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Overview of Liquefaction Evidence for Strong Earthquakes of Holocene and Latest Pleistocene Ages in Southern Indiana and Illinois

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ABSTRACT

Clastic dikes filled with sand and gravel, interpreted to have a seismic liquefaction origin, occur throughout much of southern Indiana and Illinois. Almost all of the dikes originated from prehistoric Holocene seismicity, although a few date back to latest Pleistocene and possibly earlier time. Nearly all of these liquefaction features originated from earthquakes centered in southern Indiana and Illinois, and not further south in the nearby source region of the great 1811-12 New Madrid earthquakes.

The study area encompasses most of the southern halves of Indiana and Illinois. Within this area, at least seven and probably eight prehistoric earthquakes have been documented during the Holocene, as well as at least one during the latest Pleistocene. The recognition of different earthquakes is based mainly on timing of liquefaction in combination with the regional pattern of liquefaction effects, but some have been recognized only by geotechnical testing at sites of liquefaction.

Effects of individual paleo-earthquakes in southern Indiana have been separated from one another, and it is likely that all there have been identified. Most paleo-earthquakes presently recognized lie in Indiana, but equally as many may have occurred in southern Illinois. Studies in Illinois have not yet narrowly bracketed when liquefaction occurred at many sites, which sometimes causes uncertainty in the causative earthquake, but even in Illinois the largest paleo-earthquakes probably have been identified.

Prehistoric magnitudes were probably as high as the order of moment magnitude M 7.5. This greatly exceeds the largest historic earthquake of M 5.5 centered in Indiana or Illinois. The strongest prehistoric earthquakes had epicenters in the vicinity of the lower Wabash Valley, where the valley borders both Indiana and Illinois. These epicenters are near where most of the strongest historic seismicity has taken place. Beyond the region of the Wabash Valley, prehistoric earthquakes on the order of M 6 and higher have occurred where there has been little or no historic seismicity. Numerous other strong paleo-earthquakes could have struck elsewhere in southern Indiana and Illinois, but evidence not preserved in the geologic record because of the lack of liquefiable deposits.

BACKGROUND

Numerous small to moderate earthquakes have occurred sporadically in Indiana and Illinois throughout the historic record of 200 years (Fig. 1). These earthquakes, plus the proximity to the great New Madrid earthquakes of 1811-12 (Fig. 2), and the suggestion that the tectonic setting for triggering those great earthquakes extends northward into Indiana and Illinois (Sexton, 1988), prompted a search for paleoliquefaction features. The search began in 1990 and clastic dikes interpreted to be of paleoseismic liquefaction origin were identified shortly thereafter in the Wabash Valley of southern Indiana and Illinois (Obermeier et al., 1991). The search area then was extended beyond the Wabash Valley and now includes most of southern Indiana and Illinois. The search methodology has been to do field examination of banks of streams, ditches, and sand and gravel pits for seismic liquefaction features. The methodology and details of early studies are discussed in Munson et al. (1992) and Obermeier et al. (1993).

In Indiana, establishing the ages and regional extent of liquefaction for the various earthquakes has been done primarily by P.J. Munson and C.A. Munson, and final results are discussed in Munson and Munson (1996). Geotechnical engineering studies to assess the magnitude and attenuation characteristics of the largest paleo-earthquakes have also been completed in Indiana (Pond, 1996). In Illinois, in order of field effort, searches mainly by S.F. Obermeier, W.E. McNulty, P.J. Munson, R.C. Garniewicz, and E.R. Hajic have located dikes throughout large portions of the southern half of the state. Only a small number of sites in Illinois have been carefully studied to bracket closely when liquefaction occurred. Results in Illinois are to be found in reports by Obermeier et al. (1993), Su and Follmer (1992), Hajic et al. (1995), and in abstracts by Hajic et al. (1996), Obermeier et al. (1996), and Tuttle et al. (1996). An overview summarizing the status of results in both Indiana and Illinois, current in early 1996, is given in Munson et al. (1997).

Subsequent findings and data generated by Obermeier and McNulty during the summer of 1996 have helped clarify the paleoseismic record in Illinois. The purpose of this report is to present current results from Indiana and Illinois, as well as to show how the results of the field studies accord with geologic and geotechnical understanding of the liquefaction process. Discussion of the geotechnical tie-in is included because the method of systematically searching for liquefaction features, and then using geotechnical analysis to learn about the record of paleoseismicity, is a new and rapidly evolving technique.

Where results of this paleoliquefaction study are discussed in the context of evidence for "very strong shaking," the term is intended as a semi-quantitative indicator of shaking intensity, equivalent to that associated with a Modified Mercalli Intensity (MMI) value of VIII to IX. All MMI values discussed below are "regional," whereby I mean the intensity level is commonplace within that geographic region; this use is intended to comply with relations between severity of liquefaction effects and MMI values found in the original definition of the MMI scale (Wood and Neumann, 1931). This regional value differs from the MMI value shown by Algermissen and Hopper (1985, Fig. 14) for the area potentially affected by great earthquakes in the New Madrid seismic zone, in that their MMI value is intended to be a maximum, and can be determined by single point of exceptionally severe destruction within a huge geographic area.

Throughout the text it is assumed that epicenter (which is defined as the point where rupture initiates) of a paleo-earthquake corresponds with the center of the region of strongest seismic shaking, as indicated by the severity of liquefaction effects. The region of most severe effects is also assumed to be the meizoseismal region (which is defined as region of strongest shaking). Discussion of these assumptions is deferred to late in the text.

OVERVIEW OF GEOLOGIC-LIQUEFACTION SETTING

Most of the study area in Indiana and Illinois is underlain by indurated, flat lying Paleozoic sediments. These rocks generally are veneered by a thin cover of Quaternary till, loess, or alluvium, except in some upland areas in southernmost Indiana and Illinois. In major stream valleys the alluvium generally is 10 to 30 m in thickness. These valleys contain extensive expanses of low, late Pleistocene terraces (glaciofluvial braid-bar deposits, mainly gravel and gravelly sand) into which are inset slightly lower Holocene flood plains (point-bar sediments, mainly sandy gravel, gravelly sand, and sand). The larger rivers have meandered over a relatively wide belt throughout the Holocene and left behind deposits of various ages. The sand and gravel deposits of both braid bars in low terraces and point bars are normally abruptly capped by 2 to 5 m of fine-grained (sandy silt to clayey silt) alluvium, mainly from overbank and channel-fill deposits. Bordering the valley at the level of glaciofluvial deposits and slightly higher are extensive plains of fine-grained deposits (mainly silt and clay, but sand locally). These deposits were laid down in slackwater areas during glaciofluvial alluviation, mainly in latest Wisconsinan time. Such slackwater deposits are especially widespread in southernmost Indiana and Illinois (Fig. 3).

Formation of seismically induced liquefaction features depends chiefly on the water table being shallow enough for liquefaction to take place in thick sand deposits that lie beneath a thin cap of low permeability (Obermeier, 1996). A water-table depth on the order of 5 m greatly restricts or prevents liquefaction except where ground shaking is exceptionally severe (see for example the publication by the National Research Council, 1985, p. 91, which presents examples of influence of water-table depth on liquefaction). In the study area, a large depth to the water table is indicated in many deposits older than mid-Holocene, because weathering effects (and especially oxidization) in fine-grained sediments go as much as 5 m below the paleosurface. These weathering profiles often extend below the modern depth to the water table, even during prolonged dry spells. The thick profiles probably were imposed during the early to middle Holocene, when the climate was generally warmer and drier than now (Knox, 1983). Also, streams then were incised at many places, causing the water table depth to be generally deeper than now. (This period of warm, dry weather is referred to many geologists as the "hypsithermic.") Since mid-Holocene time, the much shallower depth of weathering (generally less than about 3 m) probably reflects a much shallower water-table. Even now, though, during prolonged dry spells, the water table is 5 m deep along many streams. Because the water-table depth has frequently been quite deep, the paleoliquefaction record is doubtlessly an incomplete reflection of seismic shaking, especially during hypsithermic time.

Other than during the hypsithermic, the opportunity for liquefaction features to form doubtlessly has persisted at many places during the Holocene and latest Pleistocene. Still, even during hypsithermic time, it is likely that the water table remained shallow in special field situations, as indicated by an exceptionally thin weathering profile that lies above completely unoxidized sediment. A typical field situation where a high water table has persisted is in a wide valley underlain by thick granular deposits, in which the valley is drained by a small, underfit stream. Such relations especially occur near glacial end moraines, in valleys that served briefly as glacial sluiceways. Another situation where a high water table is indicated through much of Holocene time is in abandoned meanders of very large rivers. Such is the Ohio River valley, which at many places is a very wide valley where ancient underfit streams have persisted. A special effort was made to search the banks of such underfit streams for paleoliquefaction features.

I believe that conditions favorable for liquefaction were generally adequate to provide evidence of any very large earthquakes (say, $M > 7$, as will be shown later) through almost all of Holocene time, on the basis that the very large region shaken by such a strong earthquake should have encompassed some sites favorable for liquefaction. Smaller earthquakes may not have left liquefaction evidence behind.

The opportunity to find liquefaction features during the study is thought adequate for any stronger Holocene paleo-earthquakes (say, M > 7). Multitudes of bank exposures along most of the intermediate to larger streams (e.g., Wabash River, White River, Embarras River, Kaskaskia River; see Fig. 7) revealed deposits as much as a few thousand years to mid-Holocene in age. Only exceptionally were there sections as long as 10 to 20 km in which no exposures were at least mid-Holocene in age. Many of these exposures had lengths of 100 to 200 m and much longer. Whereas exposures of early Holocene age typically were much less abundant, they generally were adequate for a search of liquefaction features that formed as much as 6,000 to 7,000 years ago, and older yet in many places. In rare instances deposits were exposed that likely have been susceptible to liquefaction for much of the past 20,000 years.

ORIGIN OF SEISMIC LIQUEFACTION FEATURES IN A FINE-GRAINED CAP

The brief discussion following summarizes how liquefaction features, namely dikes, form in a fine-grained cap such as that found in the study area. Greatly expanded discussions of the origins and characteristics of dikes and sills induced by seismic liquefaction are to be found in Obermeier (1996).

Dikes in a fine-grained cap can be induced by at least three largely independent mechanisms: lateral spreading, hydraulic fracturing, and surface oscillations. Effects of lateral spreads reflect movement downslope or toward a topographic declivity such as a stream bank, and the effects are manifest as tabular clastic dikes that mainly parallel the low-lying area. The mechanism of hydraulic fracturing is driven by the porewater pressure in the liquefied sediment fracturing the cap. Hydraulic fracturing generally causes tabular dikes to form, mainly parallel to one another but also in an anastomosing pattern in plan view wherever liquefaction has been severe. Surface oscillations cause tabular clastic dikes to originate in response to the fine-grained cap being strongly shaken back and forth above liquefied sediment. Shaking in the cap can originate by either surface waves (Youd, 1984) or body waves (Pease and O'Rourke,1995).

The three mechanisms noted above generally are dominant in producing the larger dikes, and especially tabular dikes visible at the ground surface. Liquefaction can also leave behind small tubular clastic dikes in a fine-grained cap, especially where venting has taken place through an extremely soft cap (Obermeier, 1996). Also, small tubular dikes often develop in pre-existing holes left behind by decayed roots and in holes excavated by creatures such as crabs or crawfish (Audemard and de Santis, 1991).

A generic set of geologic criteria for ascertaining a seismic origin to features of suspected seismic origin is discussed in Obermeier (1996). Geologic verification for seismic liquefaction origin in the study area has involved demonstrating that (1) details of individual clastic dikes conform with those of known seismic origin, mainly in the meizoseismal zone of the 1811-12 New Madrid earthquakes, (2) the pattern and location of dikes in plan view on a scale of tens to thousands of meters conforms with a seismic origin, (3) the size of dikes on regional scale identifies a central "core" region of widest dikes, which conforms with severity of effects expected in a meizoseismal zone, and (4) other possible sources to the dikes, such as artesian conditions and landsliding, are not plausible. Application of these criteria follows.

Reasons for rejecting nonseismic origins for the great majority of the dikes in the study area were first discussed by Obermeier et al. (1993) and still remain valid. Since that article in 1993, though, considerably more has been learned about interpretation of features of paleoseismic origin, as well as the nature of the features in Indiana and Illinois.

DESCRIPTION AND ORIGIN OF FEATURES

Nearly all the features interpreted to be of seismic liquefaction origin are sand- or sand- and gravel-filled clastic dikes. Dikes filled mainly with gravel are not unusual. The nature of the larger dikes along the lower Wabash River is illustrated in Figure 4, which shows a dike that formed 6,100 yr BP. The sand and gravel vented onto a ground surface that is now buried by more than one meter of overbank silt and clay. Locally, gravel having a diameter exceeding 4 cm was vented onto the surface. The dike in the figure is generally tabular, steeply dipping, and of large extent in plan view. Grain size of coarser material fines upward within the dike. Bedding of granular sediment that feeds into the dike is disrupted or destroyed just beneath the base of the dike. Similar dikes in the study area range in width from a few cm to more than 2.5 m. Many of the wider dikes, especially those wider than about 15 cm, have parallel sidewalls that mirror one another through their height.

