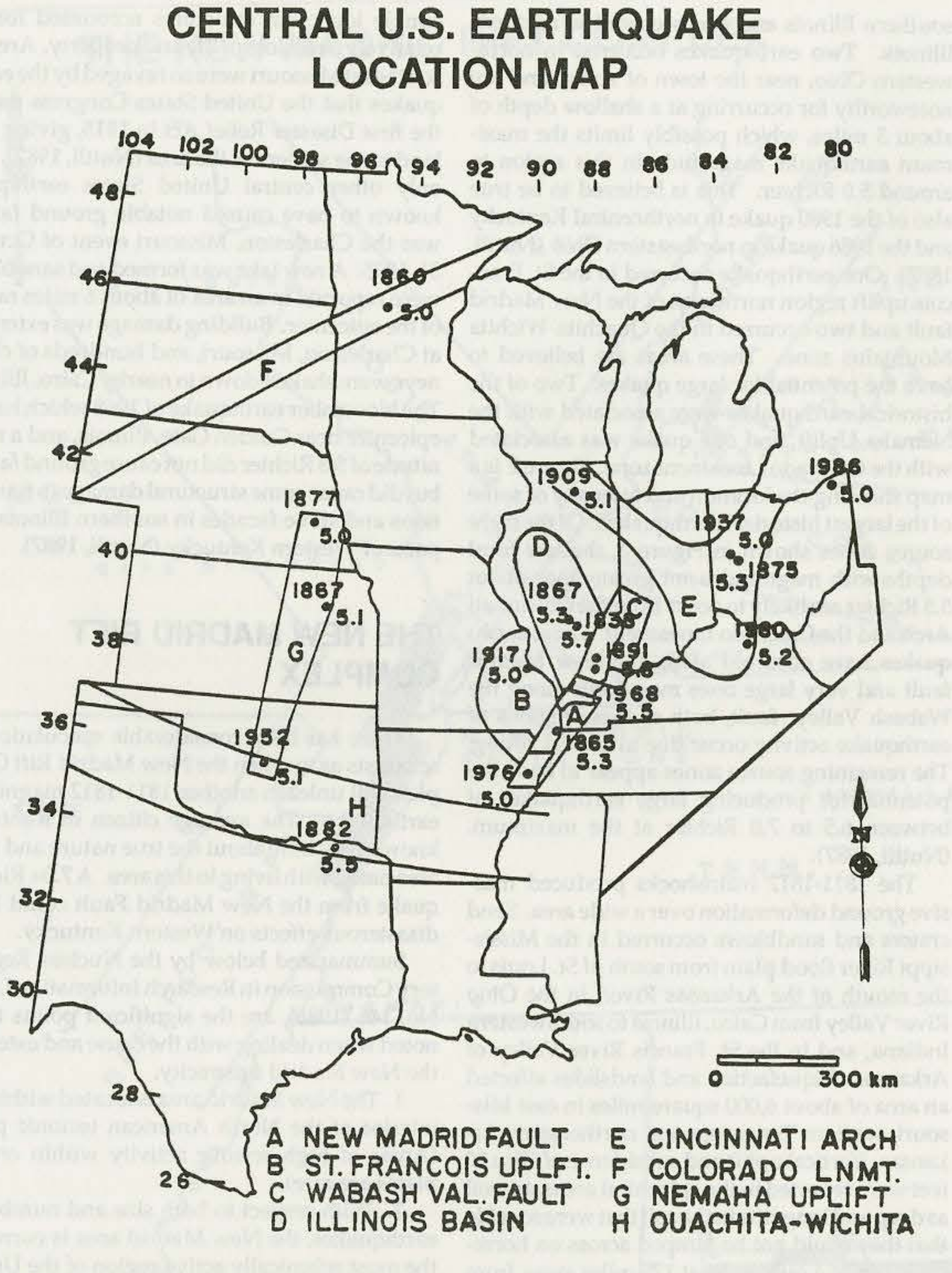
Summarized below by the Nuclear Regulatory Commission in Research Information Letter No. 146 (1986), are the significant points to be noted when dealing with the cause and extent of the New Madrid seismicity.

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

2. With respect to both size and number of earthquakes, the New Madrid area is currently the most seismically active region of the United States east of the Rocky Mountains.

3. The New Madrid earthquakes of 1811-1812 are associated with tectonic structures which are part of the New Madrid Rift Complex. The New Madrid Rift Complex is a major tectonic feature within the North American Continent.

Figure 2



Location of moderately large central United States earthquakes, of m_b 5.0 through 5.8, that occurred since 1812. The larger magnitude New Madrid earthquakes of 1811, 1812, 1843 and 1895 are not included in the figure.

Source: Nutti, (1987).

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

5. The conceptual model consists of a rift complex called the New Madrid Rift Complex, which has four arms, the Reelfoot Rift, the St. Louis Arm, the Indiana Arm, and Rough Creek Arm or Graben. (Figure 1).

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

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

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

9. Contemporary stress measurements show that the New Madrid area is now in a compressional stress regime where the principal compressive stress is oriented approximately east-northeast-west-southwest.

10. Of the four arms of the New Madrid Rift Complex, the Reelfoot is by far the most active seismically (Figure 1).

11. Based on a United States Geological Survey trenching across the Reelfoot Scarp, the recurrence interval for earthquakes in the Reelfoot Rift large enough to produce ground motion great enough to liquefy sand in the alluvium of the New Madrid Complex area to the extent it did in 1811-1812 is about 600 years.

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

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

14. Immediately to the north of the disturbed zone, contemporary seismicity strikes approximately 330 degrees, in contrast to the disturbed zone, which strikes 50 degrees; Zoback et al, (1980), using seismic reflection data, related seismicity in the area to small faults and igneous plutons of various ages.

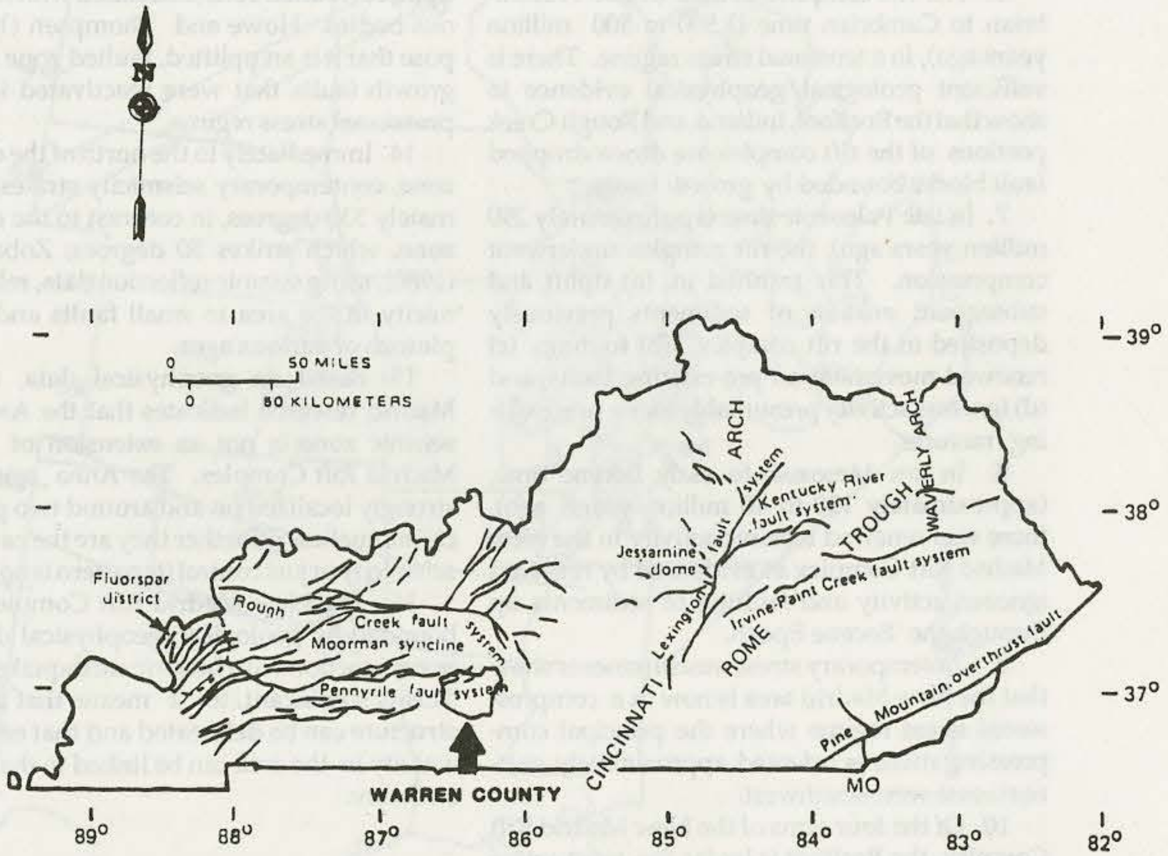
15. Based on geophysical data, the New Madrid research indicates that the Anna, Ohio seismic zone is not an extension of the New Madrid Rift Complex. The Anna seismicity is strongly localized on and around two geophysical anomalies. Whether they are the cause of the seismicity or just control its pattern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

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

GEOLOGIC FAULTS IN WARREN COUNTY

The Rough Creek fault system crosses the southern end of the Illinois basin in Kentucky and forms the northern boundary of the east-west-trending Moorman syncline (Figure 3). The Rough Creek fault zone is made up of numerous high-angle normal faults and less common reverse faults bounding a series of grabens and horsts, with a total displacement, down to the south, generally of about 300 feet, but in some

FAULT SYSTEMS OF KENTUCKY



Source: U.S.G.S., (1984).

places by as much as ten times that. The Pennyrile fault system marking the southern boundary of the Moorman syncline, is similar in form to the Rough Creek but has fewer and smaller faults; fault scarps along this system exposed by strip mining of the coal fields indicate dip-slip movement (Palmer, 1969). Whaley and others (1980), in a description of the structures of the southernmost Illinois basin, report little or no lateral offset but significant vertical movement on the Rough Creek fault system through at least Early Permian time. Geophysical studies by Soderberg and Keller (1981), indicate that the Moorman syncline is underlain by a large graben, which they name as the Rough Creek graben, that was active as early as latest Precambrian or earliest Cambrian time and that has been reactivated in the late Paleozoic and possibly Mesozoic. Buschbach and Atherton (1979) suggest that most movement on faults at the southern end of the Illinois basin took place at the end of the Paleozoic.

Northwest Warren County is located just outside the Arm of the New Madrid Rift Complex called the Rough Creek graben (Figure 4). This structure is bounded to the northwest by the Rough Creek fault system and the south and east by the Pennyrile fault system. Figure 3 is a map of Western Kentucky's geologic structures relating to the New Madrid Rift Complex. Faults found in the stratigraphy of northern Warren County are associated with the Pennyrile fault system of the Rough Creek graben (Figure 5).

The Rough Creek graben is considered to be a down dropped fault block which is bounded by growth faults (NRC/RIL 146, 1986). The faults found in the Pennyrile fault system are most probably associated with the southeastern side of the Rough Creek graben. The Rough Creek graben can be determined by its aeromagnetic and gravity signature (Figure 4). Pre-Late Cambrian rifting caused a down dropped block to form which manifested itself as a topographic depression. This depression then continued to subside as it filled with sediments. The sedimentary deposits in the central area of the Rough Creek graben are much thicker than sedimentary deposits outside the boundaries of the structure. This area between the Rough Creek fault system and the Pennyrile system contains the Moorman syncline. The faults found just outside the boundary of the Rough Creek graben may be associated with the graben as growth faults formed as subsidence continued. The faults found in northern Warren County are associated with the southern boundary of the Rough Creek graben which is the Pennyrile fault system. Much of the later sedimentary sequences, (Permian to Cretaceous), have been lost due to uplifting and erosion. The remaining stratigraphic record in Warren County is from the Carboniferous which has given rise to the karst terrain. Figure 4 uses the structural geology map of Figure 3 as a base map on which the inferred boundaries of the Rough Creek graben arm of the New Madrid Rift Complex are overlain. Although it is believed that the faults in Warren County are not presently active, they represent areas of geologic weakness which could result in movement during a large earthquake in the Rough Creek Arm of the New Madrid Rift Complex.

