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Liquefaction evidence for strong Holocene earthquake(s) in the Wabash Valley of southern Indiana-Illinois, with a preliminary estimate of magnitude

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Abstract

We have discovered hundreds of planar, nearly vertical sand- and gravel-filled dikes that we interpret to have been caused by earthquake-induced liquefaction in the Wabash Valley of Indiana-Illinois. These dikes range in width from a few centimeters to as much as 2.5 m. The largest dikes are centered about the general area of Vincennes, Indiana; they decrease in size and abundance to the north and south of this area. Preliminary studies indicate that it is highly possible that many, if not all, of the dikes were formed by a single large earthquake that took place in the Vincennes area sometime between 2,500 and 7,500 years ago. The severity of ground shaking required to have formed the observed dikes far exceeds the strongest level of shaking of any earthquake in the Central United States since the 1811-12 New Madrid earthquakes. Our engineering-seismologic analysis, based on comparison of liquefaction effects with those of historic earthquakes in the Central and Eastern United States, indicates that the magnitude of the prehistoric earthquake was on the order of M_w 7.5.

Introduction

Many small and slightly damaging earthquakes have occurred throughout the region of the lower Wabash River valley of Indiana and Illinois during the 200 years of historic record. Seismologists have long suspected that the Wabash Valley seismic zone (a weakly defined area of seismicity delineated by Nuttli (1979), inset in fig. 1) could be capable of producing earthquakes much stronger than the largest of record (m_b 5.8, M_w 5.5; Hamilton and Johnston, 1990). No Pleistocene-age faults have been discovered in the region. However, because strong earthquakes in the central and eastern parts of the United States usually do not produce surface faulting, other paleoseismic effects must be used to detect prehistoric earthquakes. For this purpose a search for earthquake-induced paleoliquefaction features was initiated in 1990 and continued in 1991 (Obermeier and others, 1991; Munson and others, 1992). The search has been mainly in the lower Wabash River valley and its tributaries, and to a lesser extent in the lower Ohio River Valley.

The Wabash Valley seismic zone contains the 'Wabash Valley fault zone,' which is made up of numerous northeasterly trending normal faults. Many studies have shown these Wabash Valley faults to be post-Pennsylvanian and pre-Pleistocene in age of formation (Bristol and Treworgy, 1979). A much earlier generation of normal faulting, possibly related to the initial opening of the New Madrid rift complex, may extend into basement rocks beneath the Wabash Valley fault zone and beyond the fault zone throughout much of southwestern Indiana (Sexton, 1988). Some researchers suggest that the deepest earthquakes are related to the reactivation of the rift complex (Taylor, 1991). Historical earthquake epicenters are rather scattered and do not show good correspondence with known geologic structures. Overall, the seismotectonic setting is poorly known.

The Wabash River valley (fig. 2), which lies along the central axis of the Wabash Valley seismic zone, provides a very good environment for formation and preservation of liquefaction features. Alluvium in the valley as thick as 10 to 30 m lies on bedrock at many places. The valley contains extensive expanses of low, late Pleistocene terraces (glaciofluvial braid-bar deposits, mainly gravel and gravelly sand) into which are inset slightly lower Holocene floodplains (point-bar sediments, mainly sandy gravel, gravelly sand, and sand). The larger rivers have meandered back and forth over a relatively wide belt throughout the Holocene, and have left behind deposits of various ages. The sand-gravel deposits of both braid bars and point bars are normally overlain abruptly by 2 to 5 m of fine-grained (sandy silt to clayey silt) alluvium, which is made up mainly of overbank 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 locally sand) that were laid down in slackwater areas during glaciofluvial alluviation. The water table appears to have been relatively shallow (<3 m deep) over large parts of the valley during much of the time following glaciofluvial alluviation, on the basis of the depth of weathering profiles (leaching of carbonates and B-horizon development) in the sandy and silty alluvium. This combination of meandering rivers, a relatively shallow water table, and the presence of widespread, thick, clean (no clay) sand deposits at shallow depths with an overlying fine-grained cap has provided an excellent opportunity for liquefaction features to form in response to strong earthquake shaking throughout much of the Holocene.

Discussed below are results of our search for paleoliquefaction features, our reasons for interpreting these features as earthquake induced, and our interpretations of the epicentral region and strength of the earthquake(s) that produced the features. Information in this report is based on data available in February, 1992.

Results

More than 200 paleoliquefaction dikes and several sills have been found in Holocene point-bar, late Pleistocene glacial outwash, and late Pleistocene slackwater deposits. Figure 1 shows the locations we searched, sites where dikes were discovered, and the size of the largest dike observed at each of the sites. Nearly all sites shown on figure 1 have multiple dikes, and many sites have more than 10. Almost all the outcrops searched were in actively eroding banks of rivers, but a few sand and gravel pits and banks of recently excavated ditches were also searched.