Much more common throughout the study area are smaller dikes that pinch together upward in the cap, but which are still tabular. Both the dikes with vented sediment and the smaller pinching dikes generally have the same morphology and sediment relations as those of known seismic origin (Fig. 5) that formed a few hundred kilometers southward during the great 1811-12 New Madrid earthquakes. Figure 5 illustrates typical dikes found in a clay-rich cap in the 1811-12 earthquake's meizoseismal zone and beyond. The dike fillings and vented deposits are composed almost entirely of sand with minor silt. The only significant difference between these dike fillings and vented deposits with those in the study area is that many in the study area contain a significant proportion of gravel.

The wider dikes in Indiana and Illinois, exceeding about 15 cm, are similar the those associated with lateral spreading during the 1811-12 earthquakes. The wider dikes are interpreted to have formed as the liquefied, fluid-like water-sediment mixture flowed into fissures between blocks of the fine-grained cap. The fissures opened as the blocks shifted laterally on liquefied sediment toward topographic lows, or as the blocks shifted laterally on the liquefied sediment in response to back-and-forth shaking. Sketches and descriptions of wide dikes in the New Madrid region can be found in Obermeier (1996).

Also found at some sites in Indiana and Illinois are horizontal and near-horizontal intrusions (sills) of sand and gravelly sand. The sills typically extend along the base of the fine-grained cap. Sills as thick as 15 cm have been observed. In a few places, low-angle sill intrusions occur within the cap. Such low-angle intrusions are very common within and beneath the fine-grained cap within the meizoseismal region of the 1811-12 New Madrid earthquakes, but seem to be much less commonplace in the study area.

The dikes and sills in Indiana and Illinois resemble not only those of the 1811-12 New Madrid earthquakes, but from other earthquakes as well. Well-documented worldwide examples of liquefaction effects in a fine-grained cap are summarized by Obermeier (1996). Some of the more relevant examples include earthquakes in California (Sims and Garvin, 1995), in coastal Oregon and Washington (Obermeier, 1995), and in Alaska (Walsh et al., 1995). Not only is the overall morphology similar between features in the study area with the examples cited above, but details too. For example, some of the dikes induced by the great Alaska earthquake of 1964 (M 9.2) are filled with clean gravel, as are some in the study area. Despite the similarities of the features in the study area with those from earthquakes elsewhere, other possible origins, mainly nonseismic landslides or artesian conditions, are considered below.

A test for seismic origin on a regional scale consists of using dike width to determine whether there is a central core region of largest features, around which the widths attenuate systematically. The core region represents the meizoseismal area, and the systematic attenuation of widths represents how shaking has diminished away from the meizoseismal region. Basis for the method is provided by Bartlett and Youd (1992), who have shown from study of historic earthquakes that the maximum displacement due to lateral spreading diminishes logarithmically from the meizoseismal zone, providing the ability to form liquefaction features remains constant. In Indiana, both maximum dike widths and summation of dike widths have been shown to work well for defining the meizoseismal area of prehistoric earthquakes (Munson et al., 1995; Munson and Munson, 1996; Pond, 1996). The larger dike widths mainly reflect the amount of lateral spreading, and generally the wider dikes define the curves of dike width versus epicentral distance.

Strengths and shortcomings of using dike widths for paleoseismic analysis are in Obermeier (1996). A major advantage of the method is that the amount of lateral spreading is largely insensitive to cap thickness (Bartlett and Youd, 1992). A disadvantage in study areas where effects of liquefaction have not been especially severe (such as far from the meizoseismal zone) is that many of the largest dikes develop very near an actively eroding face of a stream, and are destroyed shortly thereafter. Some geologists have suggested that a way to circumvent this problem of dike destruction is to use another parameter, that of dike density (i.e., the number of dikes per unit area in plan view on the ground surface). A serious problem with this approach, though, is dike development from hydraulic fracturing is highly sensitive to cap thickness (Youd and Garris, 1995). Also, dike density may be sensitive to cap properties such as tensile strength, but the influence of strength is yet unknown.

The dikes in the study area also exhibit relations characteristic of seismic liquefaction on a local scale (hundreds of meters). Munson and Munson (1995) report that the clastic dikes in Indiana typically are widest and most abundant near paleochannels. In many field situations the clastic dikes are nonexistent to sparse at distances exceeding a few hundred to several hundred meters from the paleochannel. Field observations at widespread locales in the study area by Munson and Munson (1996), and by me in the study area and in other geographic regions of known seismicity (New Madrid seismic zone and coastal Oregon), show that it is not unusual that dikes from lateral spreading can be as wide as 30 cm within a few hundred meters of a paleochannel, yet further inland no dikes exist.

This observation that dikes from lateral spreading often do not extend far inland from streams indicates the shaking threshold for lateral spreading is often somewhat lower than for other dike-forming mechanisms. The threshold, though, is probably only slightly lower for lateral spreading because all require significant pore-pressure buildup, and the rate of buildup is very abrupt for loose to moderately compact sands (e.g., Seed et al., 1985, Fig. 8). This lower threshold also complies with the status of understanding in the geotechnical community. In geotechnical terms, a lateral spread generally should be the type of liquefaction-induced feature that develops most readily, providing the Standard Penetration Test (SPT) blow count value of a source sand is equivalent to a $(N_1)_{60}$ value of less than 15 to 20 (this value typically corresponds to moderately compact or looser sands, which can be seen from data in Pond (1996) to be extremely common in the study area). Such threshold values of 15 to 20 are indicated in Seed et al. (1985, p. 1440-1441) and in Bartlett and Youd (1995). Very recent data show that lateral spreads can develop where source sands have $(N_1)_{60}$ values as high as 20 (Holzer et al., 1996) and possibly higher yet (Pond, 1996), providing seismic shaking has been very strong. The relative ease at which lateral spreads form relative to other liquefaction features at high $(N_1)_{60}$ values is still an issue to be resolved in the geotechnical community, but in many field settings lateral spreads form more readily than from other mechanisms.

Dikes originating from other mechanisms often develop far away from sites of lateral spreading. Dikes from hydraulic fracturing generally seem independent of proximity to a topographic low or slope (Obermeier, 1996). Development of dikes by surface oscillations is enhanced in broad alluvial plains (Youd and Garris, 1995, p. 808). Dike location, therefore, can be especially valuable for eliminating nonseismic landsliding as the source of the dikes, because effects of landslides are restricted to being relatively near slopes. Tabular dikes have been found to be relatively common in glacial slackwater deposits in the study area, especially in southeastern Illinois. Here there are numerous, widespread sites with dikes in slackwater deposits that are flat-lying throughout large areas, and, the sites are far removed (hundreds to thousands of meters) from any significant stream banks or other sloping topography that was ever nearby. Thus nonseismic landslides are not plausible as sources of these dikes.

The possibility has also been considered that some dikes in the study area reflect intrusions associated with nonseismic landslides, caused by great floods. I contacted numerous people in the US Army Corps of Engineers immediately after the great flood of 1993 in order to characterize landslides caused by the flooding. (The Corps of Engineers has jurisdiction over slope stability problems along the Mississippi River, and routinely examines river banks.) The slides were found to have been caused by rotational slumping rather than dominantly lateral movements of the type recorded in the paleoseismic studies. In addition, no clastic dikes were observed to have formed in association with the slumps, but sometimes narrow ground cracks formed near the slumped portion. Flood-induced slumps were not observed in association with tabular dikes or large horizontal block openings, such as those interpreted to be of liquefaction origin in the paleoseismic study.

Another extremely large flood took place in central and southern Illinois during the spring of 1995. My field searching along about 85 km of stream banks immediately after the floodwater retreated, when great lengths of bank exposures were extremely clean, revealed no features resembling those interpreted to be of liquefaction origin.

Not all large landslides observed in the study area are dominantly slumps, though. Infrequent large landslides move mainly as very slowly moving (statically failing) blocks by shearing along very weak shale at depth (Mesri and Gibala, 1971). The landslides typically occur where deep rivers have cut to great depth, removing support at the toe of the slide. The slide then moves into the river. However, features such as dikes, and especially dikes that vent large quantities of sand and gravel such as shown in Figure 4, have not been observed in association with these slowly moving slides.

Other than the lack of having observed dikes to form in association with nonseismic landsliding, there are other reasons to reject these landslides as the causative mechanism. To summarize, (1) some dike sites are located above bedrock of sandstone (Pond, 1996), thereby eliminating the possibility of sliding on shale at depth, (2) many of the dike sites are along very small streams that have never cut to depths sufficient to trigger landsliding, (3) numerous dike sites occur in deposits that have always been hundreds to thousands of meters from any significant slopes or streams, in situations that could not have experienced high artesian (nonseismic) pressures, and (4) some dikes have vented large quantities of sand and gravel and some are filled with clean gravel, which obviously implies a very high pore-water condition, and the only the only plausible mechanism for such a high water pressure in many field settings is from seismic liquefaction.

Artesian conditions as sources for the dikes have been eliminated at virtually all sites in the study area because of the observation that artesian pressures typically cause tubular (and not tabular) dikes to form through the fine-grained cap. During the great flood of 1993, artesian flow beneath levees bordering the Mississippi River induced multitudes of sand boils. Some have been examined for comparison with seismic liquefaction features. Differences in dike morphology and other aspects such as nature of vented sediment are discussed by Li et al. (1996). Artesian conditions have also been rejected as source of the great majority of dikes in the study area because only a few sites are thought to be located where high artesian pressures could have ever existed; almost all the sites are far removed from any upland areas or other topographic situations that could have caused high pressures.

The likely explanation for the lack of tabular dikes in the fine-grained cap at sites of high artesian pressures, such as the example along the levees of the Mississippi River, is that the artesian pressure increases slow enough to equilibrate throughout the cap, thereby increasing the total horizontal stress (soil mechanics sense) in the fine-grained capping material. This increase in total horizontal stress greatly increases the water pressure required for hydraulic fracturing. A very good explanation of the process is given by Lo and Kaniaru (1990).

Yet another argument for a seismic origin to the great majority of the dikes is provided by the observation that the distribution of dikes has been found not to be random in time or space, as would be expected for features of spurious origin. In addition, no dikes were found throughout some very large searched regions.

In summation, neither huge floods, nor artesian conditions, nor any other nonseismic mechanism in the study area has been observed to have produced features resembling those interpreted to be of seismic paleoliquefaction origin. The geologic evidence show that the great majority of the dikes have a seismic liquefaction origin.

MAGNITUDES OF PREHISTORIC EARTHQUAKES - METHODOLOGY

Techniques used to estimate the magnitudes of the prehistoric earthquakes in the study area are discussed in detail by Obermeier et al. (1993) and Pond (1996). No attempt will be made here to replicate material in those articles, which are more geotechnical in nature.

Two methods have been used to estimate paleomagnitude. One uses the radius from the paleo-epicenter to the farthest dike that was discovered. The radius then is compared with a curve developed from observations of historic liquefaction in the study area and in the nearby New Madrid seismic zone (which is presumed to have a similar seismotectonic setting). The curve developed from these historic observations (Fig. 6) is referred to as the magnitude-bound method. The second method is much more complex, and involves first making a crude estimate of the magnitude of the paleo-earthquake. Then, using this magnitude to determine the seismic energy that would have caused shaking at a site of lateral spreading, in combination with SPT field measurements at the liquefaction site, an evaluation is made of the average SPT $(N_1)_{60}$ value of the liquefied zone. The average SPT $(N_1)_{60}$ value is used to back-calculate the peak acceleration. Peak acceleration is back-calculated at various distances from the epicenter. Then, the curve defined by the back-calculations is compared with the curve predicted from seismologic modeling. Magnitude of the paleo-earthquake is selected as the magnitude that yields the best fit between the modeling and the back-calculated curves. This procedure involves combining the energy models of Berrill and Davis (1985) and Law et al. (1990) with the method of Seed et al. (1983, 1985). This combination is the energy-acceleration method of Pond (1996).

The energy-acceleration method of Pond is intended to provide a best-estimate of magnitude. The method should probably be viewed as somewhat unproven, although Pond (1996) has also applied the method to historic earthquakes with acceptable results.

The largest paleo-earthquake in the study area, the earthquake of 6,100 yr BP, has also been analyzed using the Seed et al. (1983, 1985) procedure to establish a lower-bound magnitude. Pond (1996, Fig. 6.13) found this minimum to be about M 7 to 7.5. The energy-acceleration method yielded M 7.7.

The curve in Figure 6 for the study area is best thought of as representing liquefaction during average ground water conditions. This is because water-table depths from the historic events used to develop the curve are unknown and may have varied over a significant range. Thus interpretations of paleomagnitude using this method should be tempered according to whether the water table of an earthquake is thought to have been high, normal, or low. In a similar vein, for the energy-acceleration method, the value of $(N_1)_{60}$ depends strongly on water-table depth.

The water-table depth at the time of the paleo-earthquake can be estimated, at least regionally, by noting at many sites the shallowest depth beneath the paleosurface to which the base of the dike extends. Base of the dike is taken as coincident with the bottom of the fine-grained cap (see Fig. 5). This approach presumes that liquefaction will not originate above the water table in the sandy (highly permeable) deposits such as those normally encountered in the study area. Interpretation of water-table depth also requires estimating the level of the ground surface at the time of the paleo-earthquake, which can be easily done where sediment was vented onto a paleosurface, making sand blows. Sand blows, though, generally are sparse, which causes more uncertainty in interpretations. Still, I believe that the depth to the water-table can be estimated within a few meters in many areas by observing the level of the bottoms of dikes.