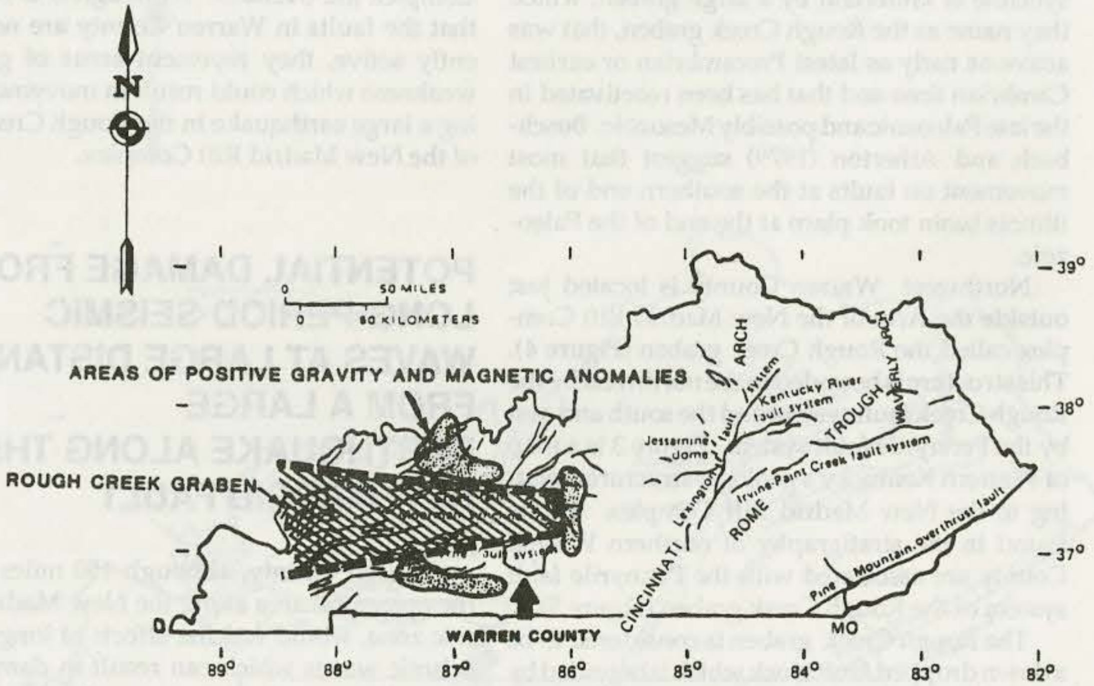
POTENTIAL DAMAGE FROM LONG-PERIOD SEISMIC WAVES AT LARGE DISTANCES FROM A LARGE EARTHQUAKE ALONG THE NEW MADRID FAULT

Warren County, although 150 miles east of the epicentral area along the New Madrid seismic zone, would feel the effects of long-period seismic waves which can result in damages at large distances from large earthquakes, especially for earthquakes occurring in the central United States. These long-period effects are another source of the variation displayed by earthquake isoseismals or intensity patterns. Two topics of particular concern are: 1) effects on tall buildings, and 2) effects on ground and water.

The moderate size 5.8 Richter 1968 earthquake in southern Illinois is reported to have caused slight damage and frightened people in Chicago skyscrapers, 269 miles away from the epicenter; to have been felt on the twelfth floor of a 16-story building at the Massachusetts Institute of Technology in Cambridge, Massachusetts, 937 miles away; and to have been felt in tall buildings in southern Ontario, Canada (Necioglu and Nuttli, 1974). Such effects are a consequence of

Figure 4

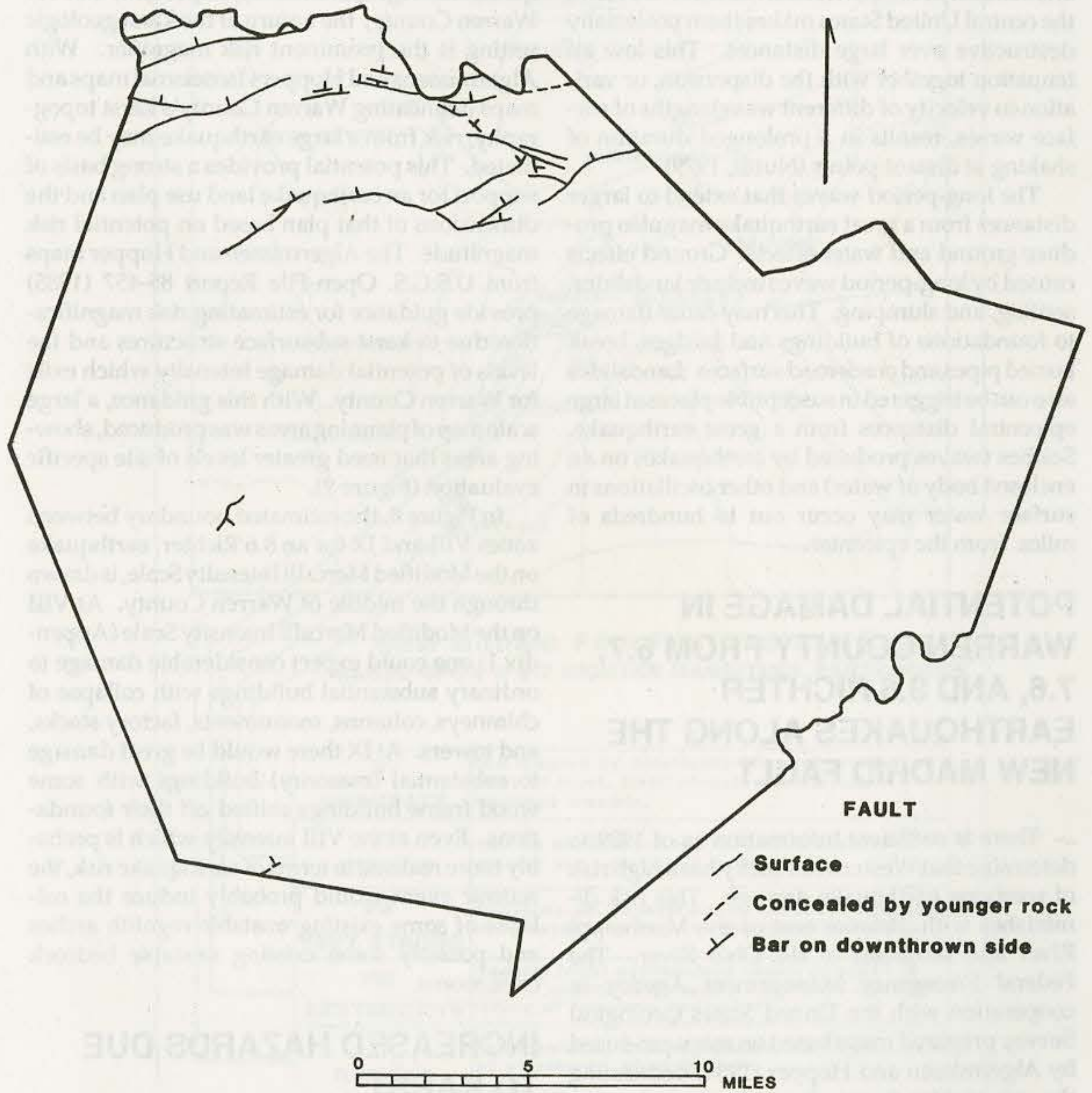
THE ROUGH CREEK GRABEN OF THE NEW MADRID RIFT COMPLEX



Source: Nuclear Regulatory Research Information Letter Number 146, (1986).

Figure 5

GEOLOGIC FAULTS OF WARREN COUNTY



Source: Schwalb and others, (1971) Oil and Gas Map of Kentucky, Sheet 2, West-Central Part.

the similarity of the predominant periods exhibited by the earthquake at those distances to the natural periods (fundamental modes of vibration) of the buildings. In the epicentral region damage is caused by the short-period, high-acceleration vibrations predominant there; farther away, the longer-period waves, having low ground acceleration for relatively large ground displacements, begin to predominate. The anomalously low attenuation of these waves in the central United States makes them potentially destructive over large distances. This low attenuation together with the dispersion, or variation in velocity of different wavelengths of surface waves, results in a prolonged duration of shaking at distant points (Nuttli, 1979).

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

POTENTIAL DAMAGE IN WARREN COUNTY FROM 6.7, 7.6, AND 8.6 RICHTER EARTHQUAKES ALONG THE NEW MADRID FAULT

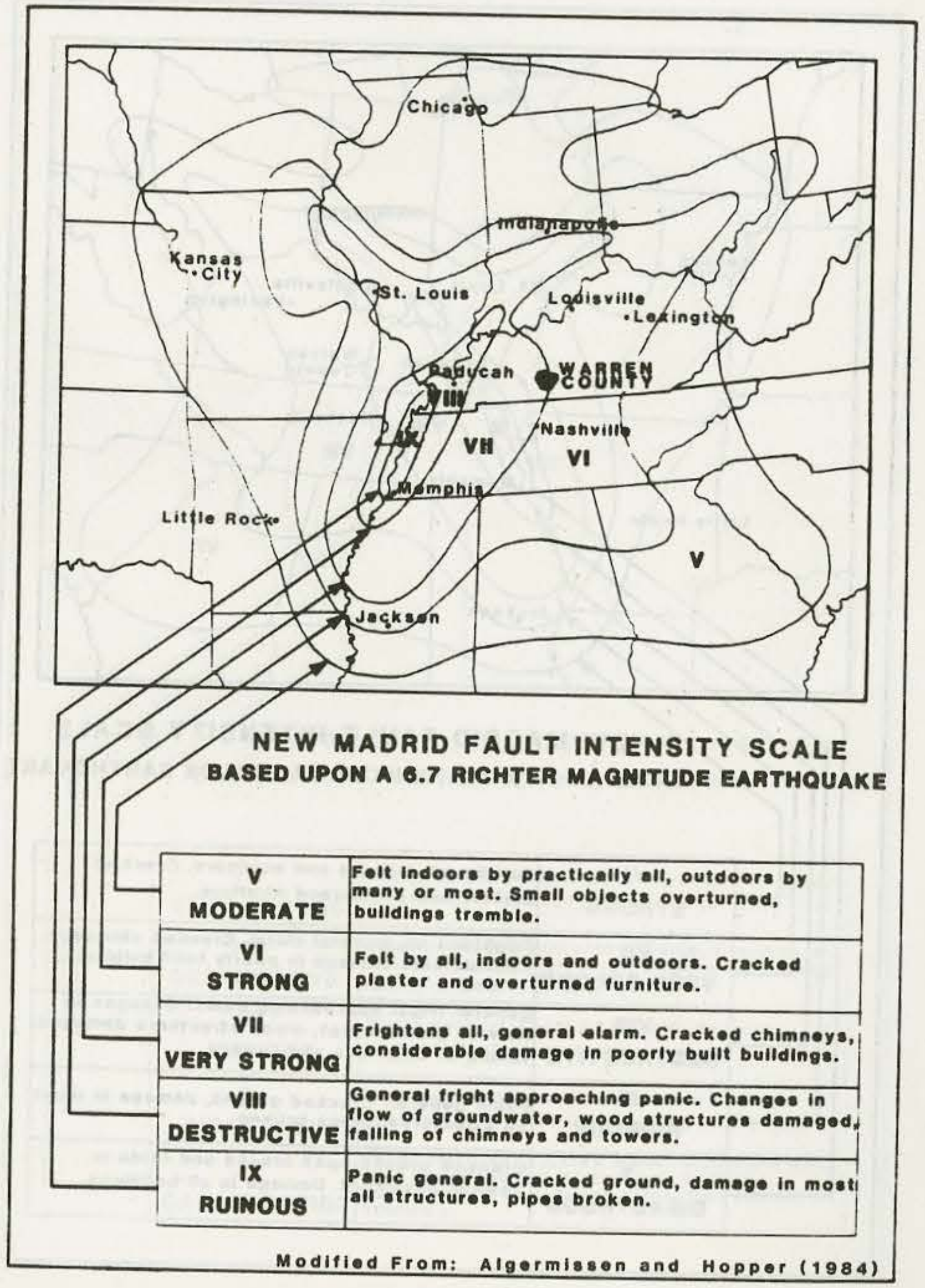
There is sufficient information as of 1989 to determine that Western Kentucky has a high risk of receiving earthquake damage. This risk diminishes with distance east of the Mississippi River and southeast of the Ohio River. The Federal Emergency Management Agency in cooperation with the United States Geological Survey prepared maps based on maps produced by Algermissen and Hopper (1984) delineating the potential for damage from a large earthquake occurring along the New Madrid Fault (U.S.G.S. and FEMA map FM-1712, 1984). These maps (Figures 6, 7, and 8) show county by county the potential for earthquake damage from a large New Madrid quake, based on the Modified Mercalli Intensity Scale of 1931 (Appendix 1). Part of the assessment of potential damage from a large earthquake associated with the New Madrid seismic zone in Warren County is the nature and distribution of alluvial soils and the nature and extent of the karst features. Alluvial soils are associated with river flood plains and the importance of these soils in increasing earthquake damage potential is important, but for Warren County, the nature of the karst geologic setting is the prominent risk magnifier. With Algermissens and Hoppers Isoseismal maps and maps delineating Warren County's karst topography, risk from a large earthquake may be estimated. This potential provides a strong basis of support for an earthquake land use plan and the dimensions of that plan based on potential risk magnitude. The Algermissen and Hopper maps from U.S.G.S. Open-File Report 85-457 (1985) provide guidance for estimating risk magnification due to karst subsurface structures and the levels of potential damage intensity which exist for Warren County. With this guidance, a large scale map of planning areas was produced, showing areas that need greater levels of site specific evaluation (Figure 9).

In Figure 8, the estimated boundary between zones VIII and IX for an 8.6 Richter earthquake on the Modified Mercalli Intensity Scale, is drawn through the middle of Warren County. At VIII on the Modified Mercalli Intensity Scale (Appendix 1) one could expect considerable damage to ordinary substantial buildings with collapse of chimneys, columns, monuments, factory stacks, and towers. At IX there would be great damage to substantial (masonry) buildings with some wood frame buildings shifted off their foundations. Even at the VIII intensity which is probably more realistic in terms of earthquake risk, the seismic event would probably induce the collapse of some existing unstable regolith arches and possibly some existing unstable bedrock cave rooms.

