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ENGINEERING GEOLOGY

Liquefaction evidence for strong earthquakes of Holocene and latest Pleistocene ages in the states of Indiana and Illinois, USA

S.F. Obermeier *

US Geological Survey, MS 955, 12201 Sunrise Valley Drive, Reston, VI 20192, USA

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Abstract

Sand- and gravel-filled clastic dikes of seismic liquefaction origin occur throughout much of southern Indiana and Illinois. Nearly all of these dikes originated from prehistoric earthquakes centered in the study area. In this area at least seven and probably eight strong prehistoric earthquakes have been documented as occurring during the Holocene, and at least one during the latest Pleistocene. The recognition of different earthquakes has been 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.

Most paleo-earthquakes presently recognized lie in Indiana, but equally as many may have occurred in Illinois. Studies in Illinois have not yet narrowly bracketed the age of clastic dikes at many sites, which sometimes causes uncertainty in defining the causative earthquake, but even in Illinois the largest paleo-earthquakes probably have been identified.

Prehistoric magnitudes were probably as high as about moment magnitude M 7.5. This greatly exceeds the largest historic earthquake of M 5.5 centered in Indiana or Illinois. The strongest paleo-earthquakes struck in the vicinity of the concentration of strongest historic seismicity. Elsewhere, paleo-earthquakes on the order of M 6–7 have occurred even where there has been little or no historic seismicity.

Both geologic and geotechnical methods of analysis have been essential for verification of seismic origin for the dikes and for back-calculating prehistoric magnitudes. Methods developed largely as part of this study should be of great value in unraveling the paleoseismic record elsewhere.

Keywords: Clastic dikes; Earthquakes; Liquefaction; Paleoseismicity; Soil mechanics

1. Background

Numerous small-to-moderate earthquakes have occurred sporadically in the states of Indiana and Illinois throughout the historic record of 200 years (Fig. 1). These earthquakes, plus the proximity to the great New Madrid earthquakes of 1811–1812 (Fig. 2), and the suggestion that the tectonic setting for triggering those great earthquakes extends northward into Indiana and Illinois (Sexton, 1988), prompted me to initiate a field search for paleoliquefaction evidence of large earthquakes. 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.,

* Corresponding author. e-mail: sobermei@usgs.gov

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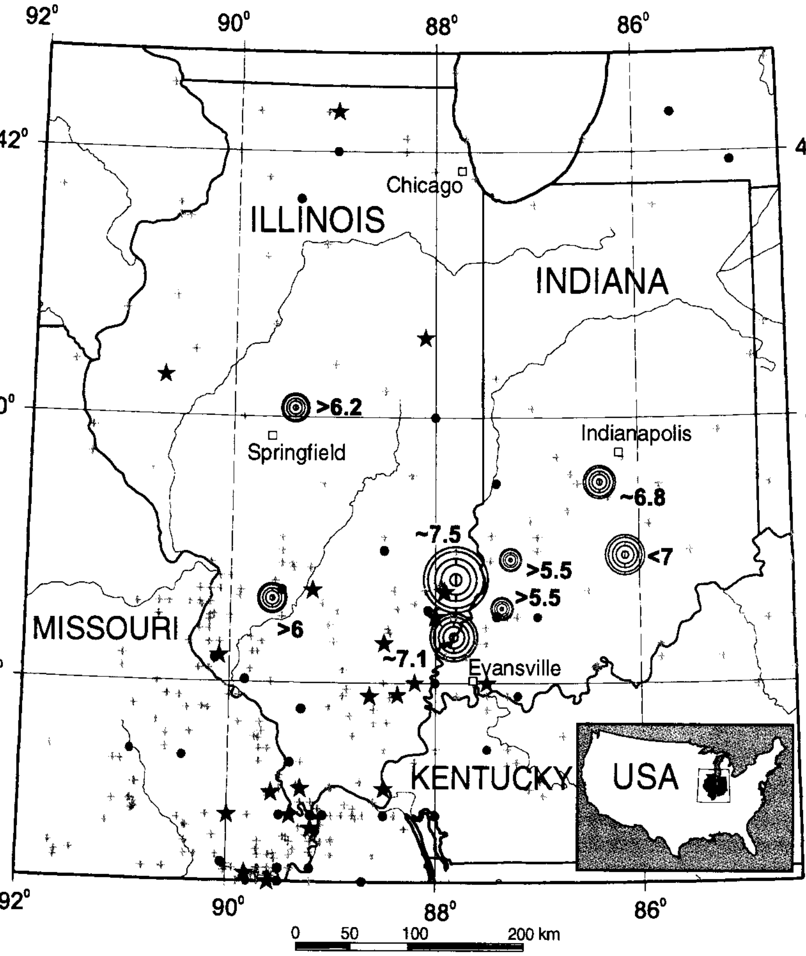

Fig. 1. Concentric circles showing estimated locations of energy sources (i.e. energy centers) for large prehistoric earthquakes. The estimated moment magnitude, M, for a prehistoric earthquake is located by the circle. Sites of liquefaction associated with the paleo-earthquakes are shown in Fig. 4. Prehistoric energy sources are mainly from Munson et al. (1997), Pond (1996), Obermeier (1997), and McNulty and Obermeier (1997). Epicenters of historic earthquakes are shown for the time period 1804–1992. A star represents magnitude of 5 or higher. A solid circle represents magnitude between 4.5 and 5. The plus symbol represents magnitude between about 2.3 and 4.5. Historic epicenters are from US Geological Survey/NEIC Global Hypocenter Data Base CD-ROM (Version 3.0). States of Illinois and Indiana are located in the outline of the conterminous states of the USA.

1991). The search area then was extended beyond the Wabash Valley and now includes most of southern Indiana and Illinois. Results of the early studies are discussed by Munson et al. (1992) and Obermeier et al. (1993).

The ages and regional extent of liquefaction for the paleo-earthquakes in Indiana have been established primarily by Munson and Munson (1996). Geotechnical engineering studies to assess the magnitude and attenuation characteristics of the largest paleo-earthquakes in Indiana were done by Pond (1996). In Illinois, searches mainly by myself, 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. Results of early studies 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). Munson et al. (1997) summa-

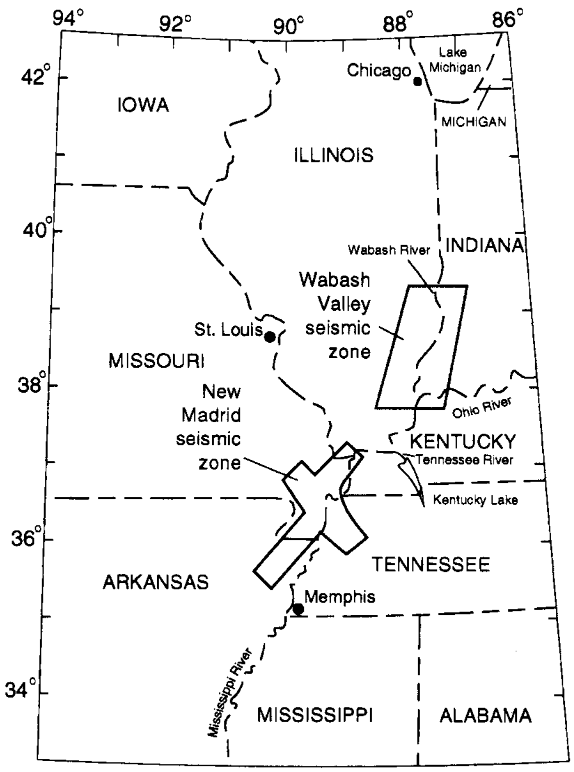

Fig. 2. Approximate limits of New Madrid seismic zone and Wabash Valley seismic zone. New Madrid seismic zone is the source area of the great New Madrid, Missouri, 1811–1812 earthquakes; the region continues to have many small earthquakes and some slightly damaging earthquakes. Wabash Valley seismic zone is a weakly defined zone of historic seismicity having infrequent small to slightly damaging earthquakes.

rized the results of studies in both Indiana and Illinois, as of early 1996. Subsequent field work and data collected by myself and W.E. McNulty greatly advanced understanding of the paleoseismic record in Illinois (McNulty and Obermeier, 1997; Obermeier, 1997).

The purpose of this report is to present current results for Indiana and Illinois, and equally to show how these results accord with geologic and geotechnical understanding of the liquefaction process. Discussion of the geotechnical connection 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. Importance and relevance of the geotechnical tie-in deserves to be more widely appreciated. This paper and another by Obermeier and Pond (1998) address many current technical issues in using liquefaction features for paleoseismic analysis.

2. Overview of geologic-liquefaction setting

I believe that conditions favorable for liquefaction have been generally adequate to provide evidence of any very large earthquakes (say, $M > 7$, as will be shown later) through almost all of the Holocene period, on the basis that the very large regions shaken by such a strong earthquake should have encompassed some sites favorable for liquefaction. Smaller earthquakes, between about M 6 and 7, may not have affected areas large enough in some places to have left behind liquefaction evidence. Only very exceptionally could earthquakes less than $M \sim 6$ be expected to have left behind liquefaction evidence.