Confidence in interpretations of magnitude using both the magnitude-bound method and the energy-acceleration method requires some assurance that adequate outcrop has been searched to locate the distal liquefaction effects of a paleo-earthquake. The energy-acceleration method is much less sensitive to this parameter, but still requires identification of liquefaction sites over a significant portion of the range from the epicenter to the distal effects. Thus estimates of magnitude can be made only by searching many kilometers of exposures. The total length of exposures that must be searched to locate adequate liquefaction sites, especially the distal sites where liquefaction effects are widely scattered, is subjective. In the study region, on average, the limit of earthquake effects is considered to be indicated by an absence of features in a length of a few tens of kilometers, along a stream where numerous exposures of potentially liquefiable deposits are available. Alternatively, only several kilometers may suffice where conditions for forming and preserving liquefaction features are deemed to have been exceptionally good, though the practice during the study has been to search many more kilometers in most areas.

The energy-acceleration method of Pond is based on locating sites of lateral spreading. As noted, lateral spreads often develop more easily that other types of liquefaction effects. In order to ascribe a lateral spreading origin or other liquefaction mechanism to the dikes may requires locating paleochannels and topographic depressions at the time of the paleo-earthquake.

The most confidence in interpretation of magnitude arises when the two methods yield the same value. Even in this case, though, there is some uncertainty because both may depend similarly on the seismic parameter of stress drop. Stress drop influences peak accelerations, with a higher stress drop causing higher accelerations (Hanks and Johnston, 1992). Another uncertainty arises because of unknown focal depth (Hanks and Johnston, 1992).

Discussion in the Hanks and Johnson article indicates that either an unusually high stress drop or an unusually great focal depth might possibly cause an estimate of magnitude using liquefaction effects to be too high. This possibility has not been rigorously evaluated. An earthquake that may show the influence of exceptionally high stress drop and (or?) great focal depth on the regional extent of liquefaction is provided by the 1988, Saguenay, Quebec, earthquake. Figure 6 illustrates that the M 5.9 earthquake caused liquefaction features to develop as far as 33 km from the epicenter. This distance exceeds that of any other comparable earthquake, worldwide. This distance greatly exceeds that of the curve developed for the study area, using historic liquefaction from earthquakes centered in the New Madrid seismic zone.

The influence of a high stress drop on the back-calculated accelerations is unclear, because for a given moment magnitude, M, a higher stress drop must be accompanied by a shorter duration of shaking. Liquefaction is strongly affected by both duration and strength of higher accelerations, and the influence of shorter duration may be offset by the higher acceleration. Possibly the use of the energy-acceleration method of Pond to estimate moment magnitude automatically circumvents the problem of unknown stress drop; moment magnitude is a measure of earthquake energy, and the back-calculated acceleration is based on whether there was adequate energy to cause liquefaction at a site. By using the energy-acceleration method, Pond (1996) has shown that back-calculated accelerations agree extraordinarily well with predictions from seismological models that are based on data from normal (average) earthquakes in the central-eastern US (see Fig. 9). This close match would seem to support that the paleo-earthquakes were of the normal type. Even for the Saguenay earthquake of 1988, geotechnical analysis by Tuttle et al. (1990) suggests that liquefaction was predictable using the method of Seed et al. (1983, 1985). The lack of observed liquefaction from historic earthquakes in the study area, as high as M 5.4, also suggests seismic behavior there is not highly atypical; the normal threshold for liquefaction, worldwide, is about M 5.5 (Fig. 6).

Whatever the seismic parameters of stress drop and focal depth in the study area, the severity of liquefaction effects and the regional extent of their development makes it clear that very strong prehistoric earthquakes have struck the region repeatedly. In summary, the estimates of magnitude using paleoliquefaction effects are most accurately thought of as representing the magnitudes under stress drop and focal depth conditions thought to be normal in the region.

GEOLOGIC FIELD STUDY

The geologic part of the field study is basically comprised of two parts, one being to locate the features and the second being to characterize the site and collect data to bracket the time when the features formed. Almost all features have been located by searching banks of streams and to a much lesser extent walls of sand and gravel pits. None of the paleoliquefaction features are visible on aerial photos or other remote sensing images, owing to their age, burial by alluviation, or severity of weathering.

Locating the features involves searching where a fine-grained cap, about 1 to 10 m thick, overlies thick sands that have been saturated for long periods of time, preferably thousands of years. Evidence for prolonged saturation is documented if the granular deposits are presently beneath the normal, modern water table. Thick sands are preferable not only because they form liquefaction features most readily, but because their thickness amplifies bedrock motions at lower levels of bedrock shaking (Pond, 1996). Maps by Soller (in press) at a scale of 1:1,000,000 are especially valuable because they show both thickness and general character of the alluvial deposits (i.e., mainly granular or mainly fine-grained). Using these maps by Soller in combination with 1:1,0000,000 scale surficial geologic maps was successful in locating candidate streams.

The field search along streams is generally done from a small boat or canoe. Generally only steep bank exposures are sufficiently clear of vegetation and slope debris, though locally the base of a stream can be observed. The best exposures are in spring soon after flood waters have withdrawn, or in late summer and early fall when stream levels are lowest. At other times, a thin veneer of silt and clay is often on the stream banks, which can make it difficult to detect dikes as much as 20 cm in width.

Age of the paleoliquefaction features at most individual sites can be bracketed only within a few to several thousand years. At some sites, though, dating can narrow formation of dikes within a few hundred years. A summary of procedures for dating the paleoliquefaction evidence is given in Munson and Munson (1996). Three methods have been used: radiocarbon dating, archeological dating, and regional stratigraphic dating. Plant remains are most acceptable for radiocarbon testing. The only plant remains that persist above the water table are charcoal that was carbonized by fires. Carbonized remains of forest or prairie fires are widely disseminated throughout many exposures, but not all. These remains are often very small, having sizes on the order of a pencil tip. A few carbonized tree stumps have been found in-place. Relatively common along some of the larger streams are hearths and earth ovens used by prehistoric Indians. Carbonized nutshells and wood are often plentiful here, and have been especially useful.

Uncarbonized plant remains are found at many places beneath the normal water level, where anaerobic conditions have persisted through time. These remains include logs, leaves, stems, and nuts, which generally are concentrated along the base of the fine-grained cap.

Artifacts of prehistoric Indians have been used to bracket when many liquefaction features formed. Projectile points and pottery shards have been used most often. Relatively narrow age ranges can often be determined. Most styles of projectile points manufactured before 4,000 yr BP can be assigned age ranges of ± 500-1,000 years, and those made after 4,000 yr BP have ranges of ± 200-500 years. Pottery, which first appeared in the region about 2,700 yr BP, generally can be assigned age ranges of ± 200 years or less (Munson and Munson, 1996).

Regional stratigraphy has also been used extensively for assigning liquefaction features to a specific earthquake. All alluvial sediments in Indiana deposited during the Holocene and latest Pleistocene belong to the Martinsville Formation (Wayne, 1963), which is approximately equivalent to the Cahokia Alluvium of Illinois (Willman and Frye, 1970). These Holocene-latest Pleistocene deposits are easily recognized at most places in the field. Important to the paleoliquefaction studies has been to subdivide these formations into different "members," deposited several thousand years apart. Samples for narrow age bracketing using radiometric and archeologic data are not present at most liquefaction sites, forcing considerable reliance on stratigraphic members. Members can generally be defined within a drainage basin, both locally and regionally, on the basis of level of a terrace and soil development (B-horizon, color, and compactness) in deposits that comprise the terrace.

From a practical viewpoint, stratigraphic members can estimate the age of host sediment only within several thousand years in most exposures, unless data from radiocarbon testing or Indian artifacts provide supplementary information. Use of members requires numerous observations of exposures throughout many kilometers in the region, by a person with extensive geologic training and experience in the area. Using only a few observations to interpret regional stratigraphy can be deceptive because the depth and severity of weathering depends strongly on the position of the water table through time. This dependence makes it mandatory that an experienced person participate throughout the conduct of the search for paleoliquefaction features, or at least examine a large proportion of the liquefaction sites. Equally important is to determine whether or not a large proportion of the exposures of a given age have liquefaction features, which again requires a competent observer throughout the search; a lack of liquefaction features often indicates that prehistoric shaking was not especially strong in that region.

RESULTS OF PALEOLIQUEFACTION STUDIES

The map of Figure 7 is an overview showing liquefaction sites discovered in Indiana and Illinois. A liquefaction site is defined as a continuous exposure with at least one dike, but tens of dikes are also present at many sites; the exposure length ranges from a few meters to as much as 4 km. The figure also shows the maximum dike width at a site.

Almost all the sites on Figure 7 are from prehistoric seismicity of latest Pleistocene and Holocene ages. Only in extreme southern Illinois are there many sites where the features could be mostly or entirely from historic earthquakes, including the great New Madrid earthquakes of 1811-12.

Limits of liquefaction are shown in Figure 7 for only the largest paleo-earthquakes, even though almost all liquefaction sites in Indiana have been associated with specific earthquakes by Munson and Munson (1996). In Illinois, incomplete limits and questionable limits are shown for most paleo-earthquakes because of the few detailed site studies to bracket ages, and the lack of geotechnical studies. All ages on the figure are radiocarbon years.

Ages of individual dikes are not distinguished on the figure. The bound of liquefaction for all earthquakes encompasses many dikes of the same age. Even though ages of dikes are not shown, the figure makes it apparent that largest dikes associated with many paleo-earthquakes lie well within the limits of the bound, thereby defining a core region of largest dikes. The figure also makes it apparent that many of the largest dikes are concentrated near the border between southernmost Indiana and Illinois. The concentration reflects liquefaction from an especially large magnitude earthquake that took place nearby about 6,100 yr BP.

Not shown on Figure 7 are locations of fissures filled with clean sand (i.e., no silt or clay) cutting through till. Most of these features clearly are not ice-wedge casts, though ice-wedge casts were observed to abound in some regions. The sand-filled fissures through the tills are suspected to be dikes of seismic liquefaction origin. At many places these fissures greatly predate the dikes shown on the figures. The suspected dikes have yet to be examined in detail for a seismic origin, but they are most plentiful in areas of greatest Holocene seismicity in the study area. Credibility that the features cutting till have a seismic origin is enhanced by the observation that dikes elsewhere have through till in response to a liquefaction from a strong earthquake (Walsh et al., 1995).

Figure 7 also shows that large areas were not searched for paleoliquefaction features. Many of these blank areas have no liquefiable deposits or have no exposures suitable for a search. Many of the searched areas are separated as much as 75 km. Thus, even a large paleo-earthquake could have struck but left no liquefaction evidence.

More detailed results of the paleoliquefaction studies are given below, first for Indiana and then for Illinois. Earthquake magnitudes are also estimated in some cases. Pond (1996) has found that for the four largest paleo-earthquakes in Indiana, the magnitude estimate using the magnitude-bound method is essentially the same as the estimate from the energy-acceleration method. Only these four were studied using both procedures.

Results in Indiana

Studies in Indiana by Munson and Munson (1996) have identified and dated paleoliquefaction features from six earthquakes in the past 11,000 to 13,000 yr BP, which were of sufficient magnitudes ($M > \sim 6$) to cause sand and gravelly sand to liquefy and flow. Two and possibly three of these likely were very large earthquakes ($M > 7$) (Pond, 1996).

The largest paleo-earthquake in Indiana, of about M 7.5, occurred about 6,100 yr BP and was centered approximately 25 km west of Vincennes, Indiana (Fig.7). In Indiana, liquefaction effects from that earthquake extend as far as 150 km from the inferred epicenter. The range of these effects is believed to be controlled by a single, very large earthquake mainly because the maximum dike sizes attenuate systematically away from the inferred epicenter (Munson and Munson, 1996; Pond, 1996), as shown in Figure 8. In a similar vein, geotechnical analysis indicates a systematic attenuation of peak accelerations away from the inferred epicenter, in which the accelerations agree with predictions by seismologists for a M 7.5 or slightly higher event (Pond, 1996), as shown in Figure 9.

The next-strongest event occurred about 12,000 $\pm$ 1,000 yr BP, was likely centered about 40 km southwest of Vincennes, and probably was of $M \sim 7.1$ or slightly higher (Munson and Munson, 1996; Pond, 1996). Effects in Indiana extend about 50 to 60 km from the inferred epicenter. All liquefaction features associated with this earthquake lie in deposits that have an age of 14,000 to 10,500 yr BP. Most occur in a terrace formed by the draining of glacial Lake Maumee (present Lake Erie) through the Wabash Valley shortly after 14,000 yr BP. Granular deposits of this terrace typically lie 2 to 3 m above those younger than 10,500 yr BP, and have a silt-rich cap only a few meters in thickness.

Nearly all liquefaction effects associated with the earthquake of 12,000 yr BP lie within the bound of those from the earthquake of 6,100 yr BP (Munson and Munson, 1996). Yet the liquefaction events are separable, largely because the features of each earthquake lie in host sediments that have a well defined age range as well as a discrete, albeit narrow range of terrace levels. The terrace levels for the two earthquakes differ because of downcutting of the Wabash

River after 10,500 yr BP. This in turn caused the water table depth in the higher, older terrace to be so deep as to prevent the possibility of liquefaction much of the time. (See also Obermeier et al. (1993, Fig. 5) and Munson and Munson (1996, Fig. 2.2) for schematic characterizations of terrace levels in the lower Wabash Valley.) This interpretation of a deepened water table preventing liquefaction in the upper level is supported by the observation that, at least regionally, the depth to the water table was probably relatively deep (about 3 to 5 m) when the earthquake of 6,100 yr BP struck (Pond, 1996).