INCREASED HAZARDS DUE TO KARST

The karst geologic setting of Warren County could magnify the risk of potential damage from a large earthquake. Portions of Warren County,

NEW MADRID FAULT INTENSITY SCALE BASED UPON A 6.7 RICHTER MAGNITUDE EARTHQUAKE

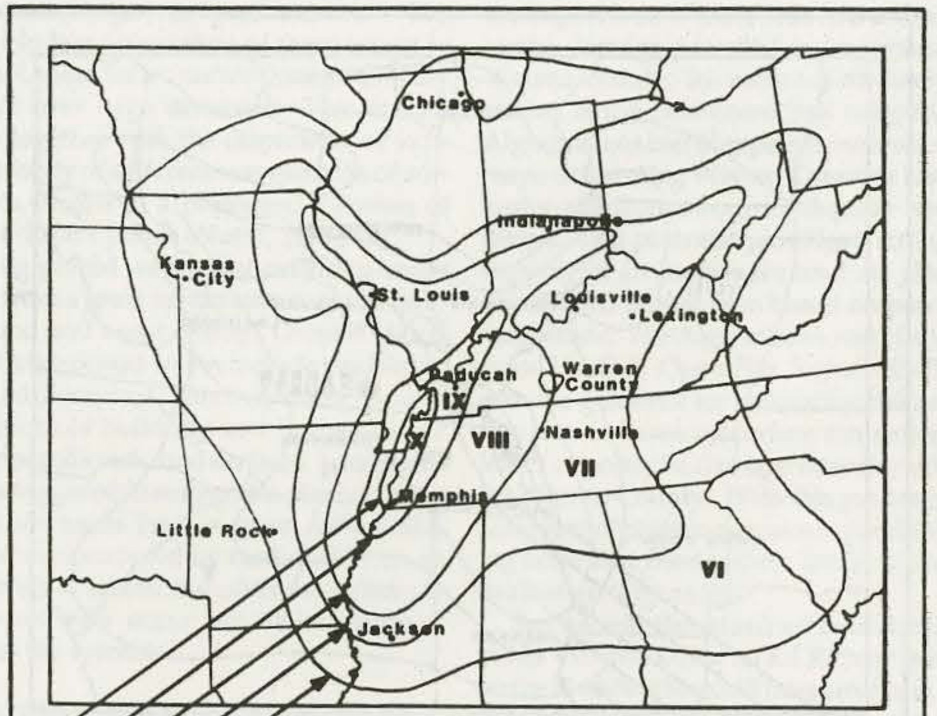


NEW MADRID FAULT INTENSITY SCALE
BASED UPON A 6.7 RICHTER MAGNITUDE EARTHQUAKE

V MODERATE	Felt indoors by practically all, outdoors by many or most. Small objects overturned, buildings tremble.
VI STRONG	Felt by all, indoors and outdoors. Cracked plaster and overturned furniture.
VII VERY STRONG	Frightens all, general alarm. Cracked chimneys, considerable damage in poorly built buildings.
VIII DESTRUCTIVE	General fright approaching panic. Changes in flow of groundwater, wood structures damaged, falling of chimneys and towers.
IX RUINOUS	Panic general. Cracked ground, damage in most all structures, pipes broken.

Modified From: Algermissen and Hopper (1984)

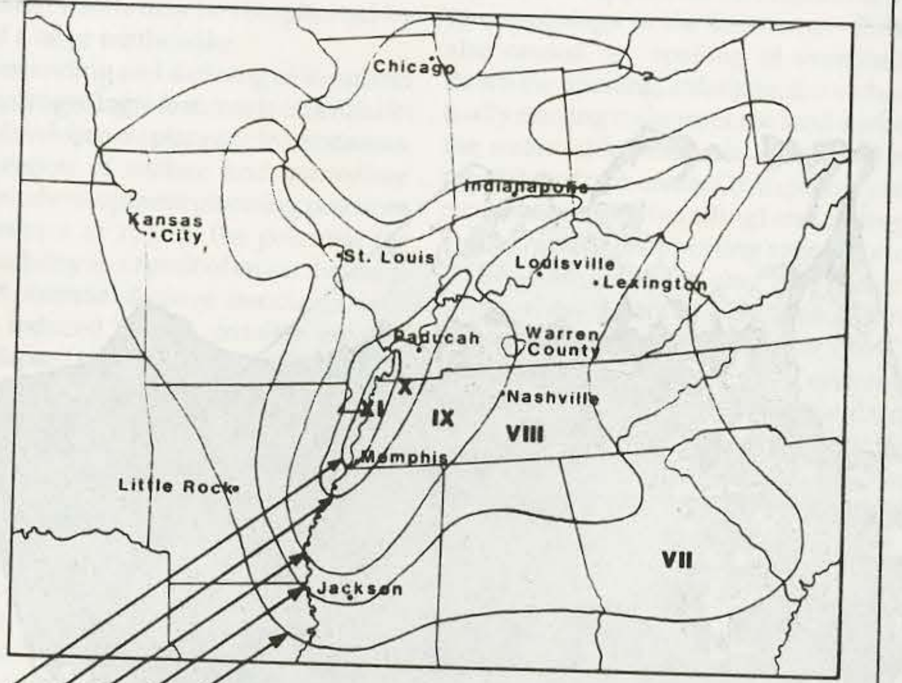
NEW MADRID FAULT INTENSITY SCALE BASED UPON A 7.6 RICHTER MAGNITUDE EARTHQUAKE



NEW MADRID FAULT INTENSITY SCALE
BASED UPON A 7.6 RICHTER MAGNITUDE EARTHQUAKE

VI STRONG	Felt by all, indoors and outdoors. Cracked plaster and overturned furniture.
VII VERY STRONG	Frightens all, general alarm. Cracked chimneys, considerable damage in poorly built buildings.
VIII DESTRUCTIVE	General fright approaching panic. Changes in flow of groundwater, wood structures damaged, falling of chimneys and towers.
IX RUINOUS	Panic general. Cracked ground, damage in most all structures, pipes broken.
X DISASTROUS	Cracked ground,open cracks and folds in cement pavement. Damage in all buildings.

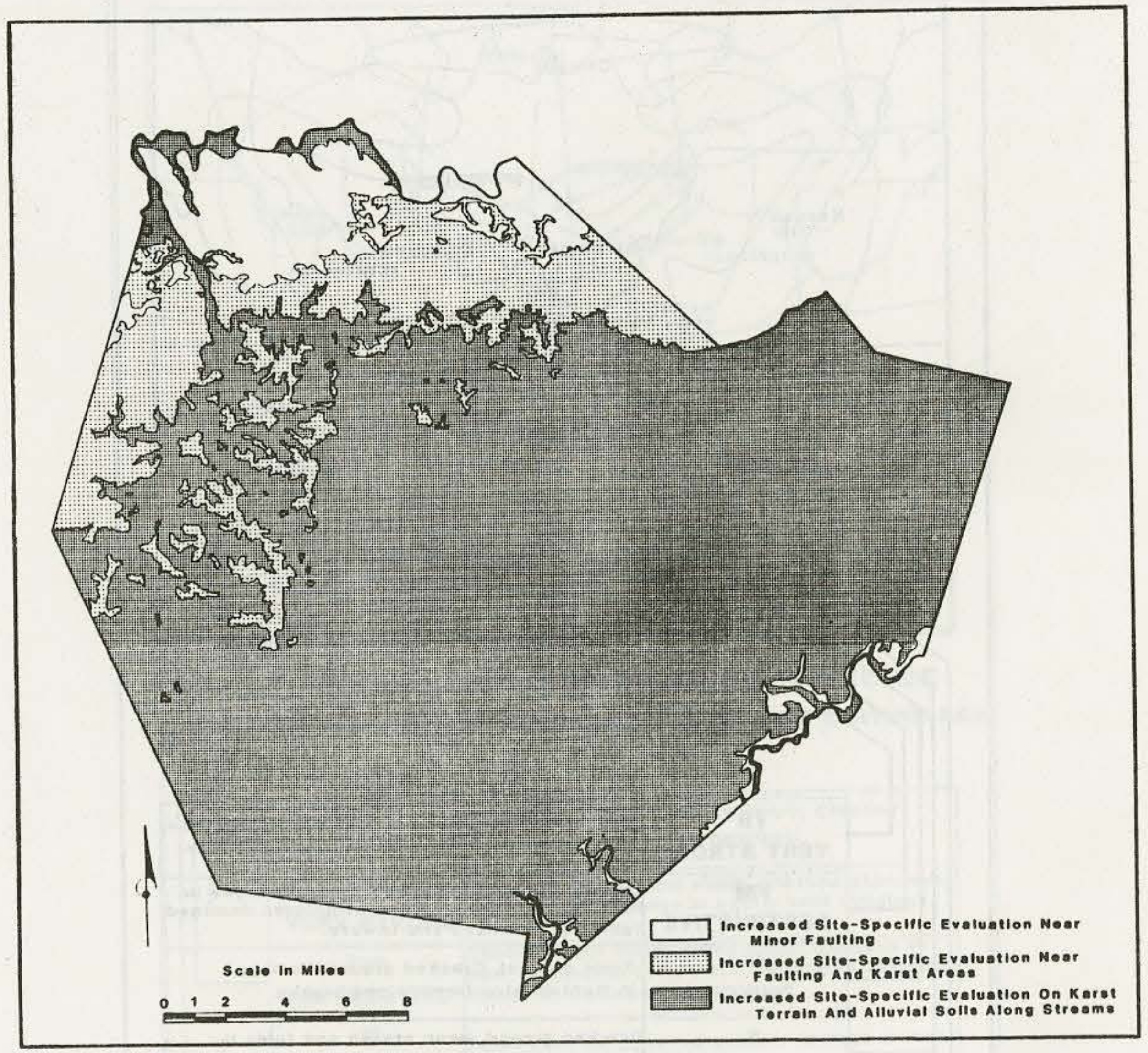
NEW MADRID FAULT INTENSITY SCALE BASED UPON AN 8.6 RICHTER MAGNITUDE EARTHQUAKE



NEW MADRID FAULT INTENSITY SCALE
BASED UPON A 8.6 RICHTER MAGNITUDE EARTHQUAKE

VII VERY STRONG	Frightens all, general alarm. Cracked chimneys, considerable damage in poorly built buildings.
VIII DESTRUCTIVE	General fright approaching panic. Changes in flow of groundwater, wood structures damaged, falling of chimneys and towers.
IX RUINOUS	Panic general. Cracked ground, damage in most all structures, pipes broken.
X DISASTROUS	Cracked ground, open cracks and folds in cement pavements. Damage in all buildings.
XI CATASTROPHIC	Broad fissures, ejected water with sand and mud. Pipelines out of service. Bridges destroyed, few masonry structures remain standing.

AREAS OF WARREN COUNTY RECOMMENDED FOR INCREASED SITE-SPECIFIC EVALUATION DUE TO SEISMIC RISK



Kentucky are located within the Pennyroyal Plain (Sauer, 1927) region of south central Kentucky (Figure 10). The Pennyroyal Plain is characterized by numerous sinkholes and a network of shallow integrated subsurface drainage systems. Associated with these subsurface drainage systems are numerous caves, regolith voids, and a highly irregular depth to bedrock. These karst features present many environmental and engineering hazards, which may be complicated by the advent of a large earthquake.

The understanding and defining of these and other karst hydrogeologic features is essential in dealing with development planning in karst areas. Proper delineation of surface and subsurface features permit development planning practices which can prevent or reduce the potential for structural instability as a result of an earthquake. The increased potential damage associated with karst can be reduced to two possible mechanisms: 1) collapse/subsidence due to failure of subsurface cavities and 2) differential compaction due to the irregular bedrock surface.

Sinkhole Collapse

While seismic activity is not considered a major threat to cavity stability, the influence of a large seismic event may induce the collapse of an existing unstable cavity. The threat of subsidence or collapse due to the presence of subsurface cavities is a common problem in the karst areas of Warren County. Prediction of exact location for possible collapse sites is very difficult. The irregular development of karst cavities makes it hard to obtain a picture of subsurface conditions which may lead to collapse. Possible collapse cavities can range in size and depth from small regolith arches within the unconsolidated material above bedrock (soil) to large cavernous rooms in solid rock. There are two basic forms of collapse: 1) regolith collapse and 2) bedrock collapse.