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 is generally 10–30 m thick. 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 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 2–5 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), which were laid down in slackwater areas during glaciofluvial alluviation, mainly in latest Wisconsinan time. Such slackwater

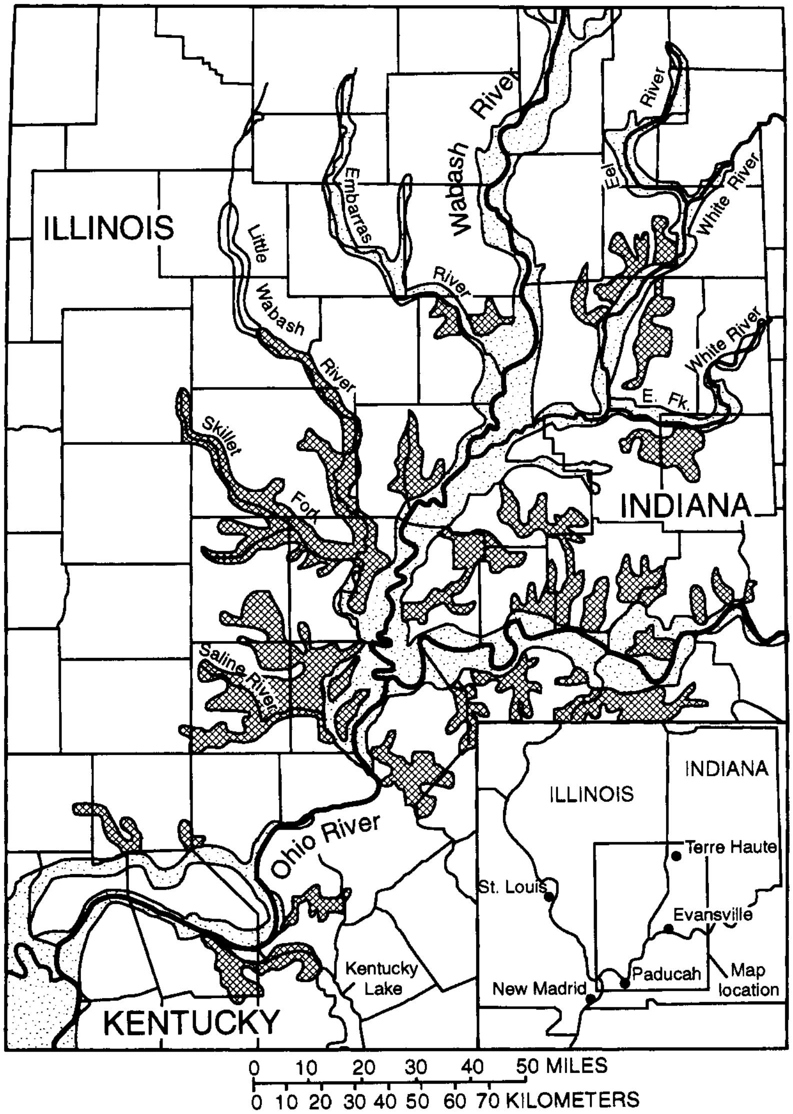

Fig. 3. Generalized locations of major fluvial and slackwater deposits near the confluence of the Wabash and Ohio Rivers. Dotted areas show late Wisconsinan outwash sand and gravel, as well as Holocene alluvial sand and gravel with subordinate silt and clay. Cross-hatched areas show late Wisconsinan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

deposits are widespread in southernmost Indiana and Illinois (Fig. 3).

Because in many regions the water table has periodically been relatively deep (say, greater than 5 m), the paleoliquefaction record is doubtlessly an incomplete record of seismic shaking. Formation of seismically induced liquefaction features that can be recognized during the field search 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. A water-table depth on the order of 5 m can greatly restrict or prevent liquefaction except where ground shaking is exceptionally severe (see

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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 of the water table, even during prolonged dry spells. The thick profiles were imposed chiefly during the early to middle Holocene, when the climate was generally warmer and drier than at present (Knox, 1983). (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) reflects a much shallower water table. Even now, though, during prolonged dry spells, the water table is 5 m deep along many streams.

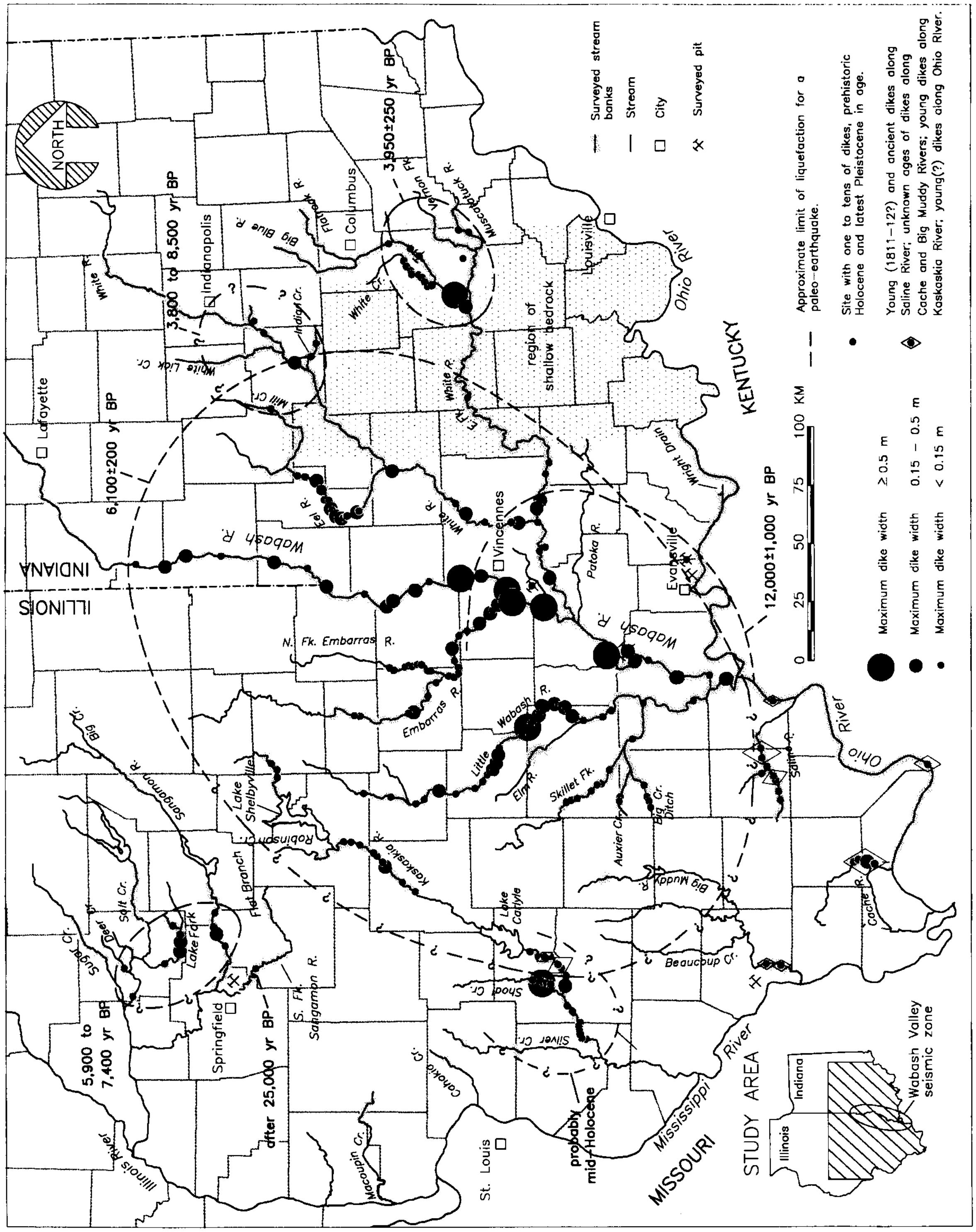
Despite generally deep water tables in hypsithermic time, special areas having shallow water tables persisted locally, making it still possible for liquefaction to occur and leave field evidence. These special field areas are indicated by exceptionally thin weathering profiles overlying completely unoxidized sediments. A typical field situation where a high water table persisted is in a wide valley underlain by thick granular deposits, in which the valley is drained by a small, underfit stream. Such relations occur especially 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 in valleys of very large rivers. Such is the Ohio River valley, which commonly is a very wide valley in which ancient underfit streams have persisted. A special effort was made to search the banks of such underfit streams for paleoliquefaction features.