Description of Features

Virtually all features that we interpret as having a seismically induced liquefaction origin are planar sand- or sand- and gravel-filled dikes that are vertical to steeply dipping and connect to a sediment source at depth (fig. 3). The dikes cut through the low-permeability cap that overlies thick source strata of silty to gravelly sand (and possibly sandy gravel). Many dikes extend upward as much as 4 m above the source zone. Sediment has vented from the dikes at many places to form 'sand blows,' but many smaller dikes pinch out upward, and erosionally truncated dikes are also fairly common. Large quantities of gravel (maximum diameters as much as 4 cm) were vented from many dikes. Dike widths (measured at least 1 m above the source bed) exceed 30 cm at 11 sites and exceed 60 cm at 4 sites. Maximum observed width is 2.5 m. Sidewalls of many dikes are parallel, especially at larger dikes. The grain size of an individual dike filling can be any one of the following: silty fine sand, sand, sand with a small amount of gravel, gravel with a trace of sand, or gravelly sand containing as much as 10 percent silt and clay. Many dikes contain clasts of sidewall material that were transported upward. The sediment within the dikes is almost everywhere structureless, except that some of the elongate gravels and clasts derived from sidewall material tend to be oriented vertically. Where gravel or coarse sand is present, there is generally a fining upward sequence of coarsest material. Within many dikes there are sharply defined, vertically intertwinned and intersecting zones containing distinctly different grain sizes. Sometimes the zones can be traced to different source strata at depth.

Sediment vented from the dikes produced sand blows that are as much as 40 m wide. Thicknesses of 0.15 to 0.2 m are not unusual near the vent. Most sand blows fine upward significantly in the vicinity of the dike, especially if gravel was vented, and become finer laterally. Still, gravels as large as 2 cm in diameter can be traced as far as 5 m from the vent. At sites where many sand blows are present, the sand-rich blows are generally much larger than those more gravel rich, in terms of volume of sediment vented onto the ground surface.

Only eight sites having sills have been observed in our study. Sills generally branch steeply upward and irregularly from the main dike and crosscut stratigraphic horizons. At a few sites though, the sills are subhorizontally extensive. Boundaries of the sills are sharply defined and usually show little or no evidence of weathering after intrusion. Sand blows, in contrast, are underlain at the base by a paleosol, and the vented sediments have at least some evidence of pedogenic alteration (see fig. 5).

At widely scattered sites we have observed the source strata that provided sediment that flowed into the dikes. (A prolonged drought caused the water table to be extremely low during our period of field work, so we were able to view these strata, which would otherwise have been submerged.) The most finely grained source stratum is a silty fine to medium sand, with a trace of clay. Most source strata are much coarser and contain at least some pebbles. Gravel is a common constituent. At Site RF there are exceptionally coarse source deposits, which contain as much as 60 percent gravel (fig. 4).

The vented sediments at sites bordering the Wabash River generally are buried beneath a 1-to 3-m thickness of overbank deposits. On slightly elevated terraces where flooding is rare, the vented sediments have been incorporated into the surface soil. Figure 5 shows soil relations for sand blows vented onto ground surfaces at sites ranging from frequently to rarely flooded. Also shown are our tentative interpretations of stratigraphic and age relations. The principal basis for age of the surface onto which sand blows vented is discussed in the following section.

Ages of Features

Munson and others (1992) examined 24 paleoliquefaction sites along the lower and central Wabash River and the White River and concluded, on the basis of the stratigraphic and pedological characteristics of the sites and archaeological and radiometric dating, that most if not all of the liquefaction features in those areas resulted from a strong earthquake that occurred sometime between 2.5 and 7.5 ka. An additional 11 sites, discovered along Skillett Fork and lower Embarras River in southeastern Illinois (fig. 1), are similar in characteristics; their locations and maximum dike sizes suggest that they resulted from the same event. Additionally, at one of the Illinois sites (WC) the dikes were erosionally truncated by a later stream channel, and a small log in the fill of this channel and directly above the dikes has been radiocarbon dated as 2.25 ± 0.07 ka (ISGS-2191).

Pedological data argue for some antiquity for the liquefaction features throughout the area, for there is typically a moderately to strongly developed B-horizon either in sediments in the dikes, in sand blow deposits, or in sediments overlying sand blows (figs. 3 and 5). By comparison, there is no discernible B-horizon development in sediments vented during the earthquakes of 1811-12, in the New Madrid area. Only three sites in the Wabash Valley seismic area (SR I, SR II, SH), all with dikes that pinch out beneath the zone of weathering, and all located southwest of the confluence of the Wabash with the Ohio River and nearest the 1811-12 New Madrid earthquakes' epicentral region, are possibly of 1811-12 origin.