The next-largest event was centered about 100 km east of the Wabash Valley seismic zone. This event took place 3,950 ± 250 yr BP with a magnitude of M ~ 6.9 or slightly higher (Munson et al., 1995; Pond, 1996). The epicentral region was about 80 km north of Louisville, Kentucky (Fig. 7). This event is of special interest because of the absence of any significant historic earthquakes in the vicinity (Fig. 1).

Another earthquake likely of only slightly smaller magnitude took place between 8,500 and 3,500 yr BP. The epicentral region is suspected to be about 30 km southwest of Indianapolis (Fig. 7). Both the timing of the earthquake and the epicentral region are poorly constrained because of the small number of exposures with liquefiable sediment. The skewed distribution of effects from southwest to northeast likely can be explained by the greatly increasing gravel content in possible host deposits, as well as the lack of bank exposures. Both the presence of the earthquake and its limits of liquefaction have been defined almost exclusively by geotechnical analysis. The geotechnical analysis demonstrated that the strength of shaking at the northernmost liquefaction sites, near Indianapolis, far exceeded what could be reasonable associated with the M ~ 7.5 event of 6,100 yr BP, centered near Vincennes (Pond, 1996). As with the earthquake of 3,950 yr BP, the earthquake near Indianapolis took place in an area of only very small and infrequent historic earthquakes (Fig. 1).

A considerable smaller event took place 4,000 ± 500 yr BP, about 35 km southeast of Vincennes. Evidence for this event occurs at only one site (site not specified on Fig. 7), where two small dikes extend less than half a meter up into the cap before pinching out. The observations that the liquefaction effects for this event are very small in size and quite restricted in area (less than 5 km according to Munson and Munson, 1996) indicates that the earthquake was near the threshold for producing liquefaction effects. Estimated magnitude using Figure 6 is between 5.5 and 6. However, in assigning a magnitude for the smaller paleo-earthquakes on the basis of range of liquefaction effects, it must be kept in mind that liquefaction effects may have extended tens of kilometers beyond what was discovered, and that the epicenter may have been tens of kilometers from any liquefiable deposits. Even a relatively small increase in distance would much increase the estimated magnitude.

At a single site are small dikes that formed 2,000 ± 500 yr BP, about 60 km east-northeast of Vincennes (site not specified on Fig. 7). Effects of this earthquake are likely of very limited areal extent according to Munson and Munson (1996), suggesting an earthquake marginally capable of producing liquefaction, but a magnitude of at least M ~ 5.5.

A paleo-earthquake possibly occurred about 20,000 yr BP (Munson and Munson, 1996). Evidence is from dikes that cut through a considerable thickness (> 5 m) of cap at a single site, located about 50 km south-southwest of Indianapolis (site not specified on Fig. 7). No other exposures of liquefiable deposits of similar age were found in Indiana, making it impossible to estimate strength of the earthquake.

Almost all work in the Ohio Valley was done by the author. Liquefaction effects in the Ohio Valley are surprisingly sparse considering the relatively high level of historic seismicity in the vicinity, especially near Evansville (Fig. 1). Figure 7 shows that in and near Indiana only small dikes have been found. Dikes were observed at only one site, in a pit thought to be in the terrace associated with the flooding caused by emptying of glacial Lake Maumee shortly after 14,000 yr BP. No liquefaction effects were discovered in other large pits containing thick liquefiable sands on a slightly lower terrace level near Evansville, located a little closer to the present Ohio River (Fig. 7). This lower terrace is well above the modern flood plain of the Ohio River. It is probably at least several thousand years to mid-Holocene in age on the basis of thickness of weathering in the fine-grained cap on the terrace, as well as radiocarbon dates from deposits in the nearby younger, lower flood plain. The relatively shallow depth of weathering (< 3 m) in the 3 to 4 m thickness of the fine-grained cap of the lower terrace indicates a relatively high water table through time, and thus a relatively high liquefaction susceptibility.

The lack of major liquefaction effects in the pits near Evansville is consistent with the lack of liquefaction effects in banks of the Ohio River along the Indiana-Kentucky border, as well as along the Illinois-Kentucky border in southeastern Illinois, downstream to at least the Saline River(Fig. 7). Ages of bank exposures near Evansville are on the order of at least 4,000 to 5,000 yrs BP at many scattered places along the searched river banks, on the basis of thickness and severity of weathering of the fine-grained cap and radiocarbon data. This cap, though, is so thick (much more than 5 to 6 m) at many places as to have restricted development of dikes from penetrating up to levels now observable along the river. Before dams were built this century, water levels were so low for at least several months each year that it would have been difficult to induce liquefaction near the river, where the water table was drawn down the most. Thus uncertainties arise in trying to interpret the paucity of liquefaction effects in the Ohio River banks. Still, my observations elsewhere in the study area indicate that lateral spreads can form dikes through a cap as much as 7 m in thickness, even where shaking almost certainly was not extraordinarily strong and the water table was 3 to 4 m deep. Therefore, near Evansville, the lack of liquefaction features indicates that very strong shaking (regional MMI values of VIII to IX) is unlikely to have occurred at least the past 4,000 to 5,000 years.

Upstream from Evansville there is also an absence of large liquefaction features in deposits that probably could have liquefied most of the time since they were laid down in the late Wisconsinan. About 3 km of excellent exposures in Wright Drain (Fig. 7) revealed glacial valley-train sediments of Cary age (late Wisconsinan) in which a 3 to 4 m fine-grained cap overlies pebbly sand. The character of weathering indicates a long-continued swampy environment following deposition (Ray, 1965). Even now these deposits are frequently flooded, and the water table is high throughout all seasons. The lack of incised surface streams in the region likewise indicates that the water table must have been high much of the time since deposition, likely between 12,400 to 14,000 yr BP (Ray, 1965). Many other exposures of Cary-age deposits, having lengths of only a few hundred meters or so, have also been searched in the vicinity of Wright Drain but cannot be shown on Figure 7 because of scale of the map. Even though minor liquefaction features may have been present in the Cary-age deposits, they could not have been seen at many places because of severity of weathering of the cap. But, any large liquefaction features would have been discernible.

Many kilometers of latest Pleistocene deposits have also been inspected in banks of the

Ohio River, upstream from Wright Drain. These deposits, from the Tazewell glacial valley train, have an age of about 20,000 yr BP (Ray, 1965); terraces comprised of these deposits are generally about 10 m above the modern Ohio River. The water table beneath these terraces doubtlessly has been too deep for liquefaction to have developed through much of Holocene time. Still, the fact that the terraces are underlain by thick, clean sand and are capped by 3 to 5 m of clayey silt indicates a situation ideal for liquefaction, especially when the water table was high during Pleistocene time. Even now, during spring flooding, these deposits are susceptible to liquefaction. Altogether, the absence of liquefaction effects upstream from Evansville indicates an absence of strong shaking throughout much, if not most, of the past 20,000 years.

Results in Illinois

Liquefaction features from the M ~ 7.5 earthquake of 6,100 yr BP, with an inferred epicenter about 25 km west of Vincennes, should extend far west into Illinois (Fig. 7). Data reported by Hajic et al. (1995) and collected by me show a concentration of dikes, especially of larger sizes, along the Little Wabash River in Illinois about 50 to 60 km west-southwest of Vincennes. Radiocarbon data I have taken to supplement regional stratigraphic observations along the Little Wabash and it's tributaries show that the dikes are at least largely, if not almost exclusively, in sediments old enough to host the event of 6,100 yr BP. In addition, all dikes that extend near the paleosurface are severely weathered. These dikes typically have a thick, strong pedological Bt (clay rich) zone that extends from the top downward for 1 to 2 meters. Clay in the Bt horizon completely fills the space between sand grains, throughout much of the horizon. Such development of the Bt shows much antiquity, which I believe is consistent with an age of 6,100 yr BP. Younger liquefiable deposits abound, yet have a paucity of dikes. Thus it is likely that the great majority of the dikes in the vicinity of the Little Wabash can be assigned to that earthquake. In addition, most of the features along the Embarras and it's tributaries likely were induced by the earthquake of 6,100 yr BP, on the basis of radiocarbon data on sediments cut by the dikes, as well as the severity of weathering of the host sediments, dikes, and vented material.

Many of the dikes as far west as the Kaskaskia River likely were induced by the earthquake of 6,100 yr BP, on the basis of radiocarbon age of host sediments and the regional pattern of liquefaction. At least many, if not most of the liquefaction features along the Kaskaskia, upstream from Lake Carlyle, were probably caused by this earthquake. This is so because of the lack of other candidates as source areas uncovered in the search. Dikes here are thought to be strong candidates for the earthquake of 6,100 yr BP, despite the lower abundance of dikes and smaller sizes of dikes along the upper parts of the Little Wabash and Embarras Rivers, which are in closer proximity to the paleo-epicenter. The regional pattern of dike abundance and sizes can be explained by bedrock shaking being amplified higher along the Kaskaskia, due to a greater thickness of unconsolidated sediment. (See Obermeier et al. (1993), and Pond (1996) for discussions of amplification of shaking in the region; see Soller (in press) for thicknesses of unconsolidated materials in the region.)

The southwestern limit for the earthquake of 6,100 yr BP is shown as extending south of Lake Carlyle. Any dikes from that earthquake are almost certainly small. Basis for placing the limit this far to the southwest is that the radiocarbon age of the host at one liquefaction site is very close to 6,100 yr BP. It is entirely possible the limit extends further to the southwest. The southwestern limit also has been drawn to encompasses the upper part of the Big Muddy

River. Even though sediments along the Big Muddy that were examined are probably old enough to host the earthquake, no liquefaction features were discovered. The absence can probably be explained because any sand deposits in the region are too thin to be easily liquefied, on the basis of map information. In Illinois, as was the case in Indiana, geotechnical testing will be required before the limits of liquefaction can be closely defined for the earthquake of 6,100 yr BP.

Dikes from the earthquake of 12,000 yr BP must extend far west into Illinois (Fig.7). Only locally along the larger rivers are there exposures of sufficient age to record this earthquake. A site thought to be from this event has been discovered near the confluence of the North Fork of the Embarras River with the Embarras River. In addition, dikes at most paleoliquefaction sites along the smaller streams, namely Skillet Fork, Auxier Creek, Big Creek Ditch, and Saline River cut through glacial slackwater deposits that are old enough to record effects from the earthquake of 12,000 yr BP. When liquefaction occurred along these streams has not been constrained, though, and may not be possible because of the lack of suitable sites. Virtually all the dikes cutting the slackwater sites are very thin (1 to 2 cm) throughout their height and pinch together in a cap that typically exceeds 3 to 6 m in thickness.

A conspicuous absence of dikes is along Elm River (Fig. 7), even though streams nearby have numerous dikes, some very large. The absence of dikes along the Elm River probably is explained by an exceptionally thick cap of slackwater deposits and an overall lack of exposures.

Exceptionally thick caps in slackwater deposits (5 to 6 m) are cut nearly through at many sites along the Saline River. Lateral spreading is not plausible at many of these sites, because many sites are in man-made portions of the river that were excavated in flat expanses of glacial slackwater deposits, far from streams. The large thicknesses of cap cut by dikes, without lateral spreading, suggests the possibility of very strong shaking (regional MMI values of VIII to IX). Alternatively, enhancement of liquefaction effects due to surface oscillations may have occurred. Site specific geotechnical testing may resolve the issue of whether very strong shaking occurred.

Dikes of at least two ages are present along the Saline River. Sand fillings in adjoining dikes exhibit large differences in weathering at many places. The fillings in many are severely oxidized in their upper parts and contain many calcareous nodules, indicating an age of early Holocene or older (see Ray, 1965, p. 44-45). Yet immediately adjoining these are dikes filled with loose, unweathered sand, indicating a very young age. Some of these dikes with unweathered sand may have been caused by the great New Madrid earthquakes of 1811-12, whose epicenters were about 200 km to the southwest and which were reported to have induced minor liquefaction effects nearby in the lowermost Wabash Valley (Berry, 1908).

Very small dikes of very young age are quite common within large dikes of much greater age along the Little Wabash River. These relations occur at least in the portion of the river from the dike exceeding 0.5 m in width (Fig. 7) to about 15 km south. The small dikes appear only in the lower parts of the larger dikes. The very small dikes show virtually no evidence of weathering, in contrast with the large dikes (which probably were induced by the earthquake of 6,100 yr BP). The small dikes may have been induced by $M \sim 5$ historic earthquakes in this vicinity of the Little Wabash River (Fig. 1).

These very small dikes are especially interesting because they are observed only within the larger, much older prehistoric dikes, even though bank exposures old enough to host the young dikes were plentiful in the area. I suspect that the young dikes developed within the older large dikes because, during the older earthquake, sand was loosened within a thin zone directly beneath the cap. Recurrence of liquefaction at the same site, and loosening of sand directly beneath the cap, has been observed in many worldwide earthquakes (Obermeier, 1996).