The search methodology has been to do field examination of the banks of streams, and, to a small extent, ditches and sand and gravel pits. The opportunity to find liquefaction features during the search is thought to be adequate for delineation of all of the stronger Holocene paleo-earthquakes (say, $M>7$). Most of the intermediate to larger streams (e.g. Wabash River, White River, Embarras River, Kaskaskia River; see Fig. 4) had multitudes of bank exposures, typically revealing deposits ranging in age from the mid-Holocene (about 5000 years old) to nearly modern. Only exceptionally were there sections of river banks as long as 10–20 km that had no exposures at least as old as mid-Holocene. Many of these exposures had lengths of 100–200 m and much longer. Exposures also were generally adequate to delineate the liquefaction effects from any very strong earthquakes (say, $M>7$) that occurred as much as 6000–7000 years ago. Exposures with deposits of early Holocene age were much less abundant. In a few instances, however, deposits were found that likely have been susceptible to liquefaction for much of the past 20 000 years.

3. Origin of seismic liquefaction features in a fine-grained cap

Multitudes of sites with dikes have been discovered in the study area (Fig. 4). More than a thousand dikes were found. The discussion following summarizes how liquefaction features, namely dikes, form in a fine-grained cap such as typically occurs 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) and Obermeier and Pond (1998).

Seismic liquefaction and shaking cause dikes to originate chiefly from three 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 pore-water pressure in the liquefied sediment, which fractures 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 also cause parallel, tabular clastic dikes to develop 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



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The three mechanisms noted earlier mainly produce 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 origin of suspected seismic liquefaction features has been presented by Obermeier (1996). Applying these criteria 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 1811–1812 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 for the dikes, such as artesian conditions or landsliding, are not plausible. Application of these criteria follows.

4. 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 Fig. 5, which shows a dike that formed 6100 yr BP. The sand and gravel vented onto a ground surface that is now buried by more than 1 m 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. The grain size of the coarser material becomes finer upward within the dike. The 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 centimeters 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.

4.1. Comparison with liquefaction effects of the 1811–1812 new madrid earthquakes.

The wider dikes in Indiana and Illinois, exceeding about 15 cm in width, are similar to those associated with lateral spreading that formed a few hundred kilometers south during the great 1811–1812 New Madrid 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.

Fig. 4. 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 using a boat for continuous examination of the banks. In general, at least 10% of the lengths of the rivers 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, although 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 sites have tens of dikes. Dike width was measured at least 1 m above the base of the dike. Liquefaction sites are bounded for specific earthquakes. Shaded areas show regions 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. Ages are radiocarbon years (uncalibrated yr BP). Figure modified from Munson et al. (1997).

Limits of liquefaction for separate earthquakes in Indiana are based on data collected mainly by P.J. Munson, C.A. Munson, R.C. Garniewicz and S.F. Obermeier. Interpretations shown in Indiana are chiefly 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. Interpretations shown in Illinois are chiefly by S.F. Obermeier.

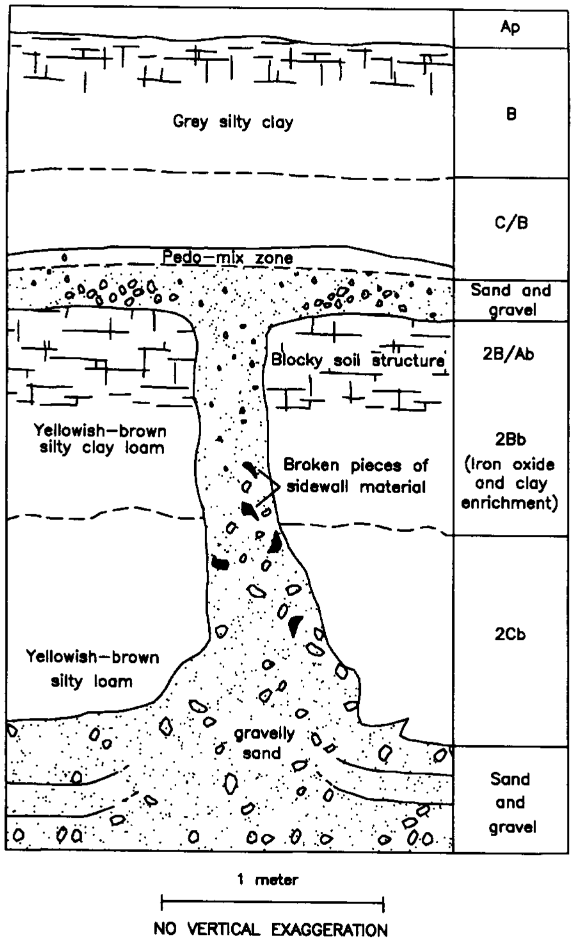


Fig. 5. Diagrammatic vertical section showing the general characteristics of buried sand- and gravel-filled dikes with their vented sediments along the Wabash River. Source beds are Holocene point-bar deposits or late Wisconsinan braid-bar deposits, which are overlain by fine-grained overbank sediment. 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 abbreviations.

Sketches and descriptions of wide dikes in the New Madrid region can be found in Obermeier (1996).

Much more common than wide dikes 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. 6) that formed during the 1811–1812 New Madrid earthquakes. Fig. 6 illustrates typical dikes found in a clay-rich cap in the 1811–1812 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; this difference can be explained because of the absence of gravel in the liquefied source beds in the New Madrid region.

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 1811–1812 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 1811–1812 New Madrid earthquakes, but those of other earthquakes as well. Well-documented worldwide examples of liquefaction effects in fine-grained caps have been 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). Both overall and detailed morphologies are similar for features in the study area and those in the examples cited above. 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 to those from earthquakes elsewhere, other possible origins, mainly nonseismic landslides or artesian conditions, are considered below.

4.2. Presence of core region

A test for seismic origin on a regional scale consists of using dike width to determine whether

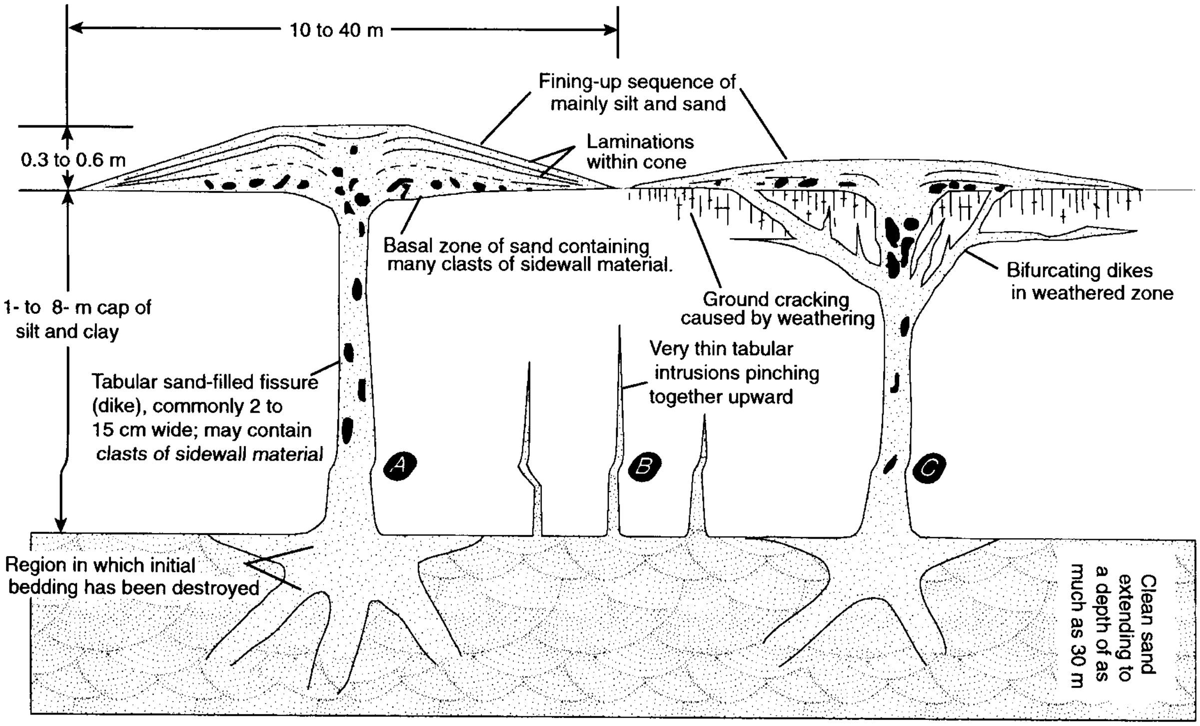


Fig. 6. Schematic vertical section showing idealized dikes cutting through a host of silt and clay strata, and also showing the overlying vented deposits. The relations shown are very commonly observed in the meizoseismal zone of the great 1811–1812 New Madrid earthquakes. All dikes are tabular in plan view, whether or not they vented to the surface. Width of a dike can much exceed the value of 15 cm shown in the figure, at sites of severe lateral spreading. (A) Stratigraphy of dike with sediment vented to the surface; (B) dikes that pinch together as they ascend; and (C) dike characteristics in fractured zone of weathering, in highly plastic clays. Schematic depictions of the influence of depth of burial and weathering on prehistoric dikes in the study area are shown in Obermeier et al. (1993), Fig. 5.

there is a central core region of largest (i.e. widest) 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 has been 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 (i.e. the location of strongest seismic shaking), providing that 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 to satisfactorily define 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 distance from the meizoseismal zone. A core region can be seen in Fig. 4 for many of the paleo-earthquakes.