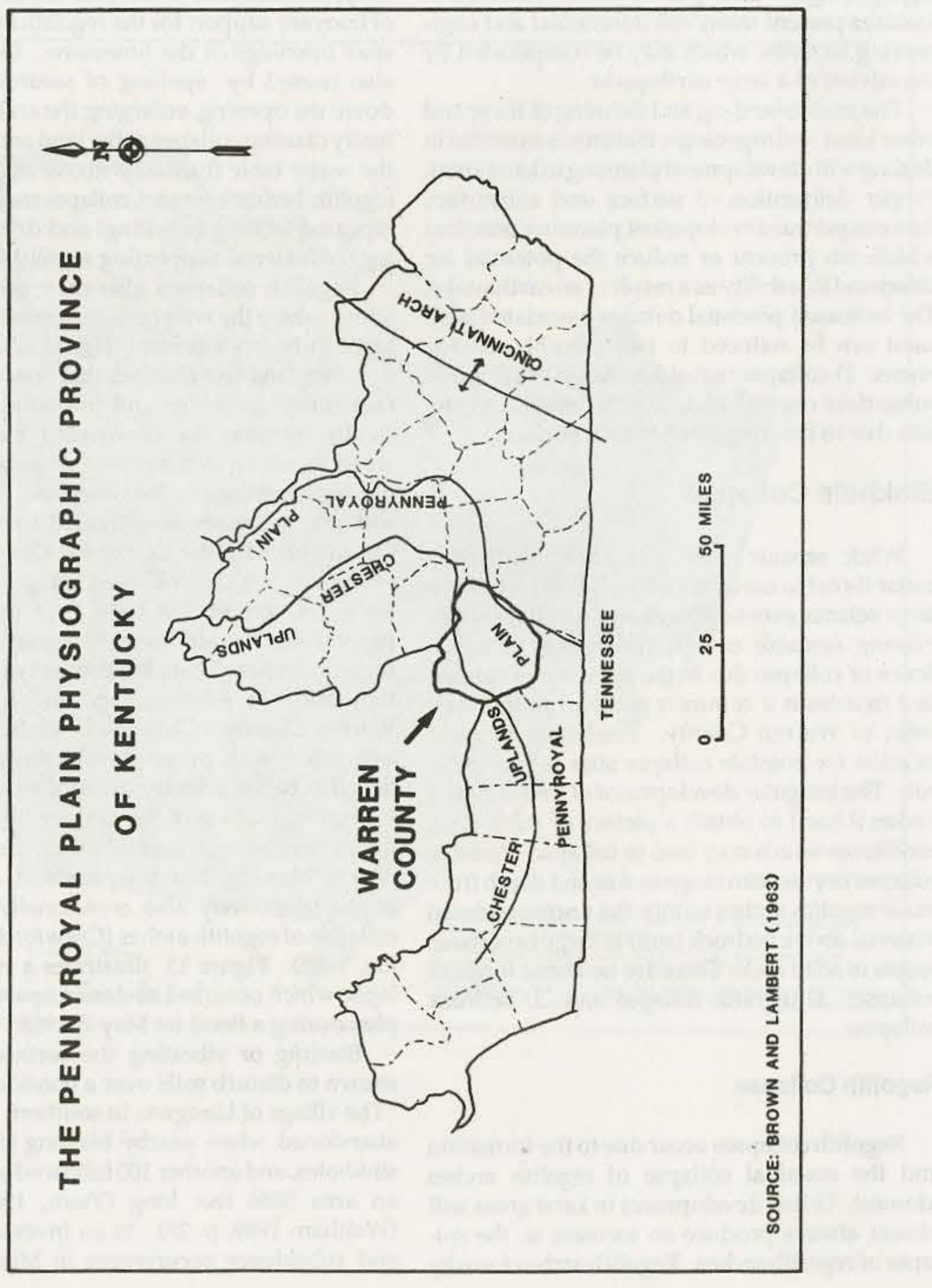
Regolith Collapse

Regolith collapses occur due to the formation and the eventual collapse of regolith arches (domes). Urban development in karst areas will almost always produce an increase in the collapse of regolith arches. Regolith arches form by the downward movement of unconsolidated sediments through openings in the bedrock. In areas where the water table is usually above the regolith-bedrock contact, collapses often occur when the water table drops below the regolith-bedrock contact, either during droughts or during high-volume pumping (Figure 11). Physically, the collapses in this case are caused by loss of buoyant support for the regolith arches which span openings in the limestone. Collapses are also caused by spalling of saturated regolith down the opening, enlarging the arch, and eventually causing collapse at the land surface. When the water table fluctuates above and below the regolith-bedrock contact, collapse may result from repeated wetting (swelling) and drying (shrinking) of material supporting regolith arches.

Regolith collapses also may occur in situations where the water table is usually below the regolith-bedrock contact (Figure 12). Construction and land use changes that concentrate surface runoff in drains and impoundments may locally increase the downward movement of water resulting in the piping of saturated regolith into openings in the limestone. Most of the sinkhole collapses investigated in the Warren County area by the Center for Cave and Karst Studies at WKU (Sinkhole Collapse Inventory, Vols. 1-4) are of this type. An estimated 70 percent are man-induced collapses of existing regolith arches. There are probably hundreds of thousands of existing regolith arches under Warren County. Changes in surface drainage associated with urban development are believed to be the primary cause of most collapses. However, loading of the surface by structures, fill, or ponded water, or vibrating the surface by nearby blasting, heavy equipment, or perhaps earthquakes, may also occasionally cause the collapse of regolith arches (Crawford and Whalon, 1985). Figure 13 illustrates a regolith collapse which occurred under an apartment complex during a flood on May 7, 1988.

Blasting or vibrating the surface has been shown to disturb soils over a considerable area. "The village of Liangwu, in southern China, was abandoned when nearby blasting triggered 40 sinkholes, and another 100 followed soon after in an area 5886 feet long (Yuan, 1983, 1987)," (Waltham 1989, p. 27). In an inventory of sink and subsidence occurrences in Missouri, Wil-

LOCATION OF WARREN COUNTY WITH RESPECT TO REGIONAL PHYSIOGRAPHIC SETTING



SOURCE: (BROWN AND LAMBERT 1963)

SINKHOLE COLLAPSES IN AREAS WHERE THE WATER TABLE IS ABOVE THE REGOLITH-LIMESTONE CONTACT

USUALLY CAUSED BY A DROP IN THE WATER TABLE

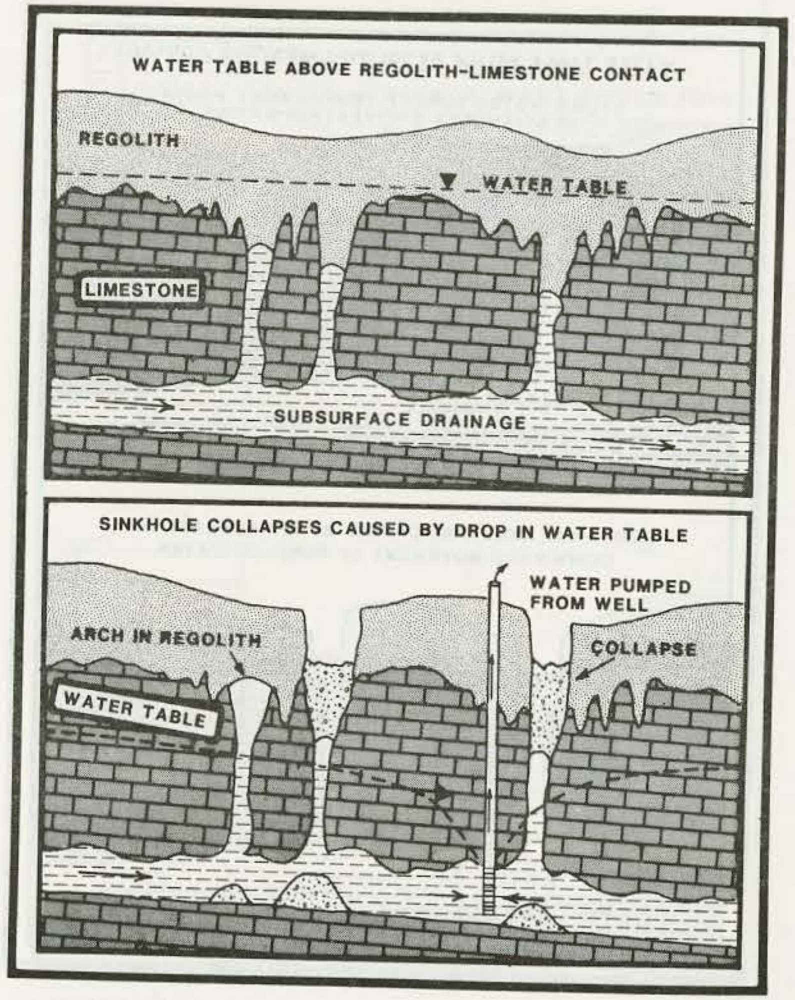


FIGURE 2 Sinkhole collapses in areas where the water table is above the regolith-limestone contact are usually caused by a drop in the water table. Regolith arches spanning openings in the bedrock collapse because of the loss of buoyant support and because of downward moving surface water.

SINKHOLE COLLAPSES IN AREAS WHERE THE WATER TABLE IS BELOW THE REGOLITH LIMESTONE CONTACT

USUALLY CAUSED BY AN INCREASE IN THE DOWNWARD MOVEMENT OF SURFACE WATER

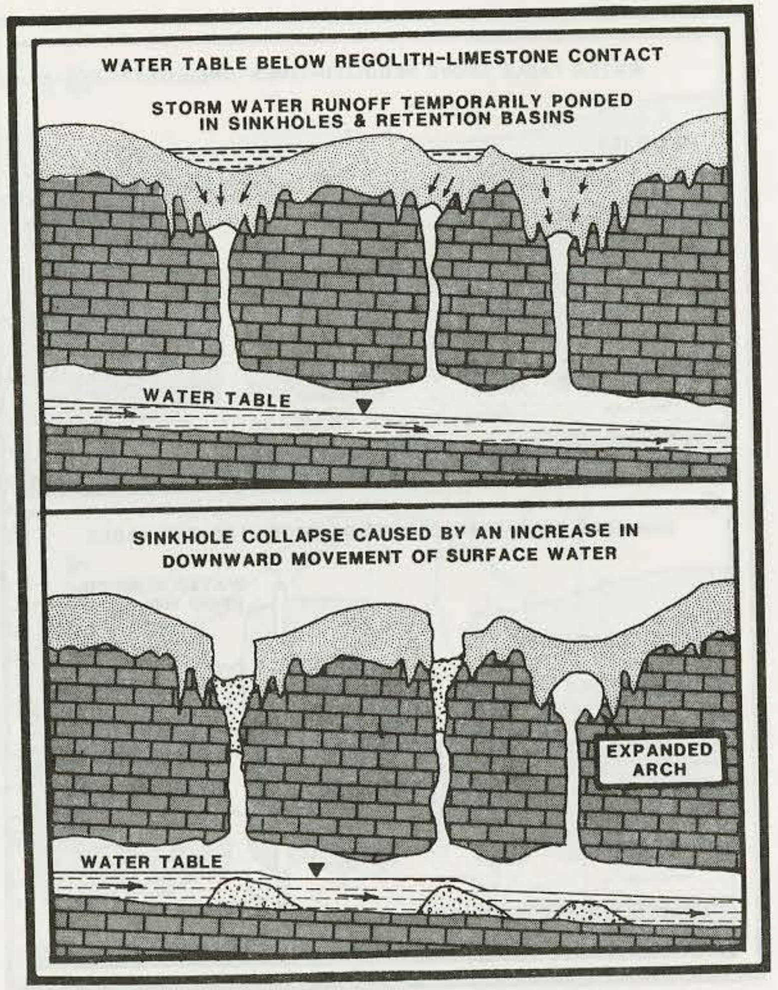
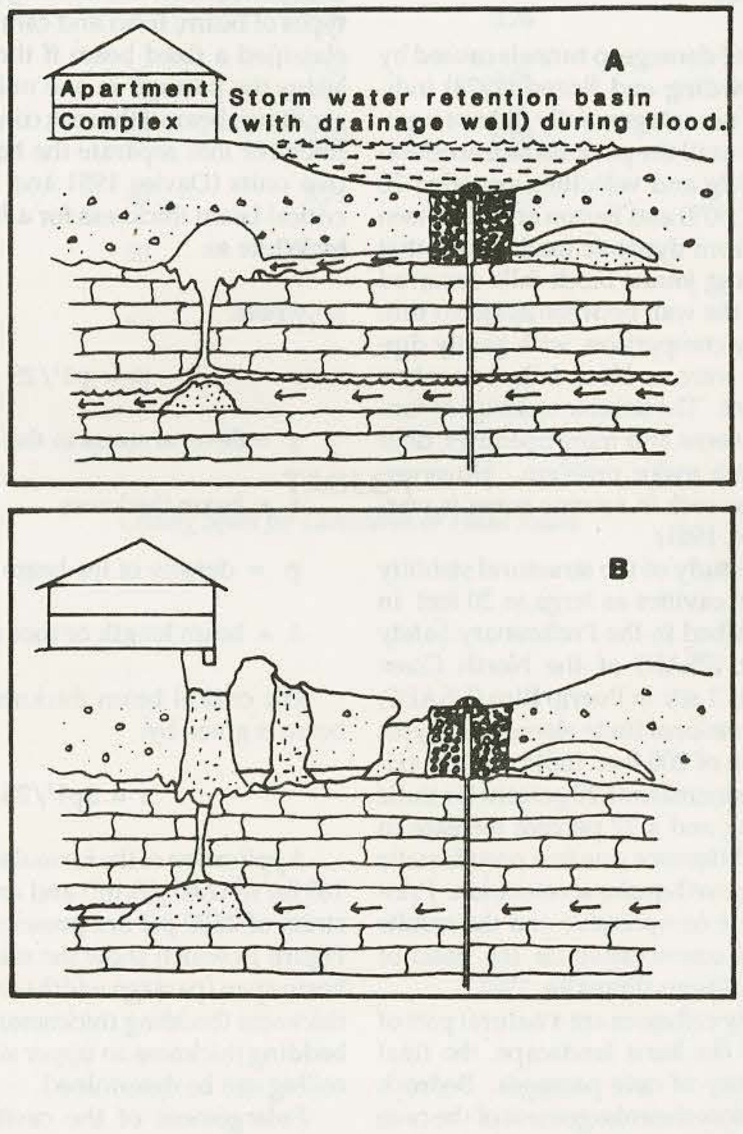


FIGURE 3. Sinkhole collapses in areas where the water table is below the regolith-limestone contact are usually caused by an increase in the downward movement of surface water. Land use changes and construction activities that concentrate surface water in drains, sinkholes, and impoundments may locally increase the downward movement of surface water and induce the collapse of regolith arches.