Occurrence of a paleo-earthquake that struck 3,750 yr BP in the upper Embarras River has previously been reported by Hajic et at. (1996), but it now appears that age is greatly in error because of misinterpretation of stratigraphic relations (Munson et al., 1997). A relatively smaller Holocene earthquake may also be represented in the liquefaction record along Skillet Fork (Su and Follmer, 1992; Hajic et al., 1996), but that issue is still to be resolved.

Another possible paleo-earthquake in the eastern half of Illinois may be represented by dikes cutting peat at a single site in the upper part of the Little Wabash River (Hajic et al., 1995). Numerous small dikes cut the peat, dated at 21,000 yr BP, but when the dikes formed cannot be bracketed.

A moderate earthquake struck in central Illinois between 5,900 and 7,400 yr BP. Evidence for this earthquake was first discovered by R.C. Garniewicz, and was reported by Hajic et al. (1995). Subsequent work by W.E. McNulty and me has limited the range and age of liquefaction in that region. The largest dike (37 cm wide) from this event is located on Lake Fork, about 35 km northeast of Springfield. The areal extent of liquefaction is limited, on the basis of the lack of liquefaction effects in the many other streams and pits searched in the vicinity, mainly upper Salt Creek, Sugar Creek, Deer Creek, Big Creek, Sangamon River, South Fork of the Sangamon, and a huge pit located just east of Springfield. Altogether, there are many exposures of liquefiable sediment in the region whose ages slightly to greatly exceed when the dikes formed along the Sangamon. (A search was also made along Flat Branch but the banks were so covered with mud that any liquefaction features would not have been visible.) The position of the bases of the dikes, in the fine-grained caps, strongly indicates that the water table was high at widespread sites. Liquefaction features appear to have maximum areal development of 30 km from the epicentral (disregarding the site with small dikes on the South Fork of the Sangamon, for reasons discussed below). The limited areal development, with a high water table, indicates the magnitude was not especially high. Use of Figure 6 to estimate magnitude is probably not appropriate because of the high water table when the earthquake struck. The figure can be used to estimate only an upper bound magnitude, M ~ 6.8. The influence of the high water table may have been partly offset because of the shallow depth to bedrock that generally prevails in the region. Such a shallow depth would have permitted little or no amplification of bedrock shaking. (The curve in Fig. 6 for the Indiana and Illinois earthquakes was developed on the basis of moderate amplification (factor of about 1.3 for peak acceleration) of bedrock shaking). Still, the magnitude of M 6.8 is probably too high. Geotechnical testing will be required to make a good estimate. Whatever the magnitude, a significant prehistoric earthquake struck in a region of virtually no historic earthquakes (Fig. 1).

Many exposures along the South Fork of the Sangamon reveal severely weathered deposits, with frost polygons, indicating ages of early Holocene-late Pleistocene. These deposits are clearly old enough to have recorded liquefaction evidence from the earthquake centered near Springfield. The only liquefaction site along the South Fork of the Sangamon has numerous closely spaced, small dikes that cut into and pinch out in a mat of sticks and other organic matter. The mat is decomposed so completely that it can be torn apart by hand. Radiocarbon age of the mat is 25,240 ± 240 yrs BP. The mat must have been decomposed when the dikes intruded. The site with the dikes was the only exposure suspected to be of such great age along the South Fork. Whereas the dikes in the mat may be from the earthquake northeast of Springfield, the paucity of dikes along the South Fork suggests otherwise. As a minimum, shaking could not have been very strong along the South Fork.

The dikes cutting the organic mat are in an unusual topographic situation, located against a very high bank. Only a half dozen or so sites throughout Illinois adjoin uplands. It is possible that high artesian pressures from water flowing from the upland hydraulically fractured the mat, making the dikes. Still, the morphology of the dikes on the South Fork of the Sangamon seems to be very similar to that reported by Tuttle et al. (1992) at a site in Quebec, where liquefaction intrusions into decomposed peaty matter created a myriad of dikelets.

Another earthquake probably was centered in the vicinity of the lower Kaskaskia River, with an epicenter near Shoal Creek (Fig. 7). Evidence for this earthquake was discovered in 1996 by W.E. McNulty. The largest dikes and their host sediments are strongly weathered, with both having strong, thick (>2 m) Bt development, indicating an age for the dikes of early to middle Holocene. Radiocarbon data suggest the earthquake took place about 6,500 to 7,000 yr BP, although it may be younger. Possibly the earthquake was as young as 6,100 yr BP, the age of M ~ 7.5 event centered near Vincennes, but a 0.5 m lateral spread on Shoal Creek is too far from Vincennes to be reasonably associated with an earthquake centered near Vincennes.

Reasons for assigning an earthquake epicenter to Shoal Creek region are the presence of the very large dike (0.5 m) on Shoal Creek, in conjunction with the observation that every exposure of sufficient age along Shoal Creek has dikes, even though the exposures are quite limited in length. Such abundance of dikes is typically limited to epicentral regions, where shaking has been quite strong. Liquefaction susceptibility and amplification of bedrock shaking have also been considered in assigning an epicenter to the Shoal Creek region.

The southernmost bound for the 6,500 to 7,000 yr BP event of Shoal Creek has been drawn relatively close to the southern limit of the searched portion of the Kaskaskia, even though Figure 7 indicates a high density of sites with small dikes in that region. The high density of sites is an artifact of the figure, however. Clean bank exposures are almost continuous throughout the lowermost 20 km or so of the searched portion of the river. Exposures are at least three or four times more abundant than further upstream, greatly enhancing the opportunity to find liquefaction features.

No liquefaction features were discovered northwest of the liquefaction sites on Shoal Creek (Fig. 7). Along Silver Creek are numerous exposures old enough to record an earthquake of about 6,500 to 7,000 yr BP. This age along Silver Creek is estimated on the basis of depth and severity of weathering of the exposures, supplemented with radiocarbon data. Bridge borings indicate that liquefiable sands likely underlie these sediments, although all sand-bearing deposits encountered beneath the cap by hand auguring were clay and silt rich. Thus, extremely strong shaking probably would have been required to have induced liquefaction. Exposures on Cahokia Creek generally were too young to record an event at 6,500 to 7,000 yr BP, on the basis of radiocarbon data.

Regional field evidence also supports that the dikes in the lower Kaskaskia were not caused by a large earthquake whose epicenter was further south. The dikes in the lower Kaskaskia are within 200 km of the New Madrid seismic zone (Fig. 2). This proximity might cause one to suspect a very large earthquake centered in the New Madrid seismic zone could have caused the liquefaction features along the lower Kaskaskia. The question of tectonic source was likely answered by a paleoliquefaction search along the lowermost Big Muddy River (Obermeier et al., 1996; Tuttle et al., 1996). The Big Muddy is situated ideally to intercept strong seismic shaking between the lower Kaskaskia and the New Madrid seismic zone. In addition, the Big Muddy has thick liquefiable sand deposits and exposures at many places. Ages of numerous exposures extend back to earliest Holocene time on the basis of radiocarbon data (M. Tuttle, oral commun., 1996) and stratigraphic index red beds that are at least as old as earliest Holocene time (E.R. Hajic, oral commun., 1995). Potential host sands along the Big Muddy commonly are in situations as favorable concerning depth to the water table and sand sizes (and thereby liquefaction) as host sands for the dikes along the lower Kaskaskia. Yet, only a few scattered dike sites were discovered along the Big Muddy. Considering all factors relative to liquefaction susceptibility, the absence of plentiful, large liquefaction features along the Big Muddy indicates strongly that the source region for the features along the lower Kaskaskia is from an earthquake(s) located considerably north or east of the Big Muddy River, and not the New Madrid seismic zone.

Also in the lowermost Kaskaskia search area are small dikes cutting host sediments probably less than a thousand years old. Some of these very young dikes may have originated from the 1811-12 New Madrid earthquakes. According to Prof. Otto Nuttli (St. Louis U., written commun.), an observation at the time of the 1811-12 earthquakes reported small sand blows in the Cahokia region, across the Mississippi River from St. Louis, which is considerably north of the lower Kaskaskia.

Liquefaction features have also been discovered along the Cache River in southernmost Illinois (Tuttle et al., 1996). Most of the features are small dikes. A dike at one site was at least moderate in size and possibly large, but was truncated, making further assessment of size impossible. Some of the dikes may be prehistoric. Host sediments are thick sands that were laid down by an ancestral Ohio River before 8,000 yr BP (Esling et al., 1995). Between 12,500 and 8,000 yr BP the Ohio River shifted south into a different drainage basin. The ancestral Ohio River valley, now termed the Cache Valley, probably has been ideal for formation and preservation of liquefaction features much of the time since abandonment by the Ohio because the valley is wide, long, and is drained only by the Cache River, which is a small, lethargic stream traversing large swampy areas.

Figure 7 indicates that dike sites are relatively common along the Cache. The abundance and size of liquefaction effects is not surprising considering the proximity to the epicentral region of the 1811-12 earthquakes and the New Madrid seismic zone. Still, the abundance and the size of the dikes along the Cache does not approach the severity of liquefaction effects in the meizoseismal region of the great 1811-12 earthquakes. Thus extremely strong seismic shaking is not indicated since at least early to middle Holocene time, though very strong shaking (regional MMI values of VIII to IX) may well have occurred.

Figure 7 also shows a near-absence of liquefaction features along the Ohio River, on the Illinois-Kentucky border. The absence can be largely explained by the overall lack of exposures. Still, a few very good, widely spaced exposures do occur. Long, clean exposures, up to kilometers in length, occur from the confluence of the Ohio and Wabash Rivers to the confluence with the Saline River. The only liquefaction features along this portion of the Ohio were a few thin dikes that pinched together upward. Host deposits at the site were at least 4,500 yr BP in age, but the sand in the dikes was very loose and unweathered, suggesting the possibility of originating from the 1811-12 earthquakes. Exposures of this age are common along this portion of the river. As in Indiana, the large thickness of the cap and the large annual fluctuations in Ohio River levels in Illinois during prehistoric time may have prevented many dikes from developing, but it is more likely that the absence of dikes reflects an overall absence of very strong shaking (regional MMI values of VIII to IX) during the past 4,000 to 5,000 years.

The only other exposures along the Ohio River, on the Illinois border, are far downstream from the confluence with the Saline River. In a 0.5 km long section a few very small, pinching together dikes had formed in a host of unknown age (Fig. 7). The exposure most downstream is a one-km-long bank located southeast of the searched portion of the Cache River. Host sediments in the bank are likely at least a few thousand years old on the basis of weathering profiles. No dikes were found in this bank.

PALEOLIQUEFACTION AND THE TECTONIC SETTING

When clastic dikes in the study area were first reported as having been induced by seismic liquefaction (Obermeier et al., 1991), there was considerable skepticism among some about the seismic origin. Part of the initial skepticism was brought about by the lack of recognition of young faults. Since then, faults of late Tertiary/Quaternary age extending to the surface have been found in southernmost Illinois (Nelson, 1996). Within the source region of the earthquake of 6,100 yr BP, though, no Quaternary seismogenic structures have been located at shallow depth, but candidate thrust faults at depth have been located (McBride and Sargent, 1996). What may be triggering the very large earthquakes is a "kink" in bedrock structure, whereby northeast trending structures suddenly change to the northwest. An east-west compressive stress field in the bedrock is suspected to cause a stress concentration at the kink (Hildenbrand and Ravat, 1997). This kink occurs near Vincennes in bedrock at the surface (Nelson, 1995) and also geophysically at great depth (Hildenbrand and Ravat, 1997). The kink is at the northern terminus of 600-km-long magnetic and gravity lineament that extends from Vincennes far into Arkansas. The notion that the kink was the critical to the larger historic earthquakes in the region was first hypothesized by Hamburger and Rupp (1988). Such kinks have also been postulated as being largely responsible for the great 1811-12 earthquakes in the New Madrid seismic zone (Johnston and Schweig, 1996).

Geologic structures that are strong candidates for the $M<7$ earthquakes have not been found in the study area, although faults and folds are commonplace throughout. The question has been raised whether the paleoliquefaction evidence for the $M<7$ earthquakes might have been caused by a bounce of seismic energy from the Moho zone at depth. Clearly such a bounce is not the case for one of the $M<7$ earthquakes. The age of the earthquake of 3,950 yr BP, in south-central Indiana, is not close to that of any other large earthquake. Also a poor candidate is the prehistoric earthquake in central Illinois, near Springfield. For this earthquake the pattern of liquefaction features is extraordinarily good, with there being a core region of largest dikes surrounded by smaller dikes, all within a relatively small region (Fig. 7). Such a well defined pattern seems best explainable by a nearby tectonic source.

Further evidence for the lack of a strong bounce of seismic energy is provided by the overall scarcity of liquefaction features throughout the study area, which could possibly be associated with a bounce of energy from the great 1811-12 New Madrid earthquakes. Focussing of energy from those earthquakes almost certainly was directed toward Illinois and Indiana (e.g., Algermissen and Hopper, 1985), yet this study has found that only small, scattered liquefaction features were induced there, except possibly in southernmost Illinois.

Possibly some of the other M < 7 earthquakes of mid-Holocene age may have been caused by the bounce of seismic energy from the hypocentral area of the earthquake of 6,100 yr BP. However, this study indicates some M < 7 earthquakes were not caused by bounce at any time.