A major advantage of using dike width for paleoseismic analysis 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 encountered in areas 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, however, is that dike development caused by 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 (however, the influence of this strength is as yet unknown).

4.3. Characteristics of pattern and scale, and their role in exclusion of nonseismic origins

The dikes in the study area also exhibit relationships that are characteristic of seismic liquefaction on a local scale (hundreds of meters). Munson and Munson (1996) reported that the clastic dikes in Indiana are typically 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 myself in the study area and in other geographic regions of known seismicity (New Madrid seismic zone and coastal Oregon; see Obermeier, 1996), show that in areas of low to moderate strength of seismic shaking 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.

Where very strong shaking has taken place, field observations from historic earthquakes show that it is not unusual that dikes caused by lateral spreading develop much further inland; for example, in the meizoseismal zone of the 1811–1812 New Madrid earthquakes, dikes from lateral spreading extend inland more than a kilometer at many places (Obermeier and Pond, 1998). Similarly, in the core region of the larger paleoearthquakes in the study area, and where backcalculations show that the strength of shaking was very high (Pond, 1996), dikes from laterally moving ground formed as far as many hundreds of meters from any stream banks.

The character of ground failure associated with dikes in the study area also accords with the geotechnical understanding of lateral spreading from seismic liquefaction. The observation that dikes caused by lateral spreading often do not extend far away from stream banks indicates that the shaking threshold for lateral spreading is often somewhat lower than for other dike-forming mechanisms. This lower threshold generally applies for loose to moderately compact sands and gravelly sands. 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 an $(N_1)_{60}$ value of less than 15–20 (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 15–20 have been noted by Seed et al. (1985), pp. 1440–1441); more recently, Bartlett and Youd (1995) reported a threshold of 15 for earthquakes of magnitude M less than 8. The threshold, however, is probably only slightly lower for lateral spreading than for the other mechanisms of liquefaction-related ground failure because all require significant pore-pressure buildup, and the rate of buildup during seismic shaking is very abrupt for loose to moderately compact sands (e.g. Seed et al., 1985, Fig. 8).

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 a paleoseismic study by Pond (1996) indicates the possibility of values higher than 20 providing seismic shaking has been very strong, although Pond's interpretation may be the result of densification of the source bed as a result of liquefaction. The ease at which lateral spreads form relative to other liquefaction features at high $(N_1)_{60}$ values is still an issue to be resolved within the geotechnical community. Still, at the great majority of places in the study area, lateral spreads should form more readily than dikes from other liquefaction-related mechanisms — as was observed to be true in the field search (e.g. Pond, 1996).

The location of dikes in relation to the local topography can also provide important evidence in elimination of nonseismic origins. Whereas sites of lateral spreading are generally restricted to being close to a topographic low or slope, dikes from hydraulic fracturing are normally 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 landslides are restricted to being relatively near slopes.

Tabular dikes are relatively common in glacial slackwater deposits in the study area, especially in south-eastern Illinois. The slackwater deposits are flat-lying throughout large areas, and the dike sites are far removed (hundreds to thousands of meters) from any significant stream banks or other sloping topography that ever occurred 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 that were caused by great floods. In 1993, a great flood along the Mississippi River caused numerous landslides along the river. US Army Corps of Engineers personnel (St Louis, Missouri, written comm, 1994), who have jurisdiction over slope stability problems along the Mississippi River, reported that the slides were exclusively rotational slumps. They did not observe horizontal movements without vertical displacement of the ground surface, in contrast to the movements associated with the dikes interpreted to be of paleoliquefaction origin. In addition, the Corps of Engineers personnel did not observe any clastic dikes that formed in association with the rotational slumps, but only narrow ground cracks along the heads of the slumps.

Not all large landslides that have been observed in the study area are primarily slumps, however. Infrequent large landslides have been observed to 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 very large rivers have cut deeply (likely ten meters or much more), thereby removing support at the toes of the slides, at the bases of the banks. The slides then move into the river. However, features such as dikes, and especially dikes that vent large quantities of sand and gravel such as shown in Fig. 5, have not been observed in association with these slowly moving slides.

Additional rationale to reject the nonseismic landslides described above as causing the dikes include: (1) some dike sites are located above sandstone bedrock (Pond, 1996); (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 high pore-water pressure, and the only plausible mechanism for such a high water pressure in many field settings is from seismic liquefaction.

Artesian conditions as the cause for dike formation has 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 numerous 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 have been discussed by Li et al. (1996). Artesian conditions have also been rejected as a cause 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 of the sites are far removed from upland areas or other topographic situations that could have caused high pressures.

Yet another argument for a seismic origin of the great majority of the tabular dikes is that the distribution of dikes is not random in time or space, as would be expected if the dikes had originated from some types of nonseismic mechanisms. In addition, no dikes were found throughout some very large searched regions.

In summation, neither landsliding nor a huge flood, 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 shows that virtually all the dikes must have a seismic liquefaction origin.

5. Estimation of magnitudes of prehistoric earthquakes — methodology

Two methods have been used to estimate the magnitudes of the prehistoric earthquakes. One method (Fig. 7) uses the radius from the source of the seismic energy (i.e. the center of the strongest seismic shaking, which in the study area is generally the center of the core region of widest dikes) to the furthest dike that was discovered for the prehistoric earthquake (Obermeier et al., 1993). 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). [Details of how historic observations were used to develop this curve for the study area (see Fig. 7) are given in Obermeier et al. (1993), Pond (1996), and Obermeier and Pond (1998).] Use of the curve developed from these historic observations for paleoseismic analysis is referred to as the magnitude-bound method. The method is based mainly on a conceptual study by Youd and Perkins (1978), supplemented with

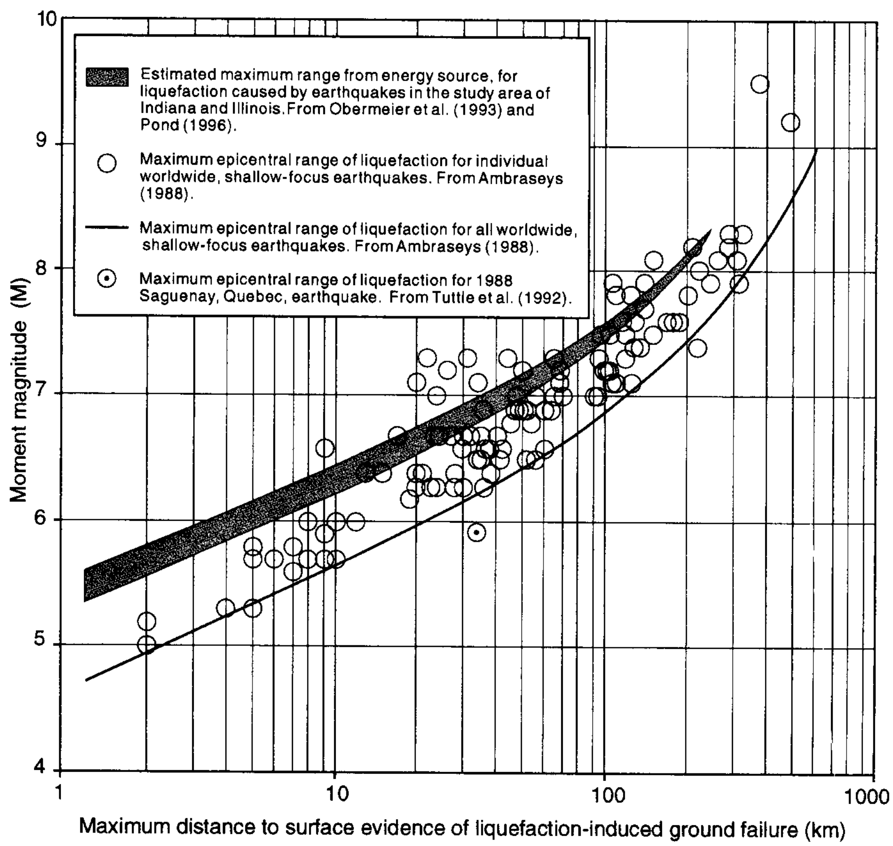


Fig. 7. Moment magnitude versus maximum distance to surface evidence of liquefaction effects. Solid line shows bound for maximum epicentral distance of liquefaction features, for worldwide, shallow-focus earthquakes (<50 km). Darkened band shows maximum distance (plan view) from energy source (i.e. energy center) for earthquakes in the study region, which was developed from the study of historic earthquakes in Indiana and Illinois and in the nearby New Madrid seismic zone (Fig. 2).

data from worldwide earthquakes (Ambraseys, 1988).