STRUCTURAL DAMAGE RESULTING FROM COLLAPSE OF A REGOLITH ARCH



This collapse occured under the Greenwood Villa Apartments in Bowling Green during a flood on May 7, 1984.

Source: Crawford (1986).

liams and Vineyard (1971) concluded that approximately 4% of the man-induced sinkhole collapses could be associated with blasting. Janic' (1962) stated that some cave roofs had caved in and the bottom of many sinkholes were opened up during the earthquakes of January, 1962 in the coastal region near Makarska (village of Kozic) in Yugoslavia (Milanovic 1981, p. 198).

Bedrock Collapse

From review of damage to tunnels caused by earthquakes, Dowding and Rozen (1978) indicate that unlined tunnels generally did not experience block falls until the peak surface accelerations exceeded 0.2g and velocities exceeded 20 cm/sec. Barton (1979) and Barton and Hansteen (1979) showed, from dynamic model tests, that for steeply dipping joints, block falls occurred progressively in the wall between adjacent tunnel openings. By comparison, with gently dipping joints there were no block falls, but only a general settlement. The seismic stability of tunnels, and thus caverns and mine openings, does not appear to be a major problem. However, treatment of loose rock in seismic zones is warranted. (Franklin, 1981)

A theoretical study of the structural stability of circular tunnel cavities as large as 20 feet in diameter is described in the Preliminary Safety Analysis Report (PSAR) of the North Coast Nuclear Plant No. 1 site in Puerto Rico (USAEC, 1975). Two-dimensional finite element analyses for a cavity depth of 200 feet indicated a maximum shear stress increase of 20 percent for static structural loading and a 27 percent increase in principal stress difference due to a pseudostatic loading for 0.35 g earthquake acceleration. Principal stresses were compressive and the results were considered conservative on the basis of linear elastic conditions (Franklin, 1981).

Solution cavity collapses are a natural part of the evolution of the karst landscape, the final event in the history of cave passages. Bedrock collapse results from the enlargement of the cave passage by the mechanical failure of the ceiling. Failure of the ceiling of a bedrock void has been termed cavern breakdown (White and White 1969). Peck (1976) suggests that rock overlying solution cavities in limestone may become loosened during seismic activity and could conceivably promote stoping and cavern breakdown.

Davies (1951) and White (1988) examined cavern breakdown by applying a simple beam model, in which a critical minimum beam thickness (bed thickness) is determined for a given beam span. The key to the development of breakdown is the transfer of the weight of the beam (rock) to the walls of the cave. The ability of the walls to support a uniformly loaded beam is dependent on the beam type. There are two types of beam; fixed and cantilever. A ceiling is classified a fixed beam if the rock is solid and spans the passage as one unit. The ceiling is a cantilever beam if the rock contains open joints or fractures that separate the beam or ceiling into two units (Davies 1951 and White 1988). The critical beam thickness for a fixed beam is given by White as:

where:

$$t = pl^2/2S$$

s = flexural stress in the extreme fiber

t = beam thickness

p = density of the beam material

1 = beam length or roof span

The critical beam thickness for a cantilever beam is given by:

$$t = 3pl^2/2S$$

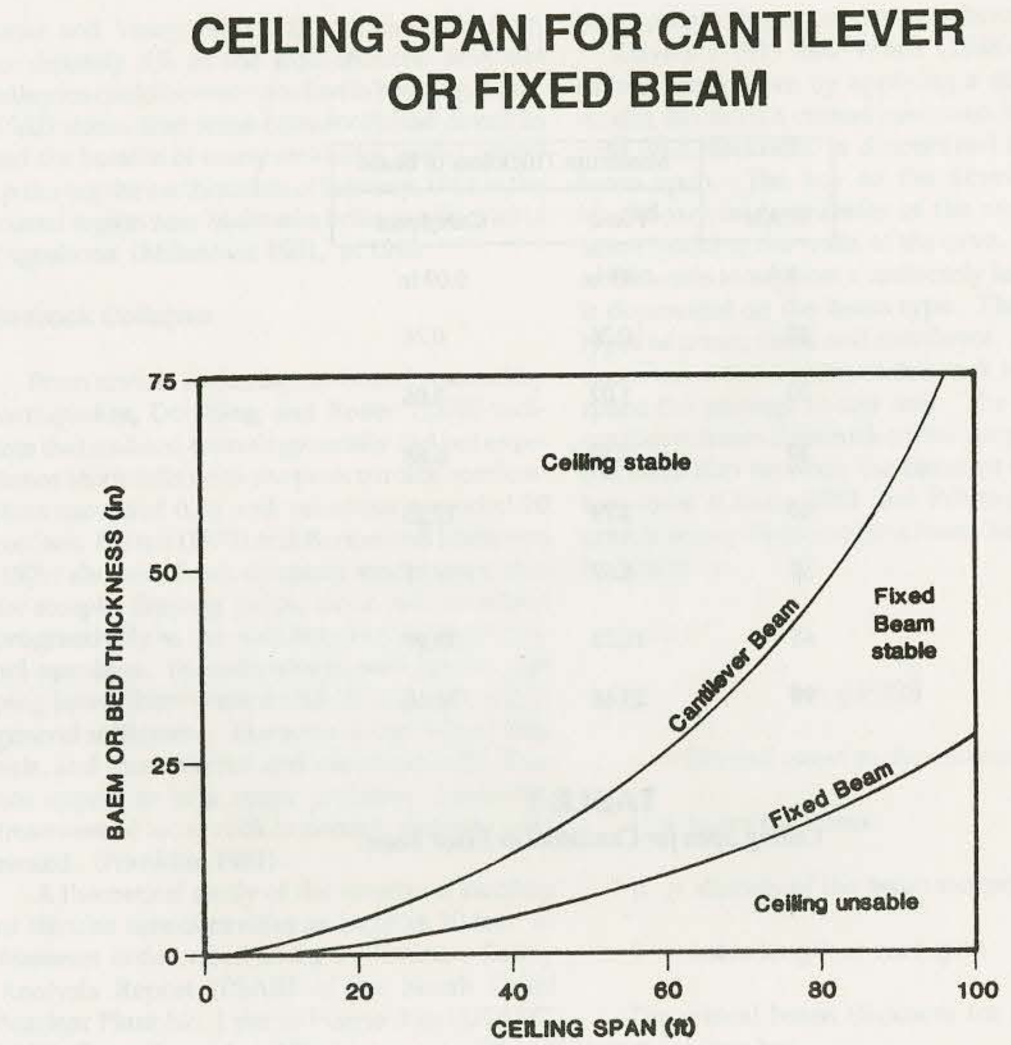
Application of the formulas using a density of 165 lb/ft^3 (2.65 g/cm^3) and an assumed flexural stress of 2600 psi are presented in Table 1 and Figure 14 which show the relationship between beam span (passage width) and minimum beam thickness (bedding thickness). Thus, for a given bedding thickness an upper size limit for a stable ceiling can be determined.

Enlargement of the cavity by progressive stoping or breakdown of the roof rock will continue to a point that either a stable arch is formed or collapse of the cavity reaches the surface. Evaluation of cavity stability for complex solution features such as those found in Warren County are extremely complex. The depth and

	Minimum Thickness of Beam	
SPAN	Fixed	Cantilever
3 ft	0.03 in	0.09 in
10	0.26	0.76
20	1.02	3.06
30	2.30	6.88
40	3.79	12.23
50	6.37	19.11
65	11.23	33.98
98	25.48	76.46

TABLE 1

Ceiling Span for Cantilever or Fixed Beam.



Critical breaking strength for ceiling beams in cave passages. Calculations based on data for Ste. Genevieve Limestone of southern Indiana, shear strength = 18.2 MPa and density = 2.65 g cm^{-3}, based on means of four samples measured by the Indiana Geological Survey. Bowling Green, Kentucky is primarily built upon the Ste. Genevieve Limestone.

Source: Modified from White, W.B. (1988), p. 232.

diameter at which a cave would be in danger of catastrophic collapse requires knowledge of joint patterns, joint strengths, intact rock compressive and tensile strengths, in situ elastic modulus, Poisson's ratio, and Ko (the ratio of the horizontal effective stress to the vertical effective stress) for the rock (Franklin and others, 1981). "Any calculation of roof stability over a cave is difficult, as conventional engineering approaches are conservative, and attempts at evaluation have found natural spans that survive with about three times the span of artificial openings at the point of collapse (Cruden et al., 1981). As a rough guide, a limestone cave roof is generally stable where the thickness of sound rock cover exceeds the cave width" (Waltham, 1989, p. 9).

The key concept to evaluating cavity stability is the tension dome that develops over the cavity in the bedrock (Figure 15). "The top of a dome extends upward into the bedrock for distances of some 1.5 times the cavity diameter. Any change in loading above the top of the dome is distributed over the cavern walls, and the ability of the formation to support the load is independent of the cavity's existence. If, however, the tension dome extended to the land surface or to the base of an excavation, additional loading would increase the shear along the walls, leading to collapse of the cavity and subsidence of the excavation" (White, 1988 p. 360). Considerable experience and judgment is required in estimating maximum possible enlargement before stress and structure loading would induce a collapse due to seismic activity.

Differential Compaction

When evaluating site stability, the depth to solid bedrock may be more important to identify than a cavity. Deep cavities are not a serious threat to many structures, while an irregular bedrock surface or an unstable cave breakdown area may present difficulties to the stability of a structure. Differential settling or subsidence may be induced by the compaction of unconsolidated material during an earthquake. During a period of earthquake vibration, unconsolidated sediment may achieve improved granular packing, resulting in reduction of porosity, loss of volume, and vertical compaction.

Differential settling of a structure could occur due to the placement of structural supports on uneven load bearing surfaces (Figure 16). If a portion of a structure is placed on a bedrock surface and partially on unconsolidated sediments, structural settling could occur. The limestone pinnacles act to support the structure while regolith cutters do not. Areas of cave collapse or a detached limestone boulder could also become unstable if compaction or a shift is induced by an earthquake.

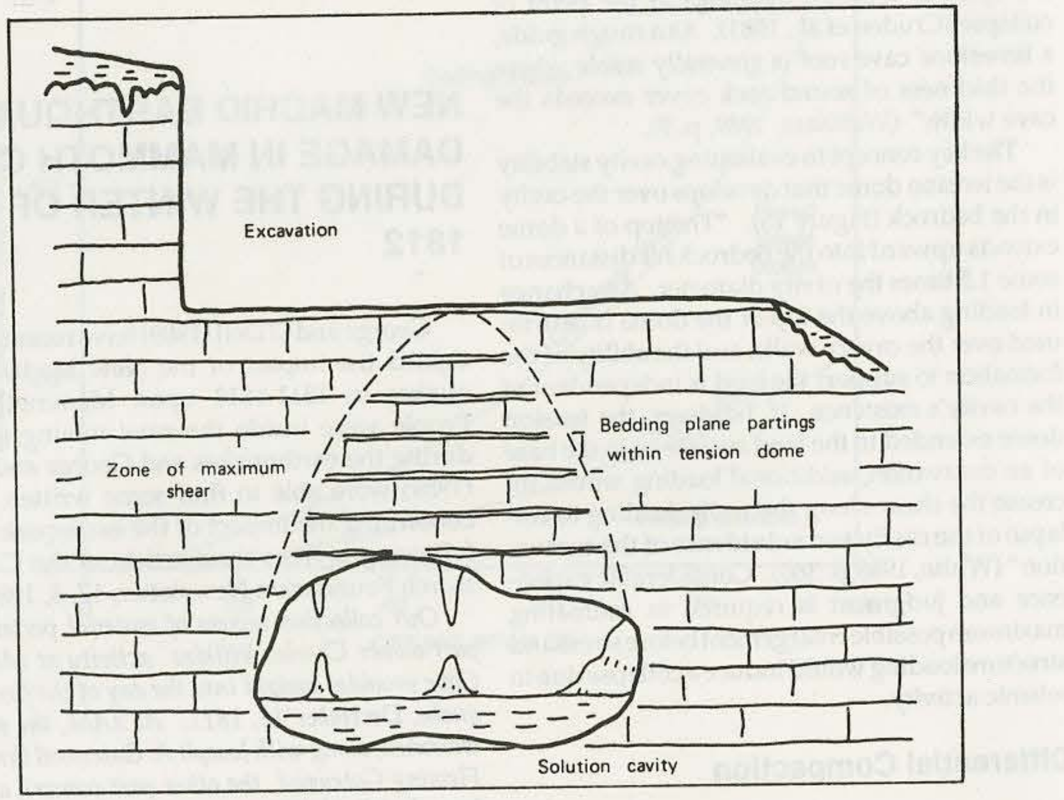
NEW MADRID EARTHQUAKE DAMAGE IN MAMMOTH CAVE DURING THE WINTER OF 1811-1812

George and O'Dell (1989) have recently investigated the impact of the New Madrid earthquakes in 1811-1812 upon Mammoth Cave. People were inside the cave mining saltpeter during the earthquakes and George and O'Dell (1989) were able to find some written reports concerning the impact of the earthquakes. The following is from their article in the Cave Research Foundation Newsletter, 17, 3, 1989.