Epicenter locations of the prehistoric earthquakes shown on Figure 1 generally are thought to accurate within a few tens of kilometers. This assessment is based on the assumption that the region of strongest shaking (i.e., the meizoseismal zone) encompasses the epicenter (i.e., the point of initial rupture). Most of the prehistoric earthquakes have a reasonably defined core region of largest, most abundant dikes, which, all things being equal, should represent the region of strongest shaking. Geotechnical analysis by Pond (1996) generally supports the interpretation of using the core as the region of strongest shaking, though this relation must always be evaluated on a case-by-case basis.

Relating liquefaction effects to location of the meizoseismal zone seems reasonable on the basis that the severity of liquefaction effects correlates well with values of MMI (indeed, this severity partly defines the value of MMI) (Wood and Neumann, 1931). As an extension of this logic, it has been found from study of five historic earthquakes in Illinois that the region of peak MMI values generally lies within 20 km or less from the epicenter (Rhea and Wheeler, 1996). Thus it is suspected that, in the main, the epicenters of the M < 7 paleo-earthquakes lie within a few tens of kilometers from the centers of the regions of largest dikes. The epicenters of the M > 7 earthquakes are suspected to be more in error, especially for the earthquake of 12,000 yr BP, though not greatly so.

SUMMARY AND MAJOR CONCLUSIONS

1. Virtually all the dikes and sills found throughout the southern halves of Indiana and Illinois have a seismic liquefaction origin.

2. The dikes and sills were induced by prehistoric earthquakes whose epicenters were almost exclusively in Indiana and Illinois. The only significant exception may be for the dikes in the Cache Valley, in extreme southern Illinois.

3. Probably nine paleo-earthquakes having magnitudes far stronger than any in historic time have been identified in Indiana and Illinois. Most of these have been well documented and are distinguishable from one another. At least seven and probably eight prehistoric events occurred at various times throughout the Holocene, mainly during the mid-Holocene. At least one paleo-earthquake took place during the latest Pleistocene.

4. Magnitude of the largest paleo-earthquake, which occurred 6,100 $\pm$ 100 yr BP, was likely on the order of $M \sim 7.5$. The next-largest earthquake, a $M \sim 7.1$ event, struck 12,000 $\pm$ 1,000 yr BP. Three more paleo-earthquakes likely had magnitudes in excess of M 6.5. Other liquefaction-inducing paleo-earthquakes, probably much smaller, have also struck. These estimates of magnitude are based on what are believed to be representative seismic parameters for the study area.

5. The two strongest paleo-earthquakes ($M > 7$) took place in the general vicinity of the most numerous and strongest historic earthquakes (M 4 to 5.5), in the lower Wabash Valley of Indiana-Illinois. Conversely, paleo-earthquakes of lower magnitude commonly have struck in regions having no significant historic seismicity.

6. Epicenters of the two strongest paleo-earthquakes ($M > 7$) have been located in proximity to one another. Conversely, paleo-earthquakes of lower magnitude are much more randomly distributed.

7. Probably not all the causative earthquakes have been identified at liquefaction sites already discovered in Illinois. Still, all paleo-earthquakes as large as $M > 7$ probably have already been identified within the study area in both Illinois and Indiana.

8. It is probable that a significant number of other strong paleo-earthquakes have struck during Holocene and latest Pleistocene time. These earthquakes are not in the paleoliquefaction record because of the lack of liquefiable deposits in many locales. Earthquakes having a potential radius of liquefaction effects of as much as 30 to 40 km could have struck without leaving liquefaction evidence. Many unrecorded events likely exceeded M 6.5.

9. Geotechnical analysis of the liquefaction features has been essential for distinguishing various prehistoric earthquakes from one another. In addition, geotechnical analysis has been essential for estimating prehistoric earthquake magnitudes.

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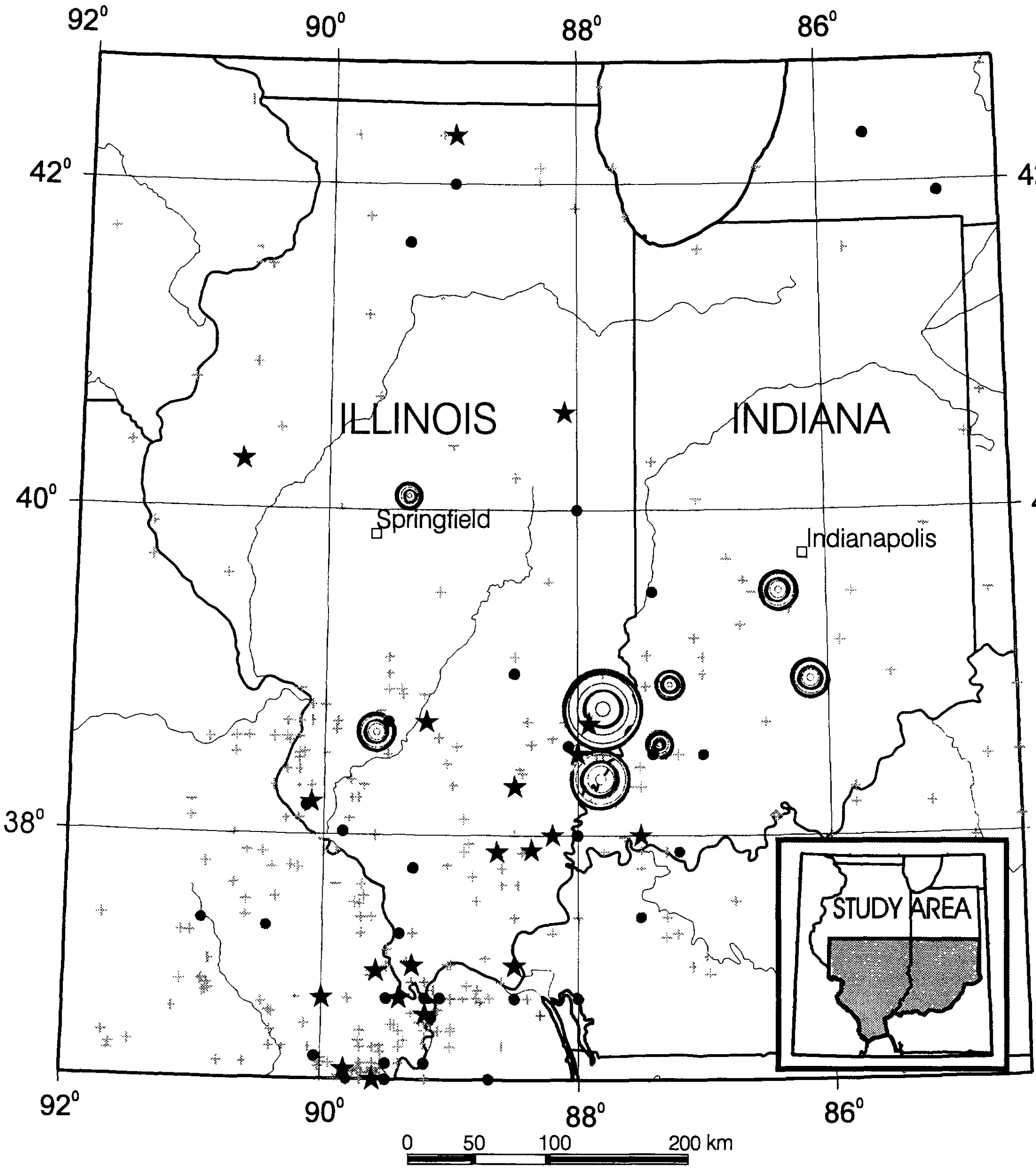


Figure 1. Epicenters of historic earthquakes in the study area for the time period 1804-1992. A star represents magnitude of 5 or higher. A solid circle represents magnitude between 4.5 and 5. Plus represents magnitude between about 2.3 and 4.5. Data from USGS/NEIC Global Hypocenter Data Base CD-ROM (Version 3.0).

Concentric circles show estimated epicenters of large prehistoric earthquakes. Diameters of the circles are scaled to indicate their moment magnitudes. Magnitude of largest paleo-earthquake was about M 7.5, and magnitude of the smallest shown was on the order of M 6 or higher. Liquefaction effects associated with the paleo-earthquakes are shown in Fig. 7. Prehistoric epicenters mainly from information in Munson and Munson (1996), Pond (1996), Hajic et al. (1995), Obermeier et al. (1993), and this report.

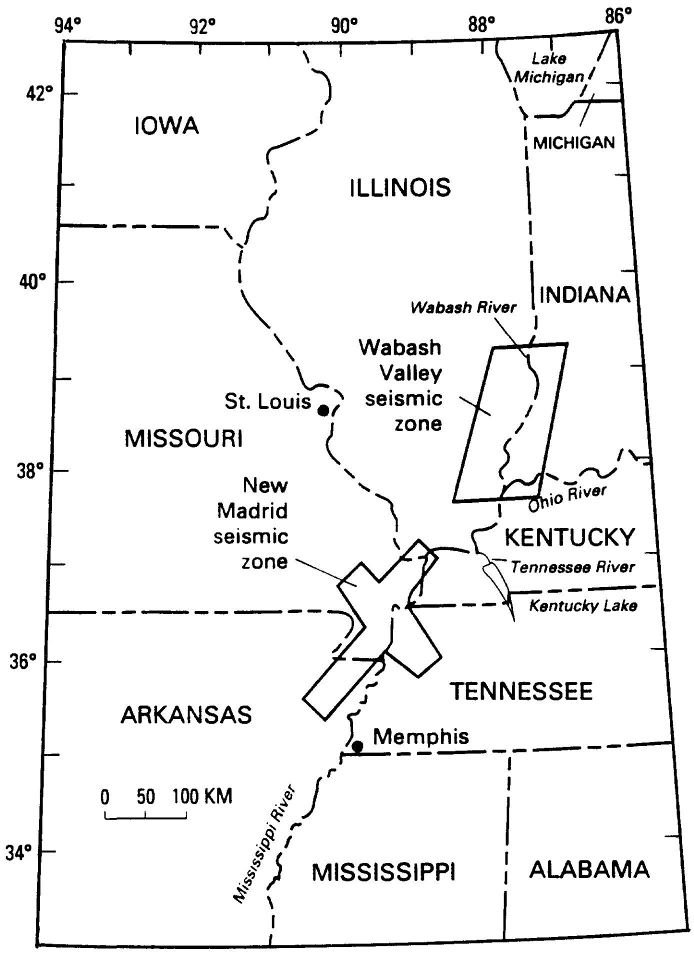


Figure 2. Approximate limits of New Madrid seismic zone and Wabash Valley seismic zone. New Madrid seismic zone is the source area of the 1811-12 earthquakes and continues to have many small earthquakes and some slightly damaging earthquakes. Wabash Valley seismic zone is a weakly defined zone of historic seismicity having infrequent small to slightly damaging earthquakes.

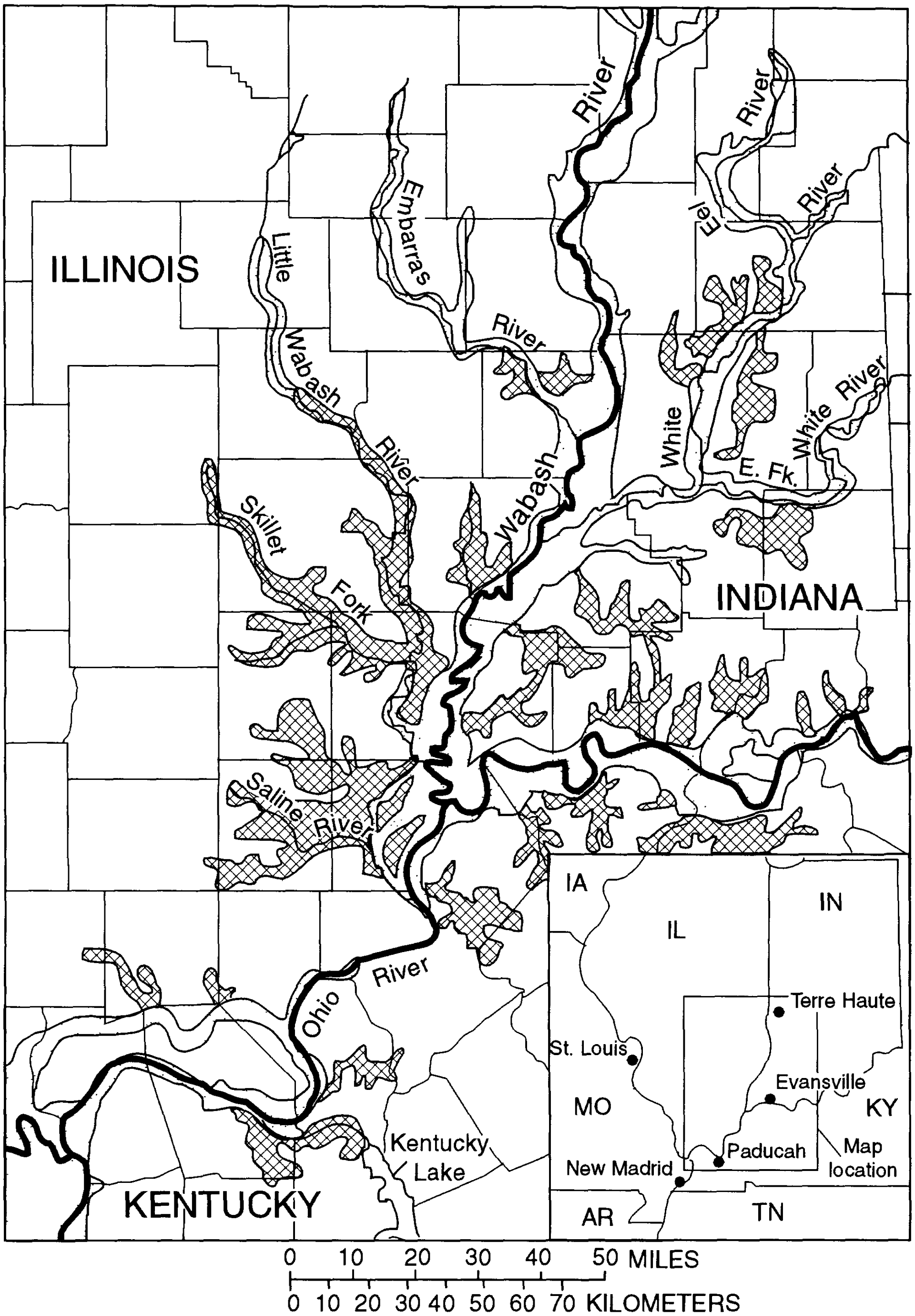


Figure 3. Generalized locations of major fluvial and slackwater deposits near the confluence of the Wabash and Ohio Rivers. Dotted areas show late Wisconsinan outwash sand and gravel, and Holocene alluvial sand and gravel with subordinate silt and clay. Shaded areas show late Wisconsinan slackwater deposits, mainly clay and silt, but locally sand. From Gray et al. (1991).