The second method for estimating magnitude is an energy-based solution that was recently developed by Pond (1996). The premise of the method is that seismic energy at a site relates to the susceptibility to liquefaction there, with the susceptibility being characterized in terms of SPT $(N_1)_{60}$ values (Berrill and Davis, 1985; Law et al., 1990). To use the energy-based method of Pond requires first making a crude estimate of the magnitude of the paleo-earthquake, as well as the location of its energy source. These estimates are used to determine the amount of seismic energy that was available at a field site of liquefaction (actually, at a site of lateral spreading). This value of energy is then used in combination with SPT blow-count measurements at the liquefaction site, in order to determine the portion that should have liquefied. Next, SPT $(N_1)_{60}$ values from the liquefied zone are used with the method of Seed et al. (1983, 1985) for back-calculation of the peak acceleration at the site. The procedure is repeated at other sites of liquefaction, located at various distances from the presumed energy source. Finally, the curve of accelerations, defined by the back-calculations at various distances from the energy source, is compared with the curve predicted from seismologic modeling. Magnitude of the paleo-earthquake is selected as that which yields the best fit between the modeling and the back-calculated curves.

Only a cursory description of Pond's method has been given above, because the logic is relatively complicated and is not intuitively obvious (the interested reader should refer to Pond (1996), pp. 241–250). Pond (1996) has tested the method, with very good results, by application to 11 sites from four historic earthquakes. Still, because of the limited verification of the method, assessment of magnitude probably should be viewed as somewhat tentative without corroboration from another technique such as the magnitude-bound method; even with corroboration, some questions persist because of the uncertain influence of seismic parameters that are discussed in a later section.

The largest paleo-earthquake in the study area, the earthquake of 6100 yr BP, has also been analyzed using the Seed et al. (1983, 1985) procedure. This procedure is generally suitable only for establishing a lower bound of acceleration at a site, and thus can establish only a lower bound of earthquake magnitude. Pond (1996), Fig. 6.13) found this minimum to be between M 7 and 7.5. The energy-acceleration method yielded M 7.8, and the magnitude-bound method yielded M 7.7.

5.1. *Influence of depth to water table*

Back-calculated accelerations using Pond's method depend strongly on the water-table depth, because of the effect of the water pressure on the value of $(N_1)_{60}$. 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. The base of the dike is taken as coincident with the bottom of the fine-grained cap (Fig. 6). 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, because the excess pore-water pressure induced by liquefaction at greater depth dissipates within the permeable sand above the water table. Interpretation of water-table depth also requires estimation of 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. However, sand blows generally are sparse, which causes additional uncertainty in interpretation. Still, the depth to the water table can be estimated within a few meters at most places in the study area, by observing the bases of the dikes.

The influence of water-table depth does not seem to strongly affect interpretation of magnitude from the magnitude-bound method, as shown by the finding that the magnitudes of the paleo-earthquakes using the magnitude-bound method almost coincide with magnitudes obtained from the energy-acceleration method (discussed later). The reason for this apparent lack of strong dependence on water-table depth can likely be explained by the fact that even if the water table was quite deep at most places (say, 5 m or so) when an earthquake struck, there would almost certainly have been numerous areas relatively nearby (within a few tens of kilometers) where the water table was much shallower and the susceptibility to liquefaction was relatively high. Thus, for the larger paleo-earthquakes (M greater than 6.5–7), the radius of strong shaking would probably have been large enough to encompass many sites susceptible to liquefaction, even during dry periods.

5.2. *Confidence in interpretation of magnitude*

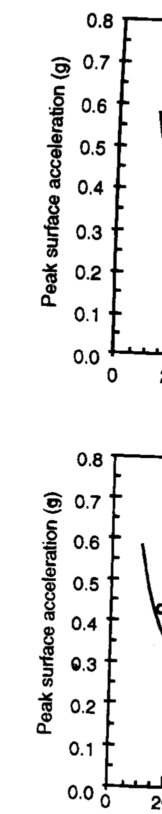
Confidence in interpretation of magnitude using the magnitude-bound method requires some assurance that distal liquefaction effects of a paleo-earthquake have been located. The energy-based method of Pond likewise requires identification of liquefaction sites over a significant portion of the range from the energy source 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, especially at distal sites where liquefaction effects are widely scattered, is subjective. In the study region, on the average, the limit of earthquake effects is considered to be indicated by an absence of features within in a length of a few tens of kilometers, along a stream with numerous exposures of potentially liquefiable deposits. Alternatively, only several kilometers may suffice where conditions for forming and preserving liquefaction features are deemed to have been exceptionally good, although the practice during the study has been to search many more kilometers in most areas.

The most confidence in interpretation of magnitude arises when the two methods yield the same value. Pond (1996) has shown that back-calculated accelerations from his energy-based method agree quite well with seismological predictions by Boore and Joyner (1991) and Atkinson and Boore (1995), which are based on average behavior of small historic earthquakes in the central and eastern US. The match Pond found between prediction and back-calculation was especially good for the earthquake of 6100 yr BP (Fig. 8), for which both paleoliquefaction data and geotechnical test data are most complete and are relatively thorough. Pond found the best fit to be M 7.8 for the earthquake of 6100 yr BP, with the fit getting significantly poorer for as little as 0.2–0.3 magnitude units higher and lower (Fig. 8). As noted previously, the estimate for this earthquake using the magnitude-bound method was M 7.7. Pond also evaluated the magnitudes of three smaller paleo-earthquakes in Indiana and found them to be of M 7.3, M 7.1 and M 6.9 using the energy-based method, and using the magnitude-bound method found them to be, respectively, M 7.2, M 6.9 and M 6.8. Thus the agreement between the two methods was remarkably good.

Even for this remarkable agreement, though, there is some uncertainty because both methods for estimating magnitude may depend similarly on the seismic parameter of stress drop. Stress drop influences peak acceleration, with a higher stress drop causing higher acceleration (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 could possibly cause too high an estimate of magnitude based on liquefaction effects. This possibility has not been rigorously evaluated, however, even from a theoretical basis. The influence of these parameters may be shown by the effects of liquefaction from the 1988, Saguenay, Quebec, earthquake, which appears to have had both a very high stress drop and a relatively deep focal depth (28 km) — as have some of the stronger earthquakes in the Illinois study area (Hanks and Johnston, 1992, p. 11). Fig. 7 illustrates that the M 5.9 Saguenay earthquake caused liquefaction features to develop as far as 33 km from the epicenter. This distance exceeds that of any other earthquake of comparable magnitude, worldwide. It should be noted, though, that this exceptionally large distance may be due in part to an extraordinary effort by Tuttle et al. (1992) to locate the most distal effects.

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



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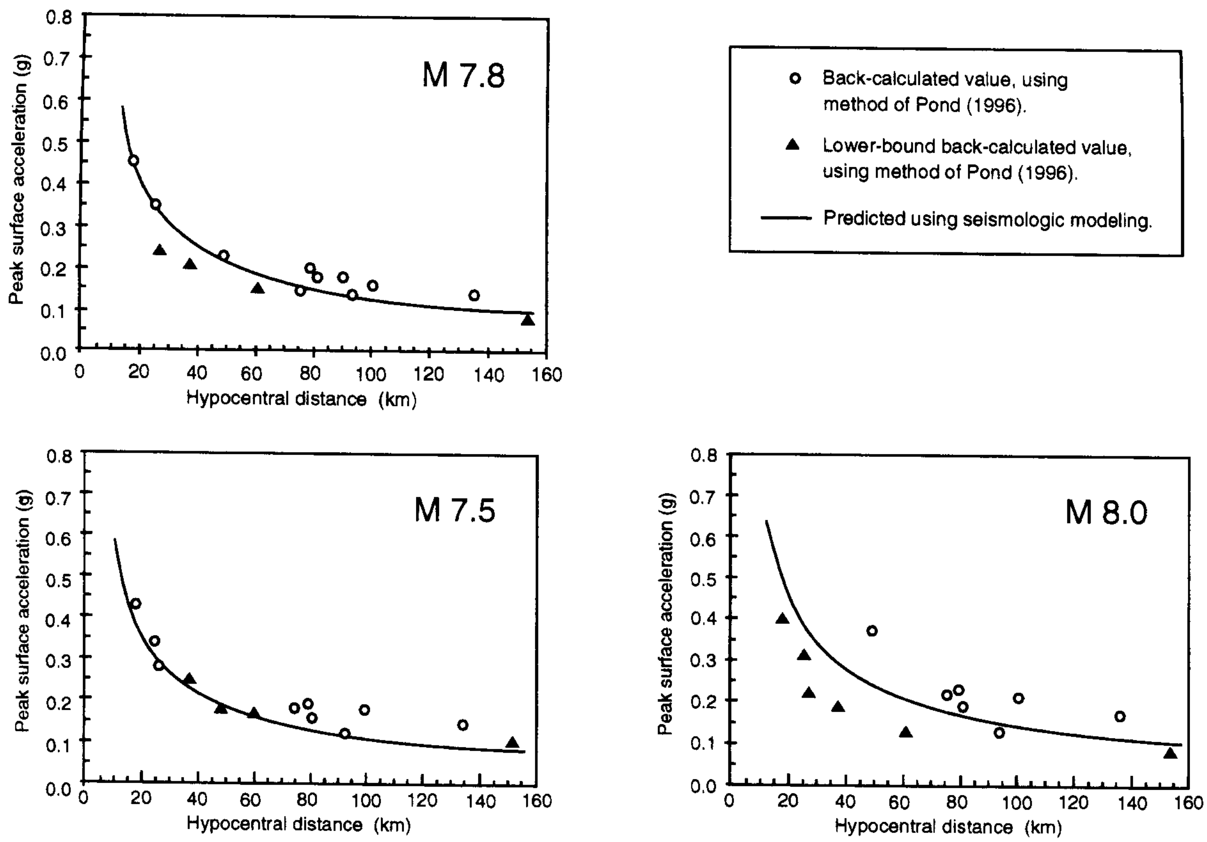