Our collection review of material pertaining to part-owner Charles Wilkins' activity at Mammoth Cave provides insight into the day of the first earthquake, December 16, 1811. At 2AM, the saltpeter workmen, along with Joseph A. Gatewood (brother to Fleming Gatewood, the other part owner), and perhaps Archibald Miller (manager or agent of the saltpeter works) were working at the Second Hoppers in Booth's Amphitheater. When the earthquake struck, they panicked and ran for the entrance. The earthquake caused major damage to the works—several of the hoppers were "thrown down" and the pump was "sunk...three feet". Two other major earthquakes occurred, on January 23 and February 7, 1812. A workers' strike occurred after each major 'quake. The earthquakes, the strikes, and a detached management fostered a 50% decrease in saltpeter production.

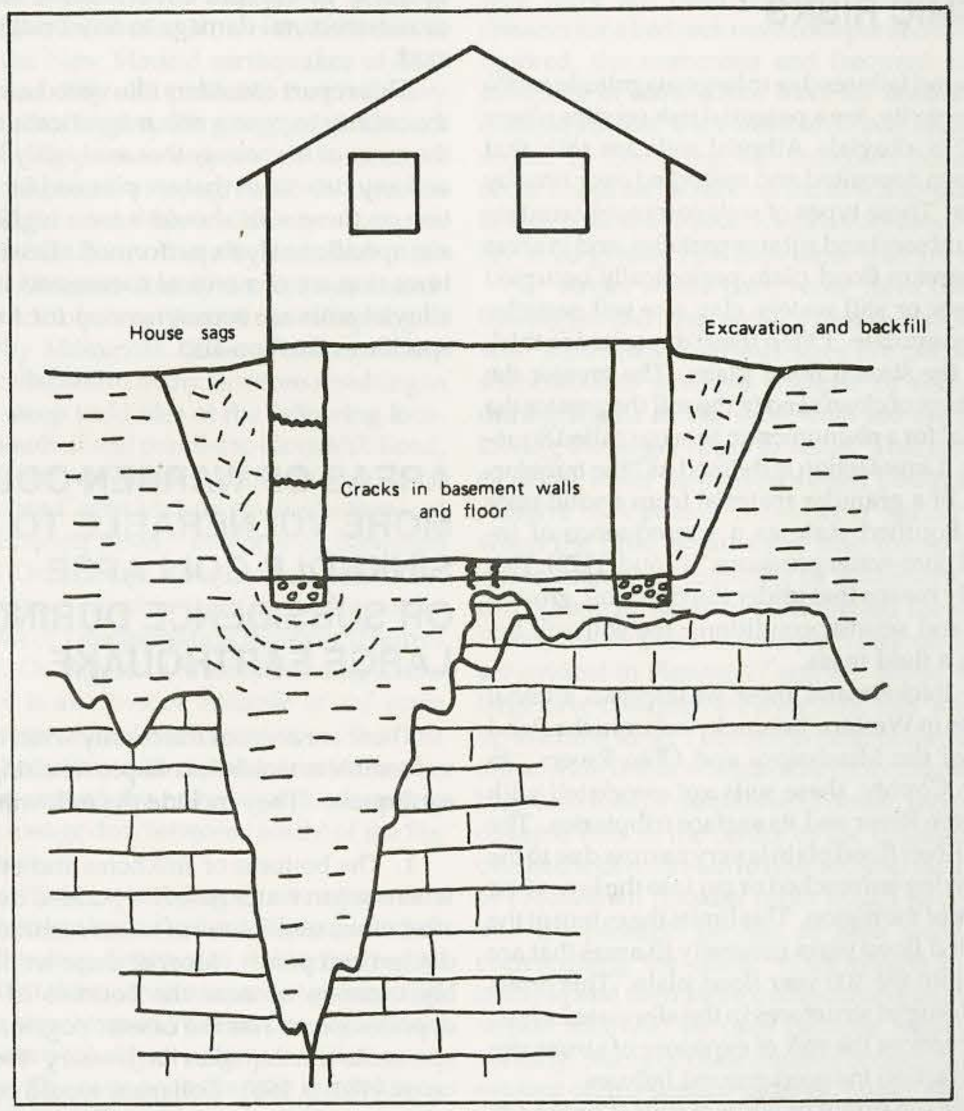
Apparently, the Rotunda pump tower was not repaired. It is still four feet too low to drain leachate back to the entrance. Some repair was done to the

STRESS REGION ABOVE A SOLUTION CAVITY, BENEATH A FOUNDATION EXCAVATION



Source: White, W.B., (1988), p. 360.

STRUCTURAL DAMAGE RESULTING FROM CONSTRUCTION ON CUTTER-AND-PINNACLE KARST SURFACE



Source: White, W.B. (1988) p. 358.

Booth's Amphitheater hopper complex—some of the hoppers have additional structural bracing. The reintroduction of V-vats at both processing sites may have been necessary to solve system failure. Production never regained its 3000 lbs. per week schedule. The cave petered out by the start of 1814.

ALLUVIAL SOILS AND SEISMIC RISKS

Ground failures due to large magnitude earthquake activity, are a potential risk on sites where the soil is alluvial. Alluvial soils are soils that have been deposited and reworked over time by streams. These types of soils commonly contain abundant sand and silt size particles, and in areas of the stream flood plain periodically occupied by slower or still waters, clay size soil particles may accumulate. Often these deposits are thick within the stream flood plain. The greater the percentage of clean sand in the soil the greater the potential for a phenomenon to occur called liquefaction. Liquefaction is defined as "the transformation of a granular material from a solid state into a liquified state as a consequence of increased pore-water pressures." (Youd, 1973). This basically means that under the right soil, ground water, and seismic conditions, the soil will behave as a fluid mass.

The thickest and most widespread alluvial deposits in Western Kentucky occur in the flood plains of the Mississippi and Ohio Rivers. In Warren County, these soils are associated with the Barren River and its surface tributaries. The Barren River flood plain is very narrow due to the river having entrenched or cut into the limestone bedrock of the region. This limits the extent of the alluviated flood plain generally to areas that are also within the 100 year flood plain. This limits the building of structures in the alluviated areas, which reduces the risk of exposure of structures to liquefaction induced ground failures.

While the extent of alluvial soils is limited to the rather narrow flood plain of the Barren River and its surface tributaries, the occurrence of these soils in the county does warrant their evaluation for site specific analysis for critical structures that may be built within the alluviated areas of the county. As a reference for further understanding potential risk from liquefaction, U.S.G.S. Open File Report 84-770 (1984) is an excellent source.

Liquefaction potential in Warren County is of minimal risk due to the limited extent of alluvial soils and the very limited level of construction in the alluviated areas. The greatest potential of exposure to alluvial soil ground failure in Warren County would be associated with bridge ramps and pilings that are not set on top of bedrock. Soil failure under seismic stress could cause structural damage to any bridges so situated.

This report considers alluviated areas within the county to pose a risk magnification equal to the areas of the county that are highly karstified, and any structures that are planned for construction on these soils should have a higher level of site specific analysis performed. Existing structures that are of a critical nature and located on alluvial soils are recommended for further site specific evaluation also.

AREAS OF WARREN COUNTY MORE VULNERABLE TO SINKHOLE COLLAPSE OR SUBSIDENCE DURING A LARGE EARTHQUAKE

There are areas of the county which are more vulnerable to sinkhole collapse resulting from an earthquake. They include the following:

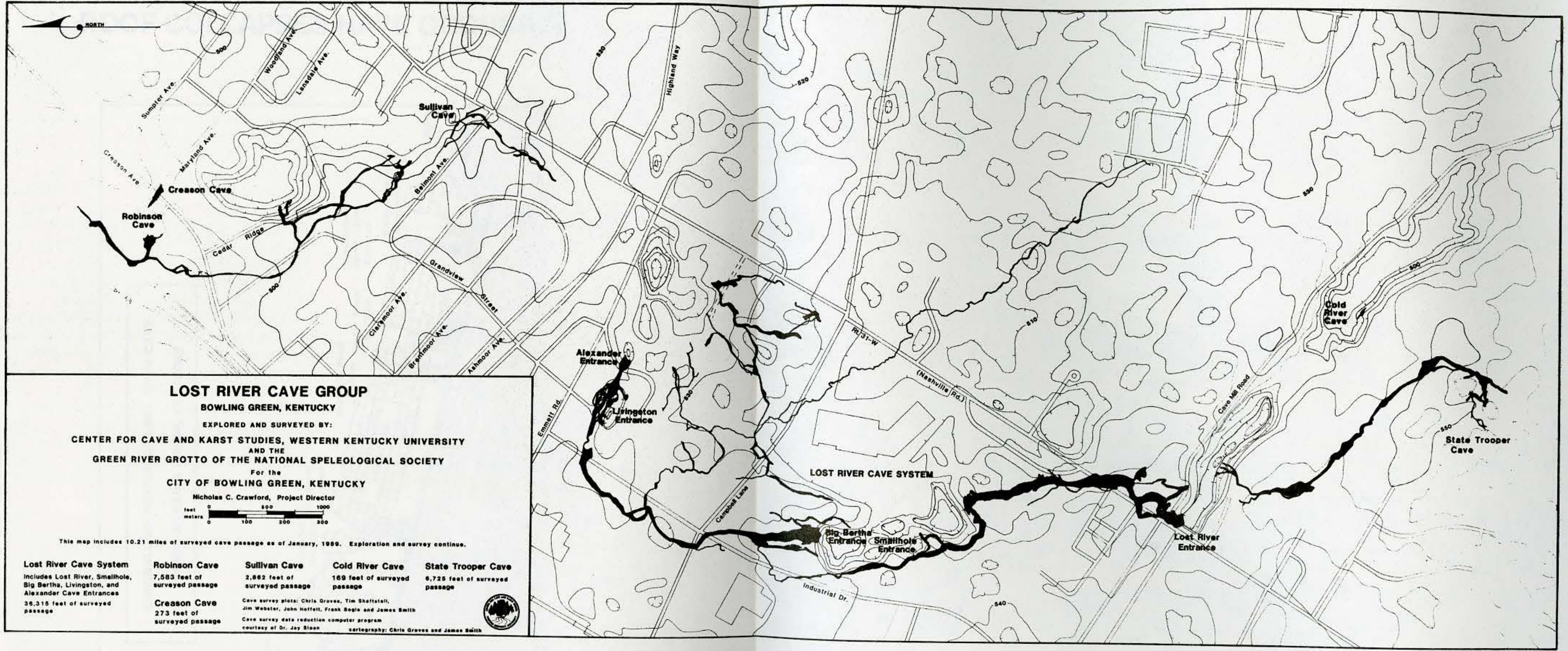
1. The bottoms of sinkholes and other areas where storm water runoff is ponded during and after rains, such as storm water retention basins, ditches and ponds. Most of these would probably occur in or near the bottoms of sinkhole depressions as was the case in Yugoslavia in response to earthquakes in January 1962 (Milanovic 1981, p. 198). Collapses would occur only where there are existing unstable regolith arches. Some differential compaction of loose sediments from previous sinkhole collapses mixed with various kinds of debris used to fill these collapses could be expected.

2. Areas with thin soils above crevices in the bedrock.

3. It is possible that a seismic event might induce the collapse of existing unstable cave roofs in limestone bedrock. There are several cave rooms under Bowling Green (which we know about and probably many more which we do not) which have collapsed almost to the surface and it is hard to explain what is supporting their roofs. Someday, these cave roofs are going to collapse and the intense vibration during a large earthquake could induce collapse of some of these cantilevered domes. However, these domes survived the New Madrid earthquakes of 1811 and 1812 and they will probably survive many more, but someday they are going to fall. Cavern collapses in the past are responsible for some of the most impressive topographic features in Bowling Green and Warren County. Unfortunately, the Lost River Cave System and other caves under Warren County do not have a sandstone caprock to protect them from collapsing as does nearby Mammoth Cave. The Lost River Cave has collapsed in many locations resulting in large and steep sinkholes at the following locations: a) south of and parallel to Cave Mill Road, a cave collapse which extends for a mile; b) west of the Bowling Green Mall on Nashville Road; c) south of Emmett Road; d) north of Newman Drive and Cedar Ridge Road; and e) southwest of Morgantown Road in front of the Kentucky Department of Transportation Building (Figures 17 and 18). On Figure 17, west of Bowling Green Mall, there is an obvious collapse of the main trunk passage of the Lost River Cave. The Lost River has been forced to dissolve another route, thus going around the collapse and reentering the main passage downstream (north) of the Big Bertha entrance.