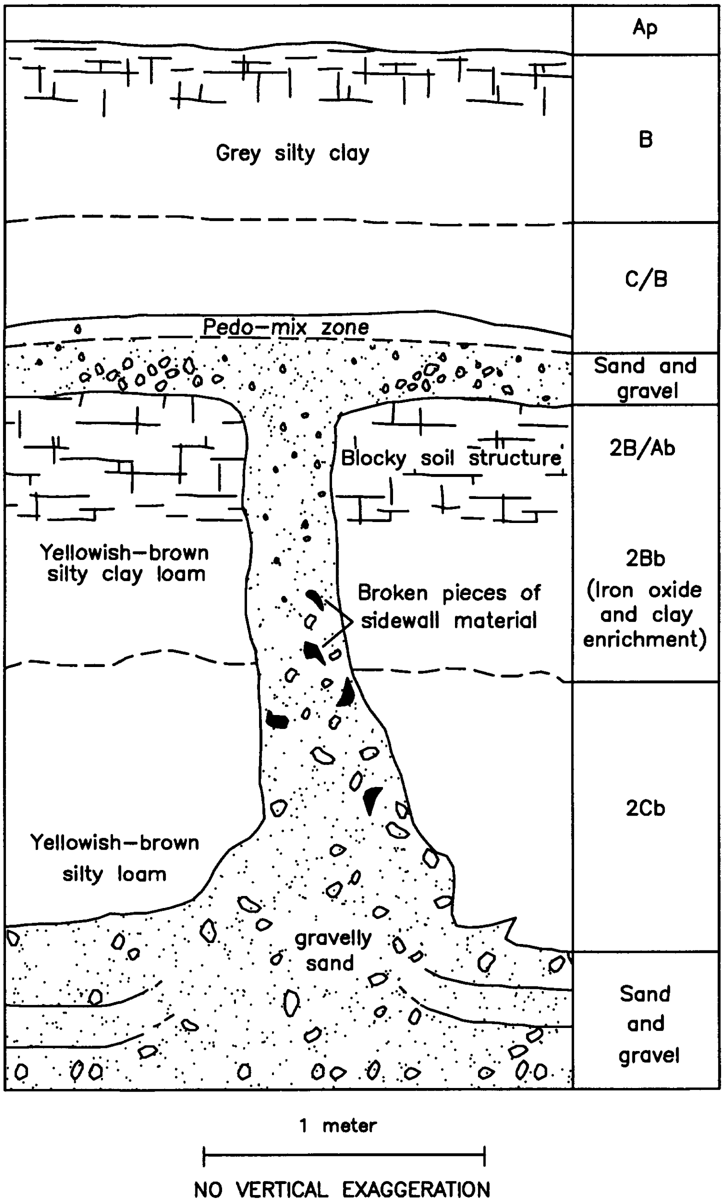


Figure 4. Diagrammatic vertical section showing the general characteristics of buried sand- and gravel-filled dikes with their vented sediments along the Wabash River. Source beds are Holocene point-bar deposits or late Wisconsinan braid-bar deposits overlain by fine-grained overbank sediment. The sediment in source beds directly beneath dikes shows evidence of flowage into dikes. In many dikes the gravel size and content decrease upward. The extreme upper part of a dike often is widened and shows evidence of ground shattering. The column on the right side of the figure contains pedological descriptions.

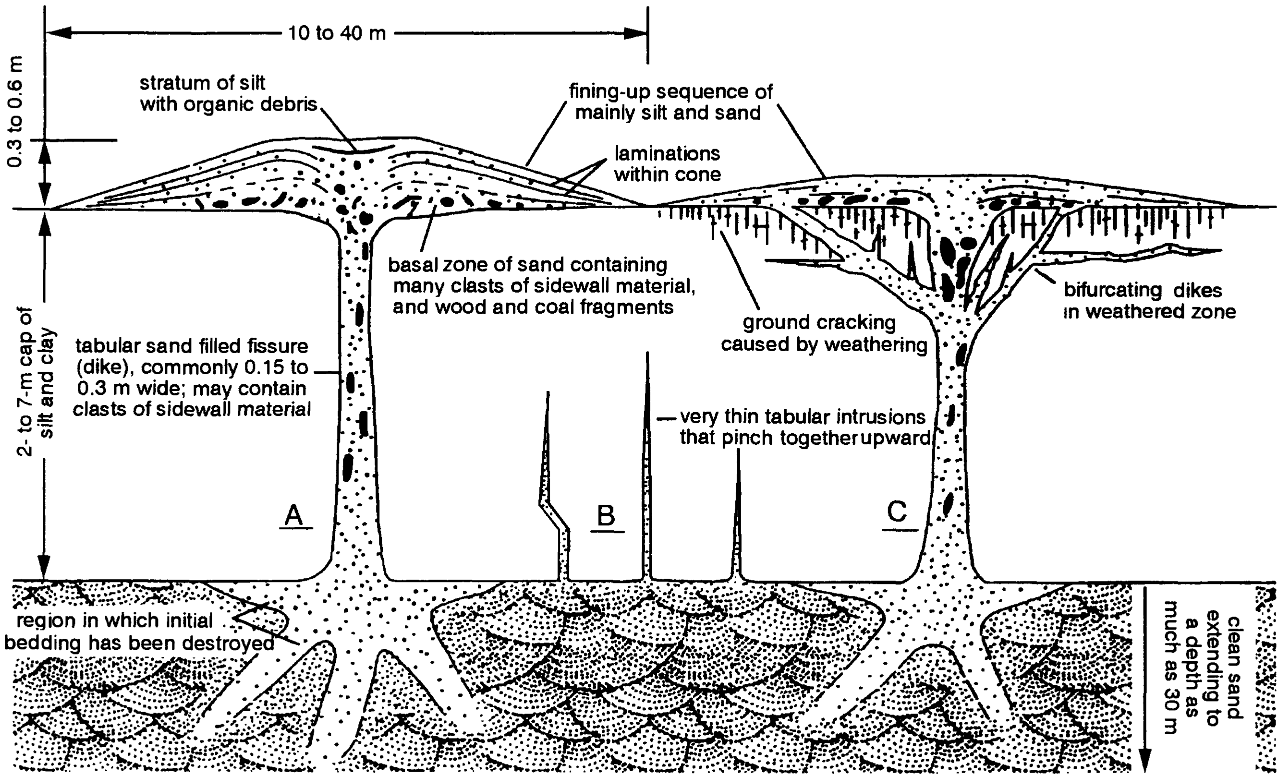


Figure 5. Schematic vertical section showing idealized dikes cutting through silt and clay strata and showing the overlying vented deposits, in the meizoseismal zone of the 1811-12 New Madrid earthquakes. Dikes shown are found in many places in the meizoseismal zone. A. Stratigraphy of dike with sediment vented to the surface. B. Dikes that pinch together as they ascend. C. Dike characteristics in fractured zone of weathering, in highly plastic clays.

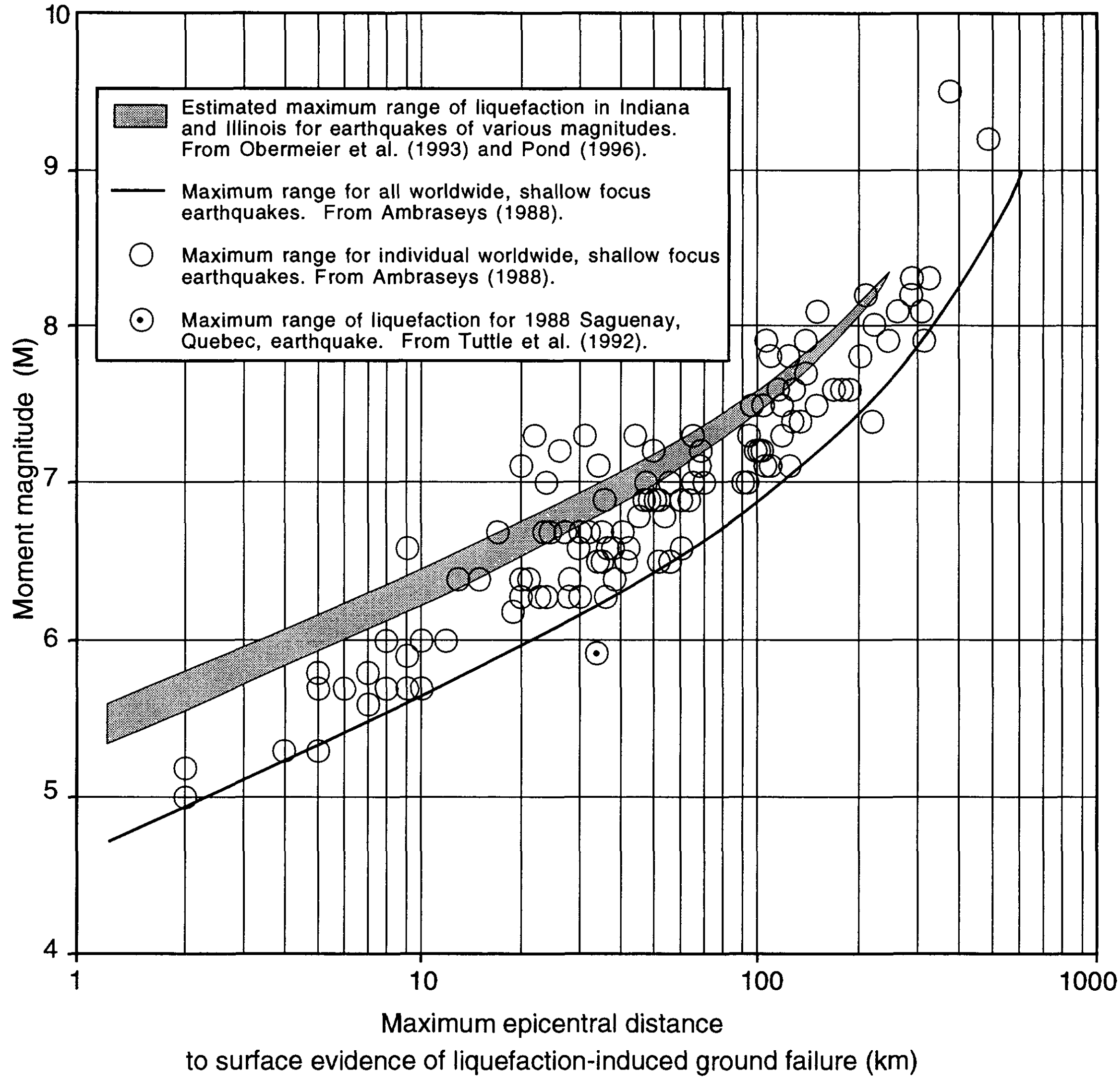
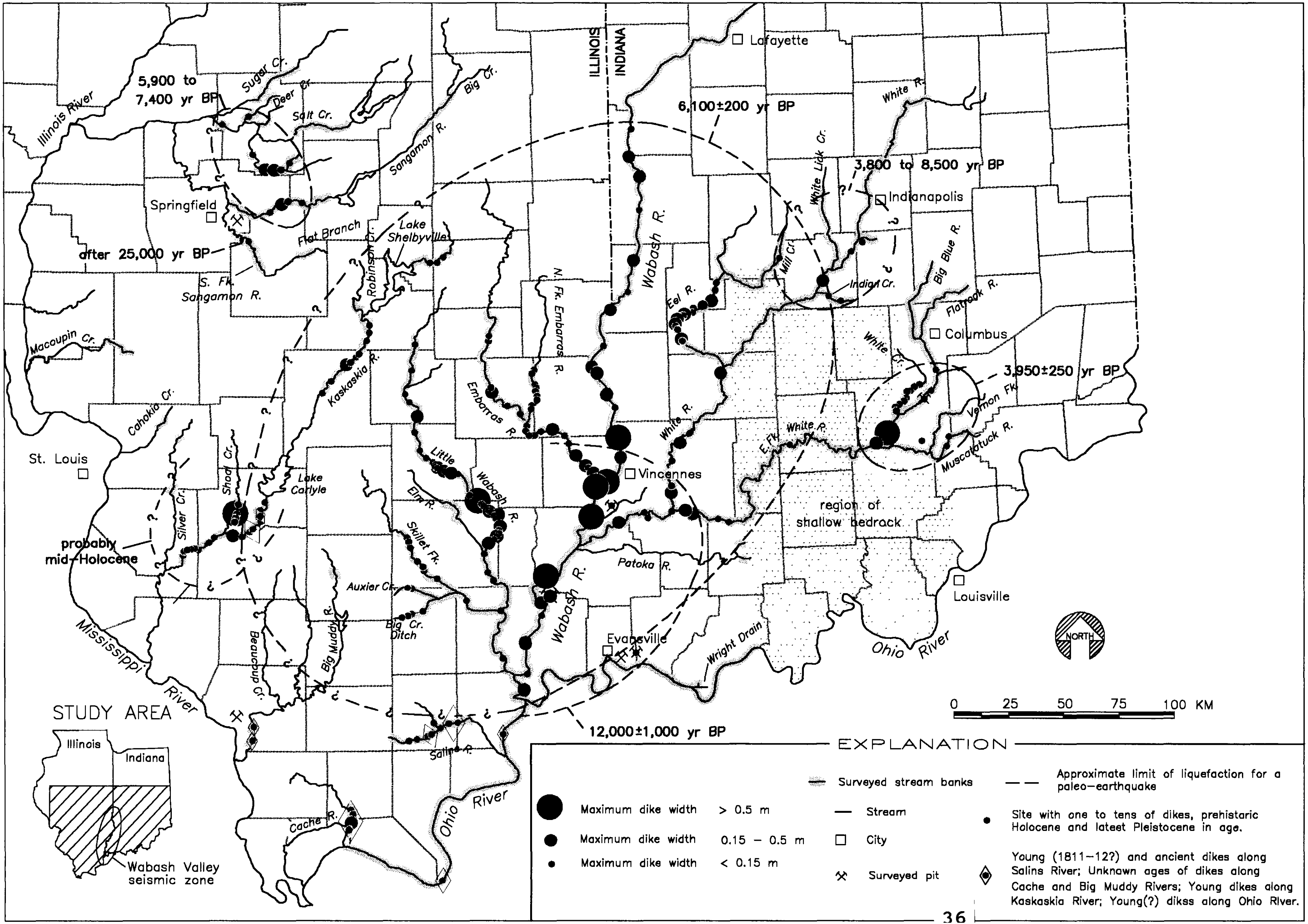