Fig. 8. Peak accelerations as a function of hypocentral distance, for M 7.5, M 7.8 and M 8.0 earthquakes in the study area. Peak accelerations determined from back-calculation (open dots) and seismological modeling (solid line). Back-calculations were performed using the energy-based method of Pond (1996) at sites of liquefaction for the earthquake of 6100 yr BP. Curves that are based on modeling are from relations developed by Boore and Joyner (1991) and by Atkinson and Boore (1995). The best fit between back-calculated and modeled accelerations is for a M 7.8 earthquake. From Pond (1996), Fig. 6.22.

the influence of shorter duration is probably at least partly offset by the higher acceleration. Possibly the energy-based method of Pond automatically circumvents the problem of unknown stress drop, because 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.

Regardless of actual magnitudes of the paleo-earthquakes, they are probably best though of as equivalent in destructive potential to the back-calculated magnitudes that were determined using the magnitude-bound method (Obermeier et al., 1993) and the energy-based method (Pond, 1996), incorporating the assumptions about stress drop and other seismic parameters implicit in these methods. This equivalence in destructive potential is, after all, of primary relevance in hazard assessment.

6. Geologic field study

The geologic part of the field study had three parts. One was to locate the features; the second was to characterize the site in terms of sizes of dikes and their locations in relation to the local topographic-geologic setting; and the third was to collect data to bracket the time when the features formed. Almost all features were located by searching banks of streams, and, to a much lesser extent, the walls of sand and gravel pits. None of the paleoliquefaction features in Indiana and Illinois was visible on aerial photos or other remote sensing images, owing to their age, burial by alluviation, or severity of weathering.

Locating the features has involved searching where a fine-grained cap, 1–10 m in thickness, overlies thick sands that have been saturated for long periods of time, preferably thousands of years. Prolonged saturation is inferred 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). A map by Soller (1997) at a scale of 1:1 000 000 was especially valuable because it showed both thickness and general character of the alluvial deposits (i.e. mainly granular or mainly fine-grained).

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

Normally the ages of the paleoliquefaction features could be bracketed only within a few thousand to several thousand years, although at some sites dating narrowed the formation of dikes to within a few hundred (radiocarbon) years. A summary of procedures for dating the paleoliquefaction evidence has been given by Munson and Munson (1996). Three dating methods have been used: radiocarbon, archeology and regional stratigraphy. 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 have been 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 firepits for hearths and earth ovens used by prehistoric native Americans. Carbonized nutshells and wood are often plentiful in the firepits, and have been especially useful.

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

Artifacts of prehistoric native Americans have been used to bracket when many liquefaction features formed. Projectile points and pottery shards have been used most often. Relatively narrow age ranges were often determined. Most styles of projectile points manufactured before 4000 yr BP can be assigned age ranges of ±500–1000 years, and those made after 4000 yr BP have ranges of ±200–500 years. Pottery, which first appeared in the region about 2700 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. Holocene-latest Pleistocene formations (mapped by Wayne (1963) and by Willman and Frye (1970)) are easily recognized at most places in the field. Subdivision of these formations into different "members," deposited several thousand years apart, has been important in the paleoliquefaction studies. 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 the strength of soil development (B-horizon, color and compactness) in deposits that comprise the terrace.

7. Results of paleoliquefaction studies

The map in Fig. 4 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 occur at many sites. The exposure length at a liquefaction site ranges from a few meters to as much as 4 km. The figure also shows the maximum dike width at a site.

Almost all of the sites in Fig. 4 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 New Madrid earthquakes of 1811–1812.

Limits of liquefaction are shown in Fig. 4 for only the six 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 limited number of detailed site studies that were available to bracket ages, and the lack of geotechnical studies.

Ages of individual dikes are not distinguished in Fig. 4. The bound of liquefaction for all earthquakes encompasses many dikes of the same age. Even though ages of dikes are not shown, it is apparent that the largest dikes associated with many paleo-earthquakes lie well within the limits of the bound, thereby defining a core region of largest dikes. It also is 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 6100 yr BP.

Fig. 4 also shows that large areas (unsurveyed stream banks and areas between the surveyed streams) 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 by as much as 75 km. Thus, even a paleo-earthquake as strong as $M \sim 6.5$–7 (see Fig. 7) could have struck but left no liquefaction evidence. Results of the paleoliquefaction studies are given below, first for Indiana and then for Illinois.

7.1. Results in Indiana

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

The largest paleo-earthquake in Indiana ($M \sim 7.5$), which occurred about 6,100 yr BP, was centered approximately 25 km west of Vincennes (Fig. 4). Liquefaction effects from that earthquake extend as far as 150 km from the inferred energy source. The range of these effects is believed to have been controlled by a single very large earthquake, mainly because the maximum dike sizes attenuate systematically away from the inferred energy source. Fig. 9 shows results for the earthquake where the widths are summarized along the total length of the bank exposures (with each exposure being a site in Fig. 4), but a similar plot for the widest individual dike at the exposure shows the same clearcut trend (Munson and Munson, 1996; Pond, 1996). In a similar vein, geotechnical analysis indicates a systematic attenuation of peak acceleration away from the inferred energy source, in which the acceleration agrees reasonably well with predictions by seismologists for a M 7.5 or slightly higher event (Pond, 1996), as shown in Fig. 8.

The next-strongest event occurred about $12\,000 \pm 1000$ yr BP, was likely centered about 40 km south-west of Vincennes (Fig. 4), and probably was of $M \sim 7.1$ or slightly higher (Munson and Munson, 1996; Pond, 1996). Effects in Indiana extend about 50–60 km from the inferred energy source. All liquefaction features associated with this earthquake lie in deposits that have an age of 14 000–10 500 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 2–3 m above terraces 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 6100 yr BP (Munson and Munson, 1996). Yet the liquefaction events are separable, largely because the fea-

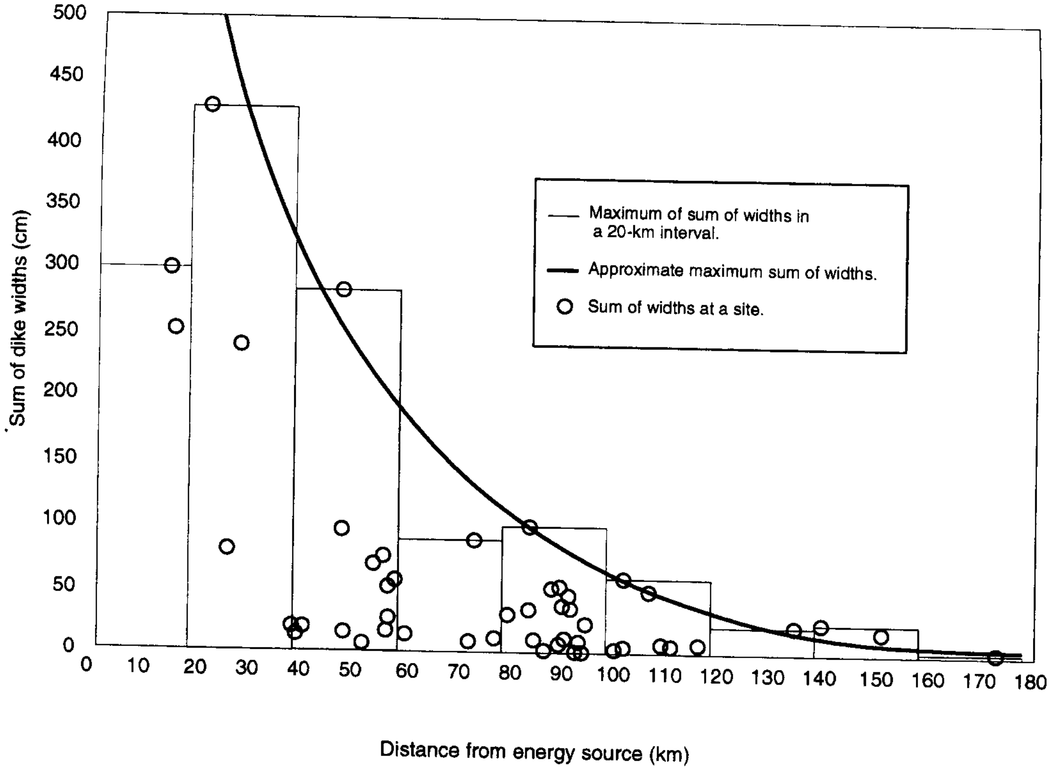

Fig. 9. Dike widths versus distance from the energy source (i.e. energy center) for the earthquake of 6100 yr BP. Widths shown are the sum of dike widths observed in a bank exposure, in which the exposure has from one to many dikes. Data are from all sites in Indiana, and from sites in Illinois along the Wabash River. From Pond (1996), Fig. 6.2; modified from Munson and Munson (1996).

tures 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. 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 3–5 m) when the earthquake of 6100 yr BP struck (Pond, 1996).