The strongest argument that all of the Wabash Valley features were generated by a single earthquake is the stratigraphic positions of the sand blows at the sites. At none of the sites have we observed venting upon more than a single paleosurface. Many of the sites are in Holocene floodplain situations where multiple episodes of sedimentation and soil development have produced one to three discernible paleosurfaces (as well as the modern surface). Engineering and geologic studies have shown that liquefaction often recurs at or near the same places for earthquakes that are both closely and widely separated in time (Kuribayashi and Tatsuoka, 1975; Youd and Hoose, 1978; Youd, 1984; Saucier, 1989; Obermeier and others, 1990; Tuttle and others, in press).

If earthquakes separated in time caused the Wabash Valley dikes, it would be anticipated that dikes would have vented at various stratigraphic levels at the sites, in a manner similar to that illustrated in figure 6. Although we have observed at several sites ambiguous indications that liquefaction occurred possibly multiple times (such as dikes containing sharply defined zones having different grain sizes), such occurrences might be explained by strong aftershocks.

A single large earthquake is also suggested by the concentration of exceptionally large liquefaction dikes (>60 cm wide) along the Wabash River from Site RF southward as far as Site CF, a distance of about 35 km. The span of exceptionally large dikes may well extend farther southward, but there is an absence of outcrops from Site CF almost to Site PB, a distance of more than 25 km. For the single large earthquake hypothesis, very large features also should have formed in the lowermost portion of the White River valley. Large features have been found in this lowermost portion at only one site. However, outcrops are so limited in both number and length along this river that a statistically meaningful characterization of sizes and abundance of liquefaction features is not yet possible.

An alternative mechanism that might explain the apparent synchronism and the distribution of the liquefaction features in the Wabash Valley would be to have scattered strong earthquakes throughout the region that occurred at approximately the same time, comparable to the situation in which four exceptionally (M_w> about 8) strong earthquakes occurred over a 3-month period in the New Madrid area in 1811-12. That mechanism is being considered as our research continues, but it is to be noted that the 1811-12 earthquake pattern is very unusual among historically known earthquakes.

Origin of Features

Criteria that we use to interpret an earthquake origin to the dikes and sand blows in the Wabash Valley are discussed in Obermeier and others, (1990), and requires satisfying the following:

1. The features should have sedimentary characteristics that are consistent with earthquake-induced liquefaction origin; that is, there is evidence of an upward-directed, strong hydraulic force that was suddenly applied and was of short duration.

2. The features should have sedimentary characteristics that are consistent with historically documented

observations of the earthquake-induced liquefaction processes.

3. The features should occur in ground-water settings where suddenly applied, strong hydraulic forces of short duration could not be reasonably expected except from earthquake-induced liquefaction. In particular, such settings should be extremely unlikely sites for artesian springs.

4. Similar features should occur at multiple locations that preferably are at least within a few kilometers of one another and have similar geologic and ground-water settings. Where evidence of age of the event is present, it should support the interpretation that the features formed in one or more discrete, short episodes that individually affected a large area and that the episodes were separated by long time periods during which no such features formed.

On the basis of these four criteria, the physical characteristics of the dikes in the Wabash Valley are consistent with what would be expected from a seismically induced liquefaction origin. These characteristics and the physical setting in which the dikes developed are described below. Because mechanisms other than earthquakes can produce similar features, we also discuss alternative mechanisms in their formation and compare characteristics that would be expected from earthquake versus other sources.

Evidence for Seismic Origin

Because a detectable vertical offset of sedimentary beds that make up the fine-grained caps cut by the dikes is rare, any ground movement associated with generation of the dikes must have been almost entirely horizontal. Presence of large dikes, many having parallel walls throughout the height of the dike, further indicates that the fine-grained caps moved laterally. The lateral movement invariably took place on thick strata of clean to slightly silty sand, gravelly sand, or sandy gravel on the basis of our many widespread field observations of flowage features in the source zones. All these relations are typical of the mode of ground failure (lateral spreading) caused by earthquake-induced liquefaction. These features in the Wabash Valley are strikingly similar to dikes and lateral spreads generated by liquefaction during the 1811-12 New Madrid earthquakes (Obermeier and others, 1990; Leffler, 1991). The only notable difference between dikes and sills in the Wabash Valley and liquefaction effects of the 1811-12 earthquakes is that sills are commonplace in the epicentral region of the 1811-12 earthquakes, but exceptional in the Wabash Valley.

An earthquake-induced liquefaction origin for the dikes of the Wabash Valley is interpreted because of the following aspects, when considered in combination: (1) the dikes widen downward or have walls that are parallel; (2) dikes are linear in plan view and exhibit strong parallel alignment in local areas; (3) the dikes vented large quantitites of sandy sediment to the surface as 'sand blows'; (4) material in the dikes fines upward and was transported upward; (5) bedding in some source beds is homogenized, and contacts with overlying fine-grained sediment are highly convoluted in some places; (6) flow structures that project upward from the source zones of sand or sand and gravel into the bottom of the dike can be observed in some places; (7) some dikes occur in flat and topographically elevated landforms, located many hundreds of meters from any steep slopes that might have existed at the time of formation of the dikes, and therefore are located in sites unlikely to have experienced high artesian pressures or nonseismic landsliding; (8) other nonseismic mechanisms that could have produced similar features are not plausible, as we discuss below; and (9) the size and abundance of the dikes along the Wabash River, which is the area where data are most complete, generally decreases with increasing distance from a central region of large dikes (fig. 1). All these aspects of the dikes listed above, including a core area of exceptionally large dikes, can be observed in the 1811-12 New Madrid earthquakes' epicentral region, which has a physical setting similar to that of the Wabash Valley.