Figure 6. Relationship between moment magnitude versus maximum distance to surface evidence of liquefaction effects. Solid line (from Ambraseys, 1988) shows bound for data from worldwide, shallow focus earthquakes (<50 km). Darkened band shows relations developed for earthquakes in the study region. From Pond (1996) and Obermeier et al. (1993).

Figure 7. Overview showing locations of paleoliquefaction sites (darkened circles) in southern Indiana and Illinois. Maximum dike width at a site is indicated by diameter of solid circle. The survey of stream banks typically was done by using a boat for a continuous examination of the banks. In general, at least 10 percent of the length of the rivers searched had freshly eroded exposures. Only exceptionally were there no fresh exposures of mid-Holocene or older sediments within a 20-km length of a river, though at places there were no exposures for longer distances along the Wabash and Ohio Rivers. Liquefaction sites plotted on the map generally have at least several dikes, and many have tens of dikes. Dike width was measured at least 1 meter above the base of the dike. Maximum dike width at a site is indicated by diameter of solid circle. Liquefaction sites are bounded for specific earthquakes. Shaded area shows region of shallow bedrock with limited exposures of liquefiable sediments, where amplification of bedrock motions was probably very small, causing a much reduced likelihood for forming liquefaction features and later finding them. Figure modified from Munson et al. (1997).

Limits of liquefaction for separate earthquakes in Indiana based on data collected mainly by P.J. Munson, C.A. Munson, R.C. Garniewicz, and S.F. Obermeier, with interpretations shown by P.J. Munson. In Illinois, data were collected mainly by S.F. Obermeier, W.E. McNulty, P.J. Munson, R.C. Garniewicz, E.R. Hajic, M.P. Tuttle, and W.J. Su, with interpretations shown by S.F. Obermeier.

Figure 7.


ILLINOIS
INDIANA
Lafayette
Indianapolis
Springfield
Columbus
Vincennes
St. Louis
Louisville
Evansville
Illinois River
Sugar Cr.
Deer Cr.
Salt Cr.
Big Cr.
Sangamon R.
White R.
White Lick Cr.
Mill Cr.
Indian Cr.
Big Blue R.
Flatrock R.
White Cr.
Vernon Fk.
Muscatatuck R.
Flat Branch
Lake Shelbyville
Robinson Cr.
S. Fk. Sangamon R.
Macoupin Cr.
Kaskaskia R.
N. Fk. Embarras R.
Embarras R.
Wabash R.
Eel R.
White R.
E. Fk. White R.
Cahokia Cr.
Little Wabash R.
Elm R.
Skillet Fk.
Shoal Cr.
Silver Cr.
Lake Carlyle
Auxier Cr.
Big Cr. Ditch
Big Muddy R.
Beaucoup Cr.
Patoka R.
Wright Drain
Ohio River
Mississippi River
Saline R.
Cache R.
region of shallow bedrock
5,900 to 7,400 yr BP
6,100±200 yr BP
3,800 to 8,500 yr BP
after 25,000 yr BP
3,950±250 yr BP
probably mid-Holocene
12,000±1,000 yr BP
0 25 50 75 100 KM
NORTH
STUDY AREA
Illinois
Indiana
Wabash Valley seismic zone
EXPLANATION
Surveyed stream banks
Approximate limit of liquefaction for a paleo-earthquake
Maximum dike width > 0.5 m
Maximum dike width 0.15 – 0.5 m
Maximum dike width < 0.15 m
Stream
City
Surveyed pit
Site with one to tens of dikes, prehistoric Holocene and latest Pleistocene in age.
Young (1811–12?) and ancient dikes along Salins River; Unknown ages of dikes along Cache and Big Muddy Rivers; Young dikes along Kaskaskia River; Young(?) dikss along Ohio River.

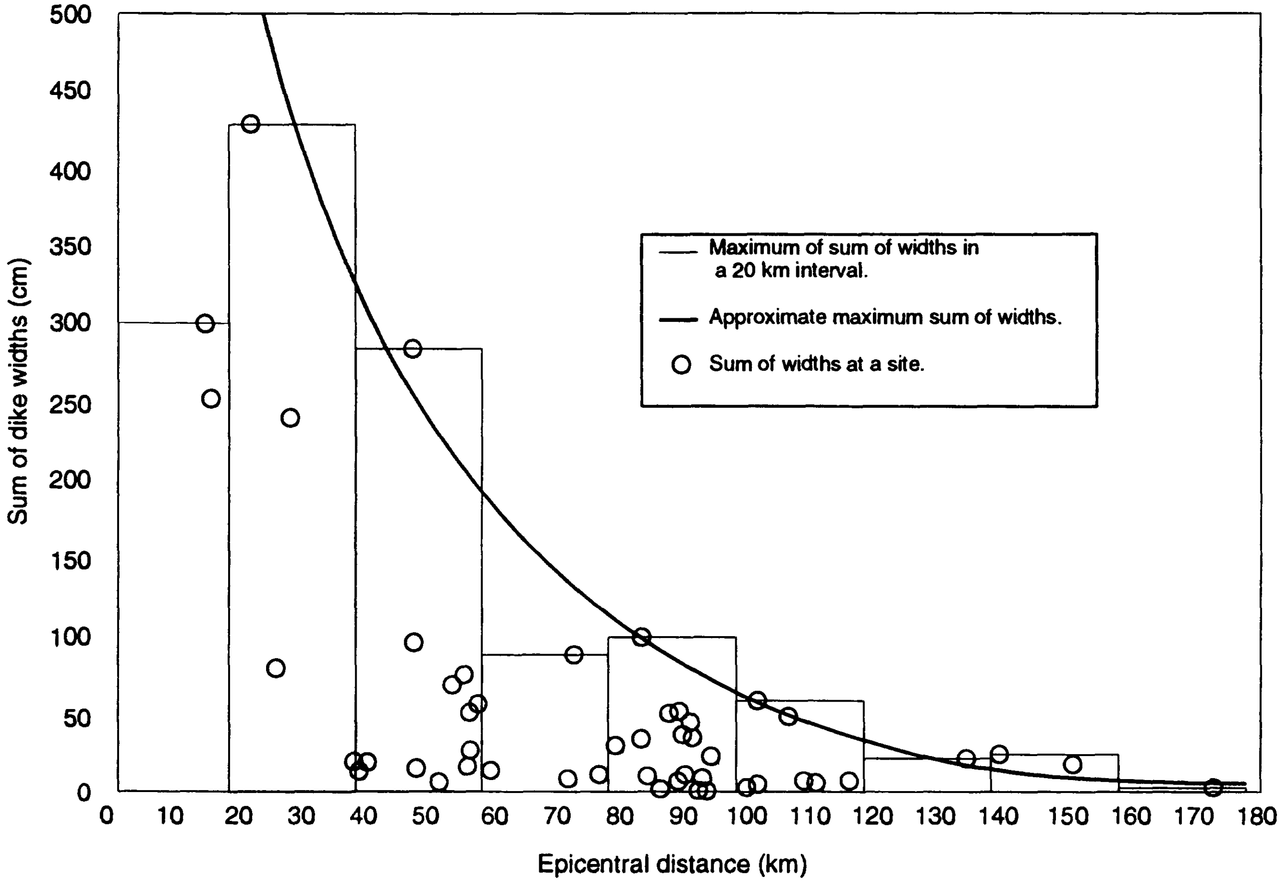


Figure 8. Dike widths versus epicentral distance for the earthquake of 6,100 yr BP. Widths shown are the sum of dike widths observed an individual liquefaction site, which has from one to many dikes. Data taken from all sites in Indiana as well as all sites along the Wabash River for an earthquake of this age. From Pond (1996, Fig. 6.2), modified from Munson and Munson (1996).

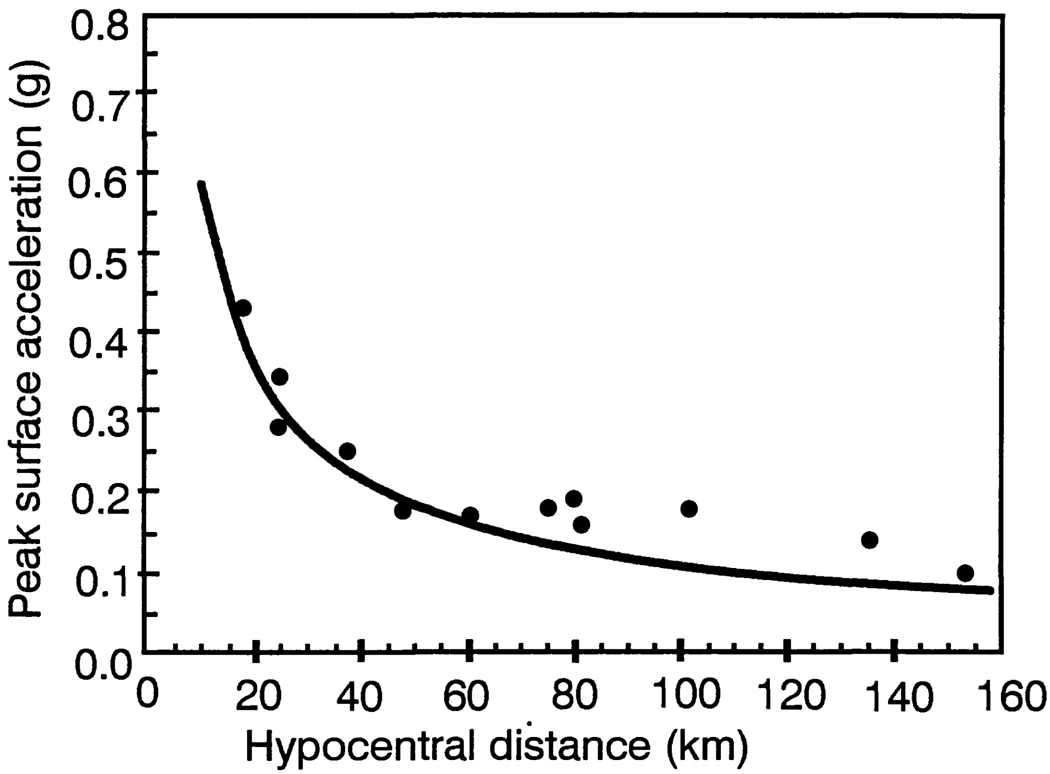


Figure 9. Back-calculated peak accelerations (solid dots) and theoretically calculated peak accelerations (solid line) as a function of hypocentral distance, for a M 7.5 earthquake. Bach-calculations were based on Standard Penetration Test data at sites of liquefaction. Theoretically derived curve from equations given by Boore and Joyner (1991) and from Atkinson and Boore (1995). From Pond (1996, Fig. 6.22).