There are homes, buildings, and major roads located directly above the Lost River and other caves in Bowling Green and it is tempting to conclude that these structures are at greater risk than other structures in Warren County. However, they are probably at no greater risk for two reasons: a. The cave system under the sinkhole plain of Warren County is incredibly complicated with cave streams having changed their courses, primarily due to collapse, many times. Even small cave streams can and frequently do have large cantilevered cave rooms created by bedrock collapse. Therefore, without an extensive investigation of the subsurface which would include bedrock borings, it is impossible to say with any degree of certainty that any home or building located on the sinkhole plain of Warren County is not located above a cave. Although cave rooms obviously do collapse, the authors do not know of a single documented bedrock cave collapse that has occurred anywhere in this county in historic times. This does not mean that they have not occurred, just that they are so rare that they have not been reported. Although the chances for a bedrock cave collapse should not be ignored, the numerous and frequent sinkhole collapses in karst areas have all been regolith collapses mixed with weathered and unattached rocks. b. Since regolith collapses can and do occur about anywhere on the sinkhole plain, the homes built above bedrock cave rooms are probably at no greater risk than those that are not.

4. Areas where cave roofs have collapsed leaving behind large areas of broken rocks mixed with sediment of various sizes are particularly vulnerable to sinkhole collapse or subsidence during floods as the sediments are eroded, allowing the larger rocks to settle. This can occur as storm water flows downward through these massive rock piles or it can occur during floods when the cave streams rise into the rocks and erode sediments resulting in settlement which can propogate itself upward toward the surface. Examples of these extremely vulnerable areas are evident in Figures 17 and 18. Some of these large cave collapses are over 1000 feet wide and up to a mile long. The reason these collapse areas are so wide is that when a cave roof collapses and begins to form a cantilevered dome, most of the collapse falls in the center of the passage. This causes the cave stream to flow around the mound of breakdown (broken rocks which have fallen into the passage) on one or both sides, thus, undercutting the walls. This results in more collapse and then more undercutting as the cave stream followed by cave collapse moves horizontally. Many of these areas of broken rocks are evident on the surface as large, rather deep, and relatively steep-walled sinkholes. For the most part, these areas have not been built upon but there are homes and businesses, particularly in the area south of Emmett Road and north of Newman Lane and Cedar Ridge Road (Figure 17), which are located upon collapsed caves. Of even greater concern, are areas of the county



LOST RIVER CAVE GROUP

BOWLING GREEN, KENTUCKY

EXPLORED AND SURVEYED BY:

CENTER FOR CAVE AND KARST STUDIES, WESTERN KENTUCKY UNIVERSITY
AND THE
GREEN RIVER GROTTO OF THE NATIONAL SPELEOLOGICAL SOCIETY
For the
CITY OF BOWLING GREEN, KENTUCKY

Nicholas C. Crawford, Project Director

This map includes 10.21 miles of surveyed cave passage as of January, 1989. Exploration and survey continue.

Lost River Cave System
Includes Lost River, Smallhole, Big Bertha, Livingston, and Alexander Cave Entrances
36,315 feet of surveyed passage

Robinson Cave
7,583 feet of surveyed passage

Creason Cave
273 feet of surveyed passage

Sullivan Cave
2,862 feet of surveyed passage

Cold River Cave
169 feet of surveyed passage

State Trooper Cave
6,725 feet of surveyed passage

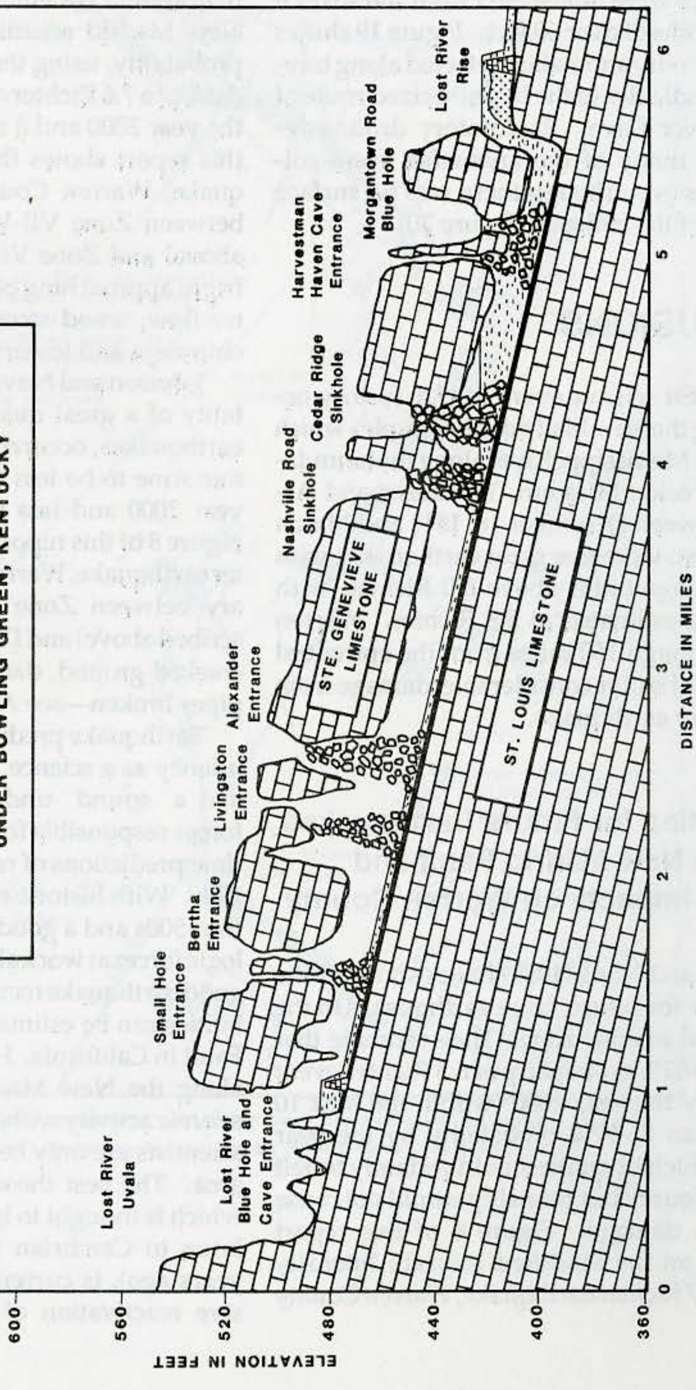
Cave survey plots: Chris Groves, Tim Shaftstall, Jim Webster, John Hoffelt, Frank Bogle and James Smith

Cave survey data reduction computer program courtesy of Dr. Jay Sloan

cartography: Chris Groves and James Smith

WKU—Printing paid from state funds, KRS 57.375.

GENERALIZED PROFILE OF LOST RIVER CAVE UNDER BOWLING GREEN, SHOWING AREAS WHERE MAJOR CAVE ROOF COLLAPSES HAVE OCCURRED



underlain by collapsed caves which have no surface expression. These areas were first discovered in 1985 when microgravity was being used by the Center for Cave and Karst Studies at WKU to locate caves during the U.S. EPA Superfund investigation of toxic/explosive fumes which were rising from cave streams under Bowling Green. Upon drilling wells into some of the low microgravity anomalies, instead of intersecting a cave, numerous small air, water, and sediment filled cavities were intersected from the surface down to depths of over 60 feet. Figure 19 shows low microgravity anomalies detected along traverses perpendicular to the hypothesized route of the Lost River Cave. Exploratory drilling revealed that many of the anomalies were collapsed caves even though there was no surface expression of the collapse (Figure 20).

CONCLUSIONS

The largest seismic event in U.S. history occurred along the New Madrid Rift Complex which parallels the Mississippi River along the boundaries of Kentucky, Missouri, Tennessee and Arkansas. Between December 16, 1811 and March 15, 1812, there were five great earthquakes with estimated magnitudes above 8.0 Richter, with one of these estimated at 8.8 Richter. Warren County, although 150 miles from the epicentral region, would suffer considerable damage from an 8.6 Richter earthquake.

Probabilities for Future Earthquakes along the New Madrid Fault and Potential Impacts on Warren County

Johnson and Nova (1985) have estimated the probabilities for future, large earthquakes in the New Madrid seismic zone. They estimate that there is a 40-63% probability of 6.3 Richter event occurring by the year 2000 (within the next 10 years) and an 86-97% probability by the year 2035. A 6.3 Richter quake would certainly be felt in Warren County but probably would not cause any serious damage. Figure 6 of this report shows that on the Modified Mercalli Intensity Scale for a 6.7 Richter earthquake, Warren County lies on the boundary between Zone VI-STRONG (felt by all, indoors and outdoors, cracked plaster and overturned furniture) and VII-VERY STRONG (frightens all, general alarm, cracked chimneys, considerable damage in poorly built buildings—see Appendix).

Dr. Ron Seeger (1989), Professor of Geophysics, Western Kentucky University, estimates that in order to have any substantial damaging effect in Warren County, a major earthquake, greater than about 7.6 Richter would have to occur in the New Madrid seismic zone. He estimates the probability, using the Johnson and Nova (1985) data, of a 7.6 Richter quake to be about 4 to 6% by the year 2000 and 8 to 10% by 2035. Figure 7 of this report shows that for a 7.6 Richter earthquake, Warren County lies on the boundary between Zone VII-VERY STRONG (described above) and Zone VIII-DESTRUCTIVE (general fright approaching panic, changes in groundwater flow, wood structures damaged, falling of chimneys and towers—see Appendix).

Johnson and Nova (1985) estimate the probability of a great quake, equal to the 1811-1812 earthquakes, occurring in the New Madrid seismic zone to be less than 1% probability by the year 2000 and less than 4% by the year 2035. Figure 8 of this report shows that for an 8.6 Richter earthquake, Warren County lies on the boundary between Zone VIII- DESTRUCTIVE (described above) and IX-RUINOUS (panic general, cracked ground, damage in most all structures, pipes broken—see Appendix).

Earthquake prediction is still somewhat in its infancy as a science. Where good historic data and a sound understanding of the geologic forces responsible for earthquakes exist, general time predictions of recurrence intervals are possible. With historic records extending back into the 1500s and a good understanding of the geologic forces at work along plate boundaries, fairly good earthquake recurrance intervals and probabilities can be estimated along the San Andreas Fault in California. However, this is not the case along the New Madrid Fault. Areas of high seismic activity within crustal plates are rare and scientists are only beginning to understand this area. The best theory is that the rift complex, which is thought to have formed in late Precambrian to Cambrian time (1,500 to 500 million years ago), is currently experiencing compressive reactivation of some structural features.