Seismic versus Alternative Origins

The following sections discuss in detail some characteristics of liquefaction-induced features that would be expected from a seismic origin, and why factors such as artesian conditions, nonseismic landsliding, sudden lowering of the river level, and other nonseismic mechanisms have been considered and eliminated as sources of the dikes.

A. Artesian Conditions

Because elimination of significant nonseismic artesian pressures is important to our arguments, a simplistic soil mechanics analysis places bounds on the artesian pressures required to cause nonseismic lateral spreading in the Wabash Valley. At many sites, dikes formed in areas where the vertical change in height of the ground surface was no more than 1 to 2 m over horizontal distances greatly exceeding 200 m (0.5 to 2 percent). For such gentle slopes to have failed by a nonseismic mechanism, artesian pressures would have been required to be so high as to permit essentially no soil strength in the failure zone of granular material beneath the fine-grained cap; this means that there would have been zero effective stress in the failure zone. Zero effective stress requires that the artesian head approach twice the thickness of the fine-grained cap above the failure zone. (This is based on the assumption that the wet unit weight of capping sediment is nearly double the unit weight of water.) The cap thickness is normally in the range of 2 to 4 m and varies from 1.5 m to probably more than 5 m. Therefore, the artesian head must necessarily have approached 1.5 to 5 m in height above the ground surface, depending on cap thickness at the site.

Two independent forms of evidence are presented to determine the possible role of nonseismic artesian conditions in formation of dikes and sand blows. Both morphology of the features and characteristics of the physical settings are discussed.

(1) Morphology of the dikes and sand blows

Locally, in the upper 0.1 to 0.2 m of the dike, just beneath the point at which sediment vented to the surface, some of the dikes widen into a shattered zone. This shattered zone is in the A- and B-horizons of the weathered soil that was at the ground surface at the time of venting. The coarsest materials (gravels) that were vented onto the paleosurface are often concentrated into or very near the basal portion of the sand blows (fig. 3).Near-surface shattering and upward fining of vented sediments are consistent with observations related to venting of sediments to the surface throughout the epicentral region of the 1811-12 New Madrid earthquakes. These characteristics are also consistent with forceful ejection of water and vented sediments during the early stage of venting, whereas forceful ejection during the early phase of venting would not necessarily be expected from artesian springs. Numerous dikes at widespread locations are filled with gravel that is surrounded by little or no finer sized material throughout the height of the dike. The gravels commonly range from 1 to 2 cm in diameter. This coarseness also attests to very forceful flowage through the dikes.

The observation that the dikes in the Wabash Valley are approximately linear and subparallel in plan view also corresponds with the form of earthquake-induced liquefaction features produced by large historic earthquakes elsewhere. Figure 7 is an aerial photograph showing long fissures and individual sand blows that formed as a result of liquefaction during the 1811-12 New Madrid earthquakes. The long fissures on the aerial photograph are underlain by vertical, sand-filled dikes that are very similar to those in the Wabash Valley. Even the individual sand blows, where formed on a clay-rich cap, are generally underlain by vertical, planar sand-filled dikes of small width and length in the horizontal plane (Obermeier, 1989, p. B50-51), just as those of the Wabash Valley.

Figure 7 also shows how the fissure patterns are controlled by the local geologic setting. Seismically induced fissures have a strong tendency to form along the tops of and to be parallel to the scrolls of point-bar deposits, even at large distances (>1 km) from the stream channel (Fuller, 1912; Obermeier, 1989). Also, liquefaction-induced fractures tend to parallel the stream channel on both sides of the stream. Figure 8 shows the close relationship between the dikes and the morphology of point-bar deposits along the Wabash River. We found at least 10 places along the Wabash River where the dikes are parallel to the scrolls of the point bars and at the time of their formation were far back (>200-300 m) from banks of the former river channel. Both strike and location of the dikes are consistent with lateral spreading that results from earthquake-induced liquefaction.