The next-largest event was centered about 100 km east of the Wabash Valley seismic zone (Fig. 4). 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). 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 8500 and 3500 yr BP. The energy source region is suspected to be about 30 km south-west of Indianapolis (Fig. 4). Both the timing of the earthquake and the location of the energy source region are poorly constrained because of the small number of exposures with liquefiable sediment. The skewed distribution of effects from south-west to north-east 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 reasonably be associated with the $M \sim 7.5$ event of 6100 yr BP, centered near Vincennes (Fig. 4)(Pond, 1996). As with the earthquake of 3950 yr BP, the earthquake near Indianapolis took place in an area of only very small and infrequent historic earthquakes (Fig. 1).

A considerably smaller event took place 4000 ± 500 yr BP, about 35 km south-east of Vincennes. Evidence for this event occurs at only one site (site not specified on Fig. 4), where two small dikes extend less than 0.5 m 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 areal distribution (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 Fig. 7 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 energy source may have been tens of kilometers from any liquefiable deposits. Even a relatively small increase in distance would much increase the estimated magnitude.

Small dikes that formed 2000 ± 500 yr BP are found at a single site about 60 km east-north-east of Vincennes (site not specified on Fig. 4). Effects of this earthquake are likely of very limited areal extent according to Munson and Munson (1996), suggesting occurrence of an earthquake marginally capable of producing liquefaction, but with a magnitude of at least $M \sim 5.5$.

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-south-west of Indianapolis (site not specified on Fig. 4). No other exposures of liquefiable deposits of similar age were found in Indiana, making it impossible to estimate the magnitude of the earthquake.

Almost all work in the Ohio River Valley was done by myself. 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). Fig. 4 shows that in and near Evansville only small dikes have been found. Dikes were observed at only one site in the vicinity, in a pit that appears 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. 4). This lower terrace is interpreted to be at least several thousand years to mid-Holocene in age on the basis of the thickness of weathering in the fine-grained cap on the terrace, as well as by radiocarbon dates from deposits in the nearby younger, lower flood plain. The relatively shallow depth of weathering (<3 m) in the 3–4 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 evidence for major liquefaction effects in the pits near Evansville is consistent with the similar lack of evidence in banks of the Ohio River along the Indiana–Kentucky and Illinois–Kentucky borders, downstream to at least the Saline River (Fig. 4). Ages of searched bank exposures near Evansville are on the order of at least 4000–5000 yr BP at many scattered places, 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 5–6 m) at many places that it may have restricted development of dikes from penetrating up to levels now observable along the river. Before large 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 deepest. 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 thick, even where shaking from a $M \sim 6$–6.5 earthquake almost certainly was not extraordinarily strong and the water table was 3–4 m deep. Therefore, near Evansville, the lack of liquefaction features indicates that very strong shaking is unlikely for at least the past 4000–5000 years.

Not far upstream from Evansville (about 35 km) 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. 4) revealed glacial valley-train sediments of Cary age (late Wisconsinan) in which a 3–4 m fine-grained cap overlies thick 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 of the year. 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 and 14 000 yr BP (Ray, 1965). Any large liquefaction features would have been discernible in these Cary-age deposits. But, small features may not have been evident at many places because of the severe weathering of the cap.

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 3–5 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, in not most, of the past 20 000 years.

7.2. *Results in Illinois*

Liquefaction features from the $M \sim 7.5$ earthquake of 6100 yr BP, with inferred energy source about 25 km west of Vincennes, should extend far west into Illinois (Fig. 4). Data reported by Hajic et al. (1995) and collected by myself, show a concentration of dikes, especially of larger sizes, along the Little Wabash River in Illinois about 50–60 km west-south-west of Vincennes. Radiocarbon data that I have taken to supplement regional stratigraphic observations along the Little Wabash and its tributaries, show that the dikes are at least largely, if not almost exclusively, in sediments old enough to host the event of 6100 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 1–2 m. Clay in the Bt horizon completely fills voids between sand grains, throughout much of the horizon. Such development of the Bt horizon shows considerable antiquity, which I believe is consistent with an age of 6100 yr BP. Younger liquefiable deposits abound, yet appear almost devoid of dikes. Thus it is likely that the great majority of the dikes in the vicinity of the Little Wabash River can be assigned to the earthquake of 6100 yr BP. In addition, my field studies showed that most of the features along the Embarras and its tributaries were likely induced by that earthquake.

My field studies also showed that many of the dikes as far west as the Kaskaskia River likely were induced by the earthquake of 6100 yr BP. Probably most of the liquefaction features along the Kaskaskia, upstream from Lake Carlyle, were caused by this earthquake. This is true because of the lack of other candidates as source areas that were uncovered in the search. Dikes here are thought to be strong candidates for the earthquake of 6100 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 energy source of the paleo-earthquake. 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.

The south-western limit for the earthquake of 6100 yr BP is shown as extending south of Lake

Carlyle. Any dikes from that earthquake are almost certainly small. The basis for placing the limit this far to the south-west is that the radiocarbon age of the fine-grained cap at one liquefaction site is very close to 6100 yr BP. It is entirely possible the limit extends further to the south-west. 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 6100 yr BP.

Dikes from the earthquake of 12 000 yr BP must extend far west into Illinois (Fig. 4). Only very 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 Embarras River with its North Fork. However, 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 is unknown and may not be possible to determine because of the lack of suitable sites. Virtually all of the dikes cutting the slackwater sites are very thin (1–2 cm) throughout their heights and pinch together in caps that typically exceed 3–6 m in thickness.

There is a conspicuous absence of dikes along the Elm River (Fig. 4), even though numerous dikes, some very large, are nearby. This absence of dikes along the Elm River is probably explained by an exceptionally thick cap of slackwater deposits and an overall lack of suitable exposures.

Relatively thick (5–6 m) caps in slackwater deposits are cut nearly through by dikes at many sites along the Saline River. Lateral spreading is not plausible at many of these sites, because the 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 caps cut by dikes, without lateral spreading, suggests the possibility of very strong shaking. 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 (Ray, 1965, pp. 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 1811–1812, whose energy sources were about 200 km to the south-west 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 commonly occur within large dikes of much greater age along the Little Wabash River, at least in the portion of the river at which a dike was found that exceeds 0.5 m in width (Fig. 4) 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 to the large dikes (which probably were induced by the earthquake of 6100 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 have been 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).

A moderate earthquake struck in central Illinois between 5900 and 7400 yr BP (McNulty and Obermeier, 1997). The largest dike (37 cm wide) from this event is located on Lake Fork, about 35 km north-east of Springfield (Fig. 4). The areal extent of liquefaction due to this earthquake 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 (Fig. 4). Altogether, there are many exposures of liquefiable sediment in the region whose ages slightly to greatly exceed the time 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 high positions 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 a maximum radial development as far as 30 km from the energy source location (disregarding the site with small dikes on the South Fork of the Sangamon, for reasons discussed later). The limited radial development, with a high water table, indicates that the magnitude was not especially high. Use of Fig. 7 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, $M \sim 6.7$. The influence of the high water table may have been partly offset by the shallow depth to bedrock that generally prevails in the region. This shallow depth would have permitted little or no amplification of bedrock shaking. Geotechnical testing will be required to make a more accurate estimate. Whatever the magnitude, a significant prehistoric earthquake took place in a region that has undergone virtually no historic earthquakes (Fig. 1).

Many exposures along the South Fork of the Sangamon reveal severely weathered deposits, with frost polygons, indicating early Holocene-late Pleistocene ages. 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. The radiocarbon age of the material comprising the mat is 25 240 ± 240 yr BP. The mat must have been decomposed when the dikes intruded. The site having 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 centered north-east of Springfield, the paucity of dikes along the South Fork suggests that the shaking from that earthquake could not have been very strong along the South Fork.