LOCATION OF LOST RIVER CAVE AS DETERMINED BY MICROGRAVITY TRAVERSES

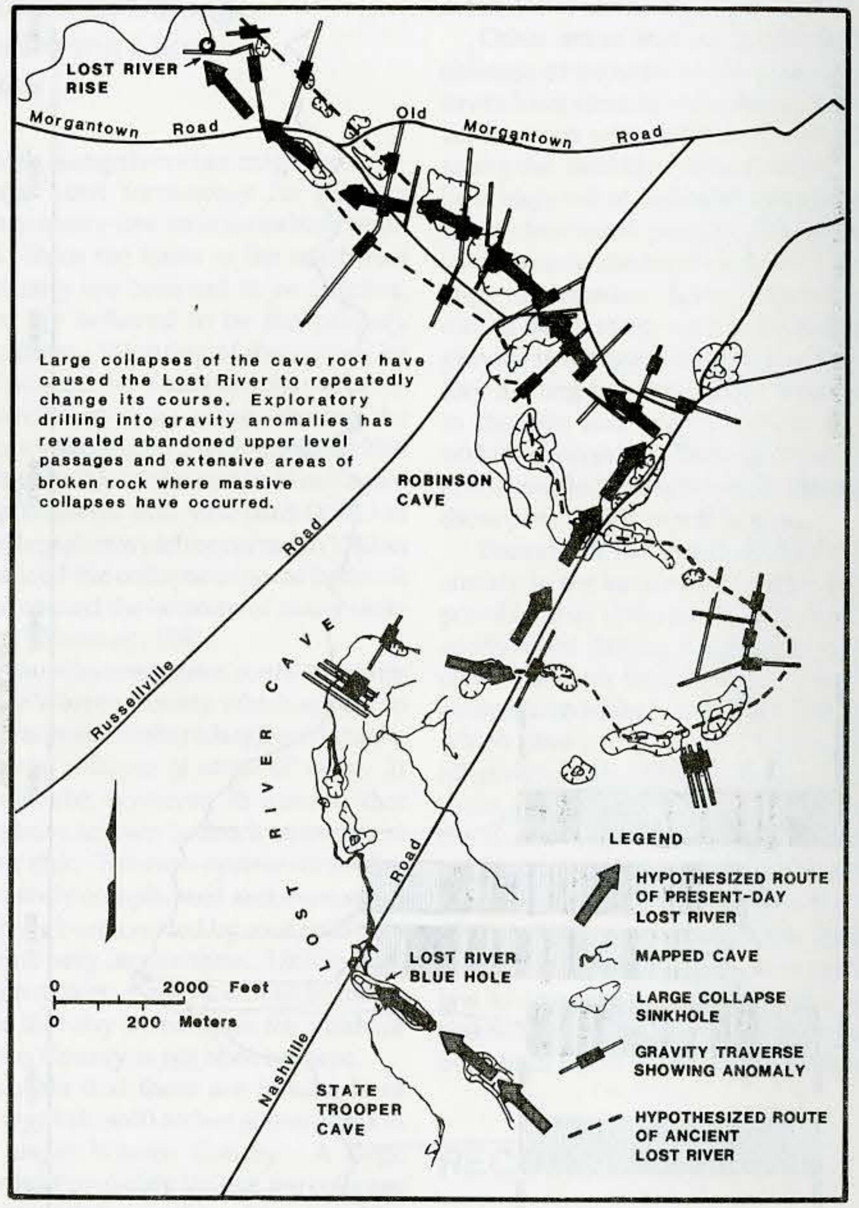
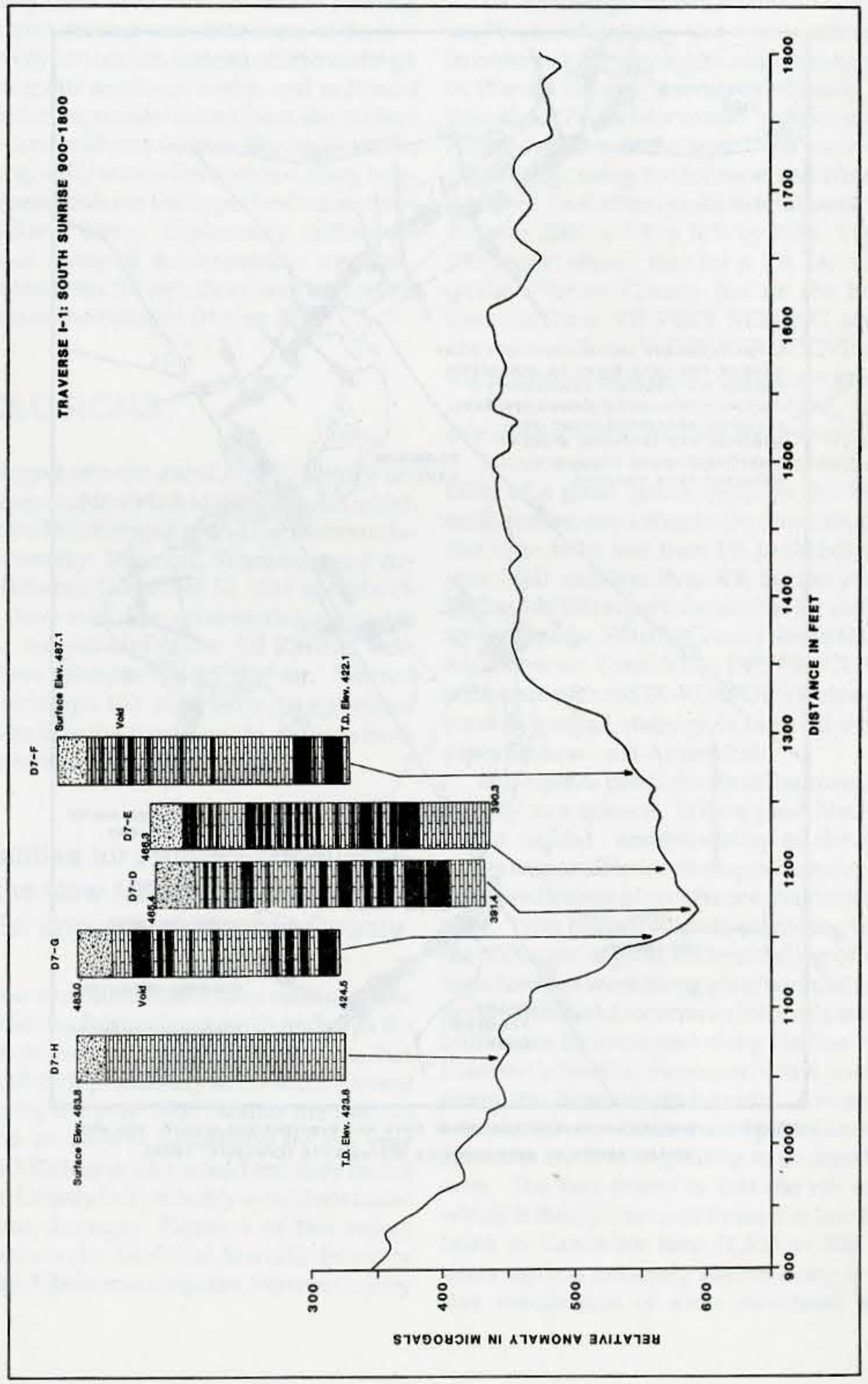


FIGURE Mapped portions of Lost River Cave and hypothesized present day and ancient routes as determined by microgravity (Crawford, 1986).

PROFILE OF A MICROGRAVITY TRAVERSE WITH WELLS INTERSECTING VOIDS



Johnson and Nova (1985) recognized that their probabilities are contingent on a number of factors which remain assumptions because of the lack of a geological or paleoseismological chronology of past New Madrid activity.

Karst Features as Damage Magnifiers During Large Earthquakes

Alluvial soils along rivers can magnify earthquake damage but fortunately for Warren County, there are very few structures built upon alluvial soils. Since the faults in the northwest part of the county are believed to be inactive, karst features are believed to be the primary damage magnifiers. Vibrating of the surface by blasting has induced the sinkhole collapse of regolith (soil) arches in other areas, causing the abandoning of a village in China (Waltham, 1989) and accounting for 4% of the sinkhole collapses in a study by Williams and Vineyard (1971) in Missouri. Earthquakes which occurred in 1962 in Yugoslavia caused the collapse of some bedrock cave roofs and caused the bottoms of many sinkholes to open (Milanovic, 1981).

There are cantilevered cave roofs in many locations under Warren County which appear to be unstable. It is possible that a large earthquake might induce the collapse of some of these. It would be a mistake, however, to assume that homes built above known bedrock caves are at greater seismic risk. The cave system under the county is extremely complicated and even small caves which have been created by roof collapses often have some very large rooms. Unless bedrock borings have been made, it would be incorrect to assume that any home upon the sinkhole plain of Warren County is not above a cave.

It is probable that there are hundreds of thousands of regolith (soil) arches above voids in the bedrock under Warren County. A large earthquake would probably induce the collapse of some of these existing arches. However, the great majority of these are believed to be in or near the bottoms of our numerous bowl-shaped sinkholes and therefore, within the sinkhole flood plain for a one-hundred year probability, three-hour storm event. Therefore, our existing storm water management plan which prohibits the building of structures within the sinkhole flood plain provides an excellent land use plan for preventing the building of structures in areas which are the most likely to have a sinkhole collapse either during a flood or during an earthquake. Therefore, an earthquake land use plan already exists for Warren County.

Other areas that are particularly at risk of collapse or subsidence are areas where bedrock caves have already collapsed. These are areas of broken rock with sediment, water and air separating the boulders. These areas are believed to be at high risk of sinkhole collapse or subsidence due to increased packing caused by erosion by cave streams during floods or vibration during large earthquakes. Some of these areas are obvious as deep, steep-walled sinkholes but microgravity investigations combined with exploratory drilling have revealed extensive areas both in the city and county which do not have a surface expression. These areas need to be found and identified. Structures should not be built on these potentially unstable sites.

Because of the cutter-and-pinnacle bedrock surface in the karst areas of Warren County, it is possible that differential compaction could be accellerated during large earthquakes and this could damage foundations. Most differential compaction is likely to occur in sinkhole bottoms which have collapsed in the past and then were filled with trash, old cars, appliances, tree stumps, rocks, etc. Again, these areas usually occur within the sinkhole flood plain and the existing storm water management plan should prevent structures from being built upon most of these areas. Unfortunately, even though it is against a county ordinance to fill sinkholes, and against the state law to dispose of waste without a permit, many sinkholes have been filled, and structures have been built upon these filled sinkholes.

RECOMMENDATIONS

Warren County is faced with a serious dilemma in terns of how to plan for a large earthquake which will occur in the New Madrid seismic zone. Some time in the future, a great quake, as large as the ones during the winter of 1811-

1812, is going to occur. If it happens in the near future it will result in major damage in Warren County. Should the county therefore launch a crash program to prepare for a great quake? Yes, if there is reason to believe it is going to happen in the near future but that does not appear to be the case.

Some day Warren County is going to have a 1000 year probability flood and there is a 10% probability that it will happen in the next 100 years and a 1% chance that it will happen in the next 10 years. Should the county prepare for it? A reasonable planning decision was made in 1976 that the county will plan for a 100 year probability, 3-hour rain event for storm water management purposes. Planning for a 100 year storm, which has a 1% probability of occurring each year, will not only eliminate flood losses during a 100 year and lesser storms, but it will greatly reduce flood losses when a 1000 year flood does occur.

A similar planning decision is needed in preparing for an earthquake. The probability for an 8.6 Richter quake in the near future appears to be small and the cost of preparing for a great quake would be very high. However, the probability for a major quake of 7.6 Richter is higher (it may or may not be 4 to 6% in the next 10 years but it has a much higher probability than an 8.6 Richter quake). Planning for a 7.6 Richter quake is far superior to doing nothing and even when the 8.6 Richter quake does occur, damages will be considerably less than they would have been without any earthquake planning. However, there are certain strategic buildings, such as hospitals, fire departments, police stations, etc., where it may be necessary to plan for a higher magnitude earthquake.

Homes and buildings in Warren County should have earthquake and sinkhole collapse insurance. Most homeowners probably do not realize that there is a potential for earthquake damage in Warren County. Many homeowners probably also believe that their homeowners insurance policy covers their home in the event of earthquake or sinkhole collapse damage. It does not unless they have paid extra for earthquake protection. Most homeowners do not have and cannot get sinkhole collapse insurance from their present insurance company. Only one or two companies presently provide both earthquake and sinkhole collapse insurance under an "earth movement" rider to their homeowners policy. The state of Florida requires all insurance companies doing business in Florida to provide sinkhole collapse protection. Kentucky should do the same. If necessary, Warren County should require that all insurance companies provide this protection.

The cost of adding earthquake (and sinkhole collapse) insurance to one's homeowners policy varies with the insurance company and the value of the home but it is usually not very expensive. (If it is, then the consumer should consider changing his insurance company).

The building code for Warren County should be upgraded to conform with the new and revised earthquake regulations in the Uniform Building Code (1988), published by the International Conference of Building Officials. Warren County is in Seismic Zone 1 with Zone 4 being the highest and Zone 0 being the lowest.

Foundation investigations for multi-storied buildings and other strategic buildings should require not only soil borings but bedrock borings as well. New buildings should not be built above cave rooms with unstable cantilevered domes or above areas of broken rock where caves have collapsed. Where possible, these buildings should have their foundations built upon solid bedrock in order to prevent differential compaction problems associated with cutter-and-pinnacle bedrock surfaces.

The present storm water management plan prevents the buildings of structures within the one hundred year probability, three-hour storm, sinkhole flood plain. Since these areas are also the most vulnerable areas for sinkhole collapse and differential compaction, Warren County already has an earthquake land use plan. However, areas of broken rocks resulting from cave collapses should be identified and structures prohibited from these potentially unstable areas.

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APPENDIX

MODIFIED MERCALLI INTENSITY SCALE

(From Wood and Neumann, 1931)

APPENDIX

MODIFIED MERCALLI INTENSITY SCALE
(From Wood and Newman, 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:

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

II

Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons.
Also, as in grade I, but often more noticeably:

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

III

Felt indoors by several, motion usually rapid vibration.

- Sometimes not recognized to be an earthquake at first.
- Duration estimated in some cases.
- Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away.
- Hanging objects may swing lightly.
- Movements may be appreciable on upper levels of tall structures.
- Rocked standing motors cars slightly.

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.
- Sensation of heavy body striking building, or falling of heavy objects inside.
- Rattling of dishes, windows, doors; glassware and crockery clink and clash.
- Creaking of walls, frame, especially in the upper range of this grade.
- Hanging objects swung, in numerous instances.

Disturbed liquids in open vessels slightly.
Rocked standing motor cars noticeably.

V

Felt indoors by practically all, outdoors by many or most; outdoors direction estimated.
Awakened many, or most.
Frightened few--slight excitement, a few ran outdoors.
Buildings trembled throughout.
Broke dishes, glassware, to some extent.
Cracked windows--in some cases, but not generally.
Overturned vases, small or unstable objects, in many instances with occasional fall.
Hanging objects, doors, swing generally or considerably.
Knocked pictures against walls, or swung them out of place.
Opened, or closed, doors, shutters, abruptly.
Pendulum clocks stopped, started, or ran fast, or slow.
Moved small objects, furnishings, the latter to slight extent.
Spilled liquids in small amounts from well-filled open containers.
Trees, bushes, shaken slightly.

VI

Felt by all, indoors and outdoors.
Frightened many, excitement general, some alarm, many ran outdoors.
Awakened all.
Persons made to move unsteadily.
Trees, bushes, shaken slightly to moderately.
Liquid set in strong motion.
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 in 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.
Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed VII 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 is 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.
Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down,
wood 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:
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.
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.
Damned lakes, produced waterfalls, deflected rivers, etc.
Waves seen on ground surfaces (actually seen, probably, in some cases).
Distorted lines of sight and level.