The morphology of the dikes in the Wabash Valley also argues against nonseismic artesian pressures as the causal mechanism. Significant nonseismic artesian pressures should cause venting at isolated spots rather than as long, linear, parallel features; that this manifestation of venting at isolated spots should be expected is demonstrated by the formation of sand boils (a sand boil is a nonseismically induced feature) near the levees of the lower Mississippi River, from Cairo, Illinois, southward. Kolb (1976) has described the effects of flooding and resulting artesian conditions beneath levees in the area. During high flooding, when artesian pressures are significant, features form that are described as 'pin boils' and 'pot holes.' Kolb describes pot holes as large as 2 m in diameter and 1 m deep. Personnel at the U.S. Army Corps of Engineers, Memphis, Tennessee (written comm., 1989), have excavated into one of these artesian-induced pot holes and found that horizontal bedding extended well down into the throat, much below the original ground surface. This bedding apparently formed as sand and organic sediment fell into the open crater. If significant localized artesian pressures had been commonplace in the Wabash Valley, we would expect to see many of the same sorts of filled craters. We have found no filled craters; therefore, an absence of high artesian conditions through the Holocene is strongly indicated.

The sand boils along the Mississippi River originated by flowage through crayfish holes and root holes, according to Kolb (1976). Great numbers of vertically tubular crayfish burrows are also present in the Wabash Valley, which should have allowed formation of spring-induced sand boils if artesian conditions had been present. We have observed several tubular dikes filled with clean sand in the Wabash Valley, but only in topographically very depressed swamps. We have found no tubular dikes that approach being filled with clean or silty sand or gravelly sand in the general vicinity of the planar dikes in the Wabash Valley. Therfore, we conclude that only minuscule (insignificant) artesian conditions through time could have contributed to formation of the dikes and that the maximum artesian pressures present in the vicinity of the dikes could not have approached a pressure head equal to the vertical effective stress applied by the low permeability cap.

(2) Role of topography and geology on ground-water conditions

We have also considered the possibility that significant artesian conditions originated from entrapment of water beneath the fine-grained cap as the ground water flowed from topographically elevated areas. We feel that this possibility can be eliminated at many sites. The situations at Sites PB (in point-bar deposits) and Site GR (in braid-bar deposits) are illustrative. At these sites there are nearby entrenched stream valleys or abandoned channels that should have bled off any significant artesian pressures. The caps are also so thin and silty at these sites that seepage through the caps, as the water moved downslope, probably would not have permitted significant build-up of artesian pressure. More detailed description of each of these two sites follows.

Figure 9 shows an aerial photograph, topographic map, and vertical section along a portion of the Wabash River banks where the dikes at Site PB are present. The dikes at this site have been bracketed as having formed between 2.5 and 7.5 ka (this is the site shown as fig. 2 in Obermeier and others, 1991). We do not know if the dikes formed when the Wabash River occupied the meander loop north of the present river or if they formed after neck cut-off of that meander, when the river might have been 1 to 3 km to the south. What is known is that the dikes cut through point-bar deposits that were formed during the migration of the paleo-meander that lies east, west, and north of the dikes; therefore, whatever the position of the Wabash River when the dikes formed, any significant artesian pressures from the terrace located to the east, west, and north would have been intersected by either an active river channel or a deep slough (see fig. 9).

If the Wabash River had been south of the dikes at the time of their formation, then its channel would have intersected any significant artesian conditions from that direction. Even if the river had been north of the dikes, the elevations of the valley surface for as far as 6 km to the south of the dikes are less than 2 m higher (elevation 385 ft) than the surface onto which the dikes vented (elevation about 380 ft). This minor difference does not support an argument for significant artesian conditions from the south.

The only possible source of artesian pressure for the Site PB dikes would have been at the central portion (present northern extremity) of Peankishaw Bend, about 1 km northwest of the dikes, where the laterally equivalent paleosol onto which the sand blow was vented (see fig. 9C) is about 1-2 m higher. Field evidence at the site suggests very strong flowage forces. The width of the largest dike at this site exceeds 0.6 m throughout the height of the dike, which exceeds 3 m, and pebbly sand was vented onto a now buried surface. Within the lower half of the dike are many large gravels. It seems unreasonable to us that a vertical planar dike having such a large width could transport upward large gravels (up to 4 cm in maximum diameter) as a result of the small artesian conditions possible in such a field setting.

We now examine the setting at Site GR, which is about 10 km south of Site PB. (This is the same as Site GR described by Obermeier and others, 1991). Figure 10 shows an aerial photograph, a topographic map, and a plan view map with locations and the strike of dikes (up to 30 cm wide) exposed in an open sand and gravel pit. The dikes cut through a 1.5- to 2-m thick sandy and clayey silt cap that sharply overlies gravelly sand (braid-bar deposits). Very probably, some of the dikes on the north and west walls were connected before the pit was excavated. The gravelly sand beneath the fine-grained cap extends at least 8 m beneath the base of the fine-grained cap, on the basis of three engineering borings around the pit. Thickness of gravelly sand and sand exceeds 20 m throughout the region, according to the pit operators and highway department boring logs taken about 300 m from the pit. Soil development in dike fillings compared with undisturbed adjacent soil shows that the Site GR dikes postdate terrace formation, all overbank deposition, and most Holocene soil development. Therefore, the dikes considerably postdate initial formation of the braid-bar surface.