Another earthquake probably was centered in the vicinity of the lower Kaskaskia River (McNulty and Obermeier, 1997), with an energy source near Shoal Creek (Fig. 4). The largest dikes and their host (the fine-grained cap) sediments are strongly weathered, both having strong, thick (>2 m) Bt horizon development, thereby indicating that the dikes are of early to middle Holocene age. Radiocarbon data suggest that the earthquake took place about 6500–7000 yr BP, although it may have been even younger. Possibly the earthquake was as young as 6100 yr BP, the age of the M 7.5 event centered near Vincennes, but a 0.5 m-wide 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 energy source to the 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 potential host of sufficient age along Shoal Creek has dikes, even though the exposures are quite limited in length. Such an abundance of dikes is typically limited to energy source (meizoseismal) regions, where shaking has been quite strong. Liquefaction susceptibility and amplification of bedrock shaking have also been considered in assigning an energy source to the Shoal Creek region.

The southernmost bound for the 6500–7000 yr BP event at Shoal Creek has been drawn relatively close to the southern limit of the searched portion of the Kaskaskia River, even though Fig. 4 indicates a high density of sites with small dikes in that part of the Kaskaskia. The high density of sites there is an artifact of the method of presenting data in the figure, caused by the extraordinary amount of bank exposures along this portion of the Kaskaskia. Clean bank exposures are almost continuous throughout the lowermost 20 km or so of the searched part of the Kaskaskia. Exposures are at least three or four times more abundant than further upstream, which greatly enhanced the opportunity to find liquefaction features along the lowermost searched portion.

No liquefaction features were discovered northwest of the liquefaction sites on Shoal Creek (Fig. 4). Along Silver Creek (Fig. 4) are numerous exposures old enough to record an earthquake of about 6500–7000 yr BP. Bridge borings indicated that liquefiable sands likely underlie these sediments, although all sand-bearing deposits beneath the cap encountered by hand auguring were rich in clay and silt. Thus, extremely strong shaking probably would have been required to have induced liquefaction.

Regional field evidence also supports the notion that the dikes along the lower Kaskaskia River were not caused by a large earthquake whose energy source was further south. The dikes along the lower Kaskaskia are within 200 km of the New Madrid seismic zone (Fig. 2). This proximity might cause one to suspect that 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 River (Fig. 4) is situated ideally to intercept strong seismic shaking between the lower Kaskaskia River 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, University of Maryland, oral comm., 1996) and stratigraphic index red beds that are at least as old as earliest Holocene time (E.R. Hajic, Jackson Hole, Wyoming, oral comm., 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 River indicates strongly that the source region for the features along the lower Kaskaskia River 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 River search area are small dikes that cut host sediments probably less than a thousand years old. Some of these very young dikes may have been caused by the 1811–1812 New Madrid earthquakes. According to Professor Otto Nuttli (St Louis University, written comm., 1985), an observation at the time of the 1811–1812 earthquakes reported small sand blows in the Cahokia region, across the Mississippi River from St Louis (Fig. 1 and 4), which is considerably north of the lower Kaskaskia.

Liquefaction features have also been discovered along the Cache River in southernmost Illinois (Fig. 4) (Tuttle et al., 1996). Most of the features are small dikes, less than 3–4 cm wide. A dike at one site was at least moderate in size and possibly large. Some of the dikes may be prehistoric. Host sediments are thick sands that were laid down by an ancestral Ohio River before 8000 yr BP (Esling et al., 1995). Between 12 500 and 8000 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 ancestral Ohio River because the valley is wide, long, and is drained only by the Cache River, which is a small, lethargic stream traversing large swampy areas.

Fig. 4 indicates that dike sites are relatively common along the Cache River. Some or most of the dikes here may have been induced by the 1811–1812 New Madrid earthquakes, whose energy source region was relatively nearby, and thus the abundance and size of liquefaction effects along the Cache is not surprising. 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 1811–1812 earthquakes.

Fig. 4 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 bank exposures. Still, a few very good, widely spaced exposures do occur. Long, clean exposures, as much as 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 4500 yr BP in age, but the sand in the dikes was very loose and unweathered, suggesting the possibility of originating from the 1811–1812 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 during the past 4000–5000 years.

8. Paleoliquefaction and the tectonic setting

When clastic dikes in the study area were first reported as the product of seismic liquefaction from very strong earthquakes (Obermeier et al., 1991), there was considerable skepticism among some about the seismic origin. Part of the initial skepticism was due to the strongest historic earthquake in the region being only M 5.5 (Hamilton and Johnston, 1990), but more than anything else the skepticism was brought about by the lack of recognition of young faults at the surface. 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 6100 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 responsible for triggering the very large earthquakes near Vincennes is a "kink" (flexure) in bedrock structure, where north-east trending structures (including large faults) suddenly change to the north-west. An east–west compressive stress field in the bedrock is the suspected cause of a stress concentration at the kink (Hildenbrand and Ravat, 1997). This kink near Vincennes occurs in bedrock at the surface (Nelson, 1995) and also has been indicated at great depth by geophysical methods (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. Late Quaternary faulting with major offsets have recently been found in proximity to this lineament, near the Missouri–Illinois border (Harrison et al., 1996; Langenheim and Hildenbrand, 1997).

The notion that the kink near Vincennes was a critical element in occurrence of 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 1811–1812 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 features taken as evidence for the M<7 earthquakes might instead have been caused by a bounce of seismic energy from the Moho zone at depth, from a more-distant, larger earthquake. Clearly such a bounce cannot be so for one of the M<7 earthquakes. The age of the earthquake of 3950 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. 4). Such a well-defined pattern seems best explained by a nearby tectonic source.

Further evidence that the shaking caused by Moho reflection is insufficient to account for the liquefaction observed in the study area is provided by the overall scarcity and small size of liquefaction features in the study area that can be associated with Moho reflections from the great 1811–1812 New Madrid earthquakes. This study has found that only small, scattered liquefaction features were induced in the study area, except possibly in southernmost Illinois along the Cache Valley, which lies relatively close (within 100 km) to the meizoseismal region of the 1811–1812 earthquakes.

Energy source locations of the prehistoric earthquakes shown on Fig. 1 generally are thought to be 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 energy source. 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 supported 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 modified Mercalli Intensity (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 modified Mercalli Intensity values generally lies less than 20 km from the epicenter (Rhea and Wheeler, 1996). Thus it is suspected that, in the main, the epicenters (and thereby the energy sources) of the $M<7$ paleo-earthquakes lie within a few tens of kilometers from the centers of the regions of largest dikes. The energy sources 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 because of the reasonably well-defined core region of largest liquefaction features.

9. Summary and major conclusions

(1) Virtually all of the dikes found throughout southern Indiana and Illinois originated from seismic liquefaction.

(2) The dikes were induced by prehistoric earthquakes whose energy sources (and epicenters) were almost exclusively in Indiana and Illinois. The only significant exception may be for the Cache Valley, in extreme southern Illinois, where the dikes may have been induced by the great New Madrid, Missouri, earthquakes of 1811–1812.

(3) Probably nine paleo-earthquakes having magnitudes far stronger than any in historic time have been identified in Indiana and Illinois. At least seven and probably eight prehistoric earthquakes having moment magnitude M of 6 or higher occurred at various times throughout the Holocene, mainly during the mid-Holocene. At least one paleo-earthquake took place during the latest Pleistocene.

(4) The magnitude of the largest paleo-earthquake, which occurred 6100 ± 100 yr BP, was likely on the order of $M \sim 7.5$. The next-largest earthquake, a $M \sim 7.1$ event, struck $12\,000 \pm 1000$ yr BP. Three more paleo-earthquakes likely had magnitudes exceeding M 6.5. Other liquefaction-inducing paleo-earthquakes, probably much smaller, have also struck. These estimates of magnitude are based on the regional extent of liquefaction that is associated with each of the earthquakes, as well as on geotechnical analysis of the strength of shaking that was required to cause liquefaction at widespread sites of liquefaction.

(5) The two strongest paleo-earthquakes ($M>7$) were in proximity to one another and took place in the general vicinity of the most numerous and strongest historic earthquakes (M 4–5.5), in the lower Wabash Valley of Indiana–Illinois. Paleo-earthquakes of lower magnitude were much more randomly distributed and commonly have struck in regions having no significant historic seismicity.

(6) Virtually all liquefaction sites that have been discovered in Indiana have been associated with the paleo-earthquake that caused the liquefaction. Probably not all the causative earthquakes have been identified at liquefaction sites discovered in Illinois. Still, all paleo-earthquakes of $M>7$ probably have already been identified in both Illinois and Indiana.

(7) It is probable that a significant number (10 or more) of moderate to strong paleo-earthquakes (M 6–7) struck during Holocene and latest Pleistocene time, but are not in the paleoliquefaction record because of the lack

of liquefiable deposits that were nearby. There are many regions containing no liquefiable deposits, within which an earthquake (M 6.5–7) having a potential radius of liquefaction of as much as 30–40 km could have struck and left no liquefaction evidence.

(8) Geotechnical analysis at paleoliquefaction sites is sometimes required for distinguishing effects of individual prehistoric earthquakes from each other.

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