Various possible ground-water conditions at the site are relevant in regard to possible artesian conditions. High artesian pressures could not have originated from a source west of the pit, because point-bar scrolls clearly show that the Wabash River has continously occupied that region. South and east of the pit is the Black River, which extends to the northeast from the area shown on the maps; this river should have bled off any significant artesian pressures originating in the terrace deposits and uplands to the northeast. The only source region for such artesian conditions would have been along the base of the bedrock hill, north of the town of Griffin and about 1.5 km north of the features. The confining clayey silt cap is so thin throughout this region, however, that any buildup of signficant pressures seems unlikely.

Not shown on Figure 10C is an approximately 100-m wide slight swale that is filled with an approximately 2-3 m thickness of gleyed clay (southwestward projection of swale is shown in fig. 9B). Also not shown are small vertical, planar, sand-filled dikes about 100 m east of and parallel to the swale; thus, northeasterly oriented dikes are present both east and west of the swale. We do not know if a small stream occupied the swale at the time of formation of the dikes. However, if a stream occupied the swale, then the stream would have intersected artesian pressures from the north, precluding artesian-induced formation of the sand dikes on the west side of the swale. If a stream did not occupy the swale, then the dikes (parallel to both the course of Black River and to local relief) would have formed at least 1 km from the banks of the Black River. Horizontal block movements required to have formed the sand-filled fissures, at such a large distance on nearly flat ground and far from any stream banks, are best explained as a result of seismically induced liquefaction.

We emphasize that there are many more such sites where it can be shown that significant artesian pressures were very unlikely as a factor in forming the dikes. Sites PB and GR were chosen largely because of their ease of access to anyone interested in doing field examinations of the dikes.

B. Nonseismic Landsliding

To determine whether nonseismically induced landslides are a candidate mechanism to have formed the sand-filled dikes, we have considered historical accounts of regional landslide behavior, particularly along the Wabash, Ohio, and Mississippi Rivers, in addition to accounts of worldwide landslide behavior and engineering mechanics of landsliding.

Landslide experience in the lower Mississippi River valley is summarized by Obermeier and others, (1990, p. 27):

> "Long irregular fissures through which sand has vented [similar to fissure pattern shown on fig. 7 in this paper] - - - have not been observed to have originated by springs in the alluvial lowlands of the St. Francis Basin [this basin occupies the region along the Mississippi River between Cairo, Illinois, and Memphis, Tennessee]. Slumps and lateral spreads along rivers (generally caused by rapid hydraulic drawdown after floods) can generate fissures, but we have not observed sand flowing to the surface through the fissures except for small amounts associated with water oozing through the slide mass. In addition, (nonseismic) lateral spreads and slumps that we have observed do not extend back from banks along large rivers more than 50 m. Thus we believe that fissures associated with vented sand that are located more than 50 m from present or former banks of rivers can generally be attributed to seismically induced slope instability. Confidence in this interpretation increases with increasing width of the sand-filled fissure and with increasing distance from the banks. In order to confidently attribute an earthquake mechanism to a specific vented-sand fissure, however, the location of the river at the time of fissure formation must be established, an undertaking that may be quite difficult."

The 50-meter distance was provided by Mr. J. E. Monroe, one of the co-authors in Obermeier and others, (1990), and was intended to be a conservative (large) distance from the head to the toe of the landslide. In addition, this distance was intended mainly for thinly interbedded sands and clays, where artesian pressures can locally be present during periods of rapid drawdown of the river. Sliding block failures in response to rapid drawdown of the river are reported to be fairly common along the Ohio River (Springer and others, 1985), but here too, the failure zones are in very thin sand layers bounded above and below by low-permeability materials. Springer and others made a comprehensive study of streambank stability in the Ohio River system and noted that large slumps are a common type of failure, but they make no mention of lateral spreading on thick, clean sand deposits.

Some scattered landslides in the study area are initiated by shear failure which takes place on or through softened Pennsylvanian-age shales that underlie the alluvium in the river valleys. These shales have minimum shear-strength (residual) angles that can be as low as 7 to 8 degrees (Mesri and Gibala, 1971). At places where the shale-alluvium interface is only gently dipping, a sliding block can move toward a stream, especially where the bank is being undercut and when the stream level drops rapidly. An example of such a failure along the Ohio River near the confluence with the Wabash River has been studied extensively by Mundell and Warder (1984). Here block movement, which perhaps began prehistorically, has shown horizontal displacement of a distance of 1.5 to 2 m over a period of 20 years. The block extends about 50 m back from the river. Relatively slow movement taking place within 50 m of the river's edge seems to be the normal mode of failure of sliding on (or through) the shale throughout the Wabash Valley area (J.A. Mundell, Geotechnical engineer, ATEC Corp., Indianapolis, Ind., oral commun., 1991). Such a scenario of a slowly moving sliding block does not explain our observation that at many Wabash Valley sites, on virtually level ground far from steep slopes, there are sand- and gravel-filled dikes. The static-failure sliding block mechanism does not seem to us to provide a means whereby large quantitites of sand, and especially relatively clean gravel, could be transported vertically up the dikes as much as 3 to 5 m and then be vented onto the ground surface.

Both our field observations and our engineering borings in the Wabash Valley show a correlation between dike width and dike filling. The source zones for the widest dikes generally contain medium sand with little or no gravel, whereas nearby much narrower dikes commonly have gravel-rich source zones. If the origin of the dikes were a statically induced sliding block, there should be no relation between dike width and dike filling. This relation between dike width and dike filling seems best explained by an earthquake-induced liquefaction origin. (A gravelly sand doubtlessly is generally more difficult to liquefy and cause to flow than a clean sand because of large differences in permeability and large differences in the threshold flow velocity required to transport sediment.)

We have also considered the mechanism of statically induced liquefaction for the dikes. Static liquefaction may be responsible for causing large lateral spreads that initiate by failure of sensitive (or 'quick') clays, such as has occurred Scandinavia and in the St. Lawrence Valley. We are not aware of any accounts in the literature of static subaerial liquefaction on virtually level ground causing large lateral spreads by failure in thick, clean sands, or gravelly sands. In addition, senior geotechnical engineers at the Norwegian Technical

Institute (T. Loken, oral commun., 1991) and at the Swedish Geotechnical Institute (C.L. Viberg, oral commun., 1991) are unaware of any such failures in Scandinavia. However, subaqueous slumps and mudflows appear to have been induced by spontaneous liquefaction on very gentle slopes in Scandanavia and elsewhere around the world (Andersen and Bjerrum, 1968); a characteristic common to all these slides is that failure originated in uniformly graded fine sands and coarse silts, with both having extremely high porosities. In the Wabash Valley, by comparison, our data show that liquefaction originated in sediments much denser, more well graded, and much coarser than the sediments that experienced spontaneous liquefaction.

If the dikes in the Wabash Valley had been caused by slumping, then strata should be vertically displaced. Vertical displacement across a dike has been observed at only two of the Wabash Valley sites, and this was small.

If the dikes in the Wabash Valley were caused by nonseismic landsliding, we would also expect to see many dikes in the Ohio Valley because of similar physical-geologic settings in the two valleys. As figure 1 shows, we searched many kilometers of outcrop in the Ohio Valley in proximity to the Wabash Valley, and we found only two small dikes, which were at a single site (SH).

In summary, we conclude that the model of nonseismic landsliding as the source of the linear dikes in the Wabash Valley is not supported by the field evidence.

C. Sudden Lowering of River Level

We have also considered sudden lowering of the level of the Wabash River as a possible source for residual pore-water pressures that formed the dikes. As noted previously, we suspect that most if not all of the dikes formed at the same time. The only mechanism that we can postulate to have caused a sudden lowering would be rupture of a huge ice-jam or log-jam or a sudden change in river course. None of these mechanisms can explain the wide distribution and sizes of dikes that we have found. The dike distribution (fig. 1) shows a 35-km-wide core region with dikes having widths exceeding 60 cm, and these are bounded regionally by smaller dikes. Sudden changes in water level at a point source along the river could not produce such a pattern far up and down the Wabash River. Sudden withdrawal of floodwaters also has been eliminated as a source mechanism, because residual excess pore-water pressure would not remain after drainage of surface floodwaters.

D. Syndepositional Processes, Weathering, and Frost Action

Syndepositional processes in many sedimentary environments create large flow structures and intrusions, so early in the study we made a special effort to investigate the possibility of this mechanism as a source for the dikes. We eliminated syndepositional processes as the origin for some dikes because they cleanly cut (make brittle breaks) across sediment much younger than the source sands, and other dikes cut through very thick, highly plastic clay that accumulated slowly in a swamp environment. In addition, many of the source beds are thick, highly permeable sands, gravelly sands, or sandy gravels that would drain rapidly and thereby eliminate the possibility of pore-water pressure buildup caused by deposition of overlying sediments.

Weathering by chemical processes has produced karst-like development in calcareous outwash deposits in the Ohio River valley (Carroll, 1979). These weathered features are more or less tubular in plan view. We have observed what may be features caused by the same process in braid-bar deposits along some of the older, higher terraces in the Wabash Valley. The karst-like weathering features reported by Carroll and observed by us do not resemble the dikes in the Wabash Valley.

We have also considered the possibility that the dikes could have been produced by frost action. A report by Johnson (1990) summarizes the characteristics of frost-related features in an area near our field study and points out that sediment is transported downward in frost features, in constrast to the evidence of upward movement of sediment that we have observed in the dikes. In addition, many or all of the dikes formed sometime between 2.5 and 7.5 ka, and this time period greatly postdates the period of significant frost action in the region.

Paleoseismic Implications

The source region and probable strength of the earthquake(s) that produced the dikes are evaluated below.

Source Region

Consideration of dike sizes and distribution throughout the Wabash and Ohio Valleys, in conjunction with the regional geologic setting and seismic record, indicates that the tectonic source zone almost certainly is located in the Wabash Valley. The regional distribution of the dikes, the location of the largest dikes in the lower and central Wabash Valley, and the presence of only scattered small dikes in the Ohio Valley show that the New Madrid earthquake region, about 200-250 km to the southwest, could not have been the source for the Wabash Valley features. Further support for this interpretation is provided because extensive paleoliquefaction studies by Wesnousky and Leffler (1992) in the 1811-12 New Madrid earthquakes' meizoseismal region have not detected any evidence of a very large earthquake during the past 5 to 10 ka. Our search of about 20 km of stream banks in the lowermost Ohio River valley and lowermost Tennessee River valley (fig. 1), in sediments of early Holocene age at many places, also revealed no evidence of exceptionally strong prehistoric shaking. We know of no reason to suspect exceptionally high or exceptionally variable amplification of bedrock accelerations that might explain how an earthquake outside the Wabash Valley could cause this concentration of large features in southeastern Illinois and southwestern Indiana. On a regional basis, the liquefaction susceptibility does not vary greatly throughout the major river valleys because of the widespread occurrences of moderately to highly susceptible sand, high water tables, and the similar range of alluvium thicknesses (although almost certainly a 30-m thickness of alluvium experiences significant amplification of bedrock motions, as we discuss later). Consequently, on the basis of size and distribution of liquefaction features, we strongly suspect that the source region for the strongest earthquake(s) was in the general vicinity of Vincennes, Indiana.

The apparent increase in size of liquefaction features along the White River from west to east might suggest another earthquake source far to the east of our lower or central Wabash River source zone. However, we suspect that this inverse pattern is due to lack of adequate outcrop (Munson and others, 1992) or could be due to variations in ground shaking caused by factors such as varying thicknesses and properties of alluvium. Further studies, particularly along the Embarras and White Rivers, are needed to resolve this question.

Strength of Earthquake(s)

A basis for placing limits on the strength of the paleoearthquake(s) is provided by relating the areal distribution and size of liquefaction features in the Wabash Valley to those of historic earthquakes elsewhere in central and eastern North America. We make such a comparison with three historic earthquakes: the 1811-12 New Madrid earthquakes, the 1895 Charleston, Missouri earthquake, and the 1886 Charleston, South Carolina earthquake. The recent 1988 earthquake in Saguenay, Quebec, induced liquefaction but had a focal depth, stress drop, and shaking characteristics that are not believed typical of intraplate earthquakes of the Central and Eastern United States (Boore and Atkinson, 1992); therefore, we make no comparison with the liquefaction effects of that event. Our evaluation uses the moment magnitude values most commly used by the seismological community for historic, pre-instrumental earthquakes, although some recent studies suggest that these magnitude estimates possibly are too large (Bollinger, 1992; Hanks and Johnston, 1992). Insight into the probable magnitude may eventually result from an ongoing study by Martin and Pond (co-authors) to place limits on the accelerations that formed the observed dikes. For now, we assume that the dikes were produced by a typical intraplate earthquake.

Liquefaction is produced mainly by upward propagation of shear waves from bedrock to the ground surface, and so any estimate of earthquake magnitude must account for (1) bedrock motions and their amplification in unconsolidated or soft sediments above bedrock, and (2) liquefaction susceptibility. After these have been accounted for, the span and sizes of liquefaction features can be calibrated to magnitude by two methods: (1) the Liquefaction Severity Index method (LSI of Youd and Perkins, 1987; Youd and others, 1989) and (2) scaling to the outer limit of sand blows (Youd, 1991). The LSI method is a measure of horizontal displacement caused by lateral spreading as a function of distance from the epicenter and is based on lateral spread movement being largest where earthquake shaking is strongest, other factors being equal. The technique of scaling to the outer limits of sand blows is simply a comparison of the spans of sand-blow development. Factors that control sand-blow development and their areal distribution in the Wabash Valley are the subject of a study by Martin and Pond (co-authors), which helps provide for some of our preliminary interpretations.

Sufficient data are available in the Wabash Valley to place lower bounds on the areal distribution of sand blows and lateral spread displacements. The north-south distance over which we have discovered sand blows (from Sites MA to OC) from what we suspect to be a single earthquake is at least 175 km (the sand blows at Site OC are not small, so the span is larger), and the east-west span (from Sites NT I to AL) is at least 105 km. Near the central part of the span of sand blows is the region of largest dikes, where dikes are as wide as 0.7 to 2.5 m. Vertically planar dikes having widths exceeding 0.15 m (6 in) throughout the height of the dike occur from Sites GR to OC, some 160 km apart. Actual maximum horizontal displacement at a Wabash Valley site probably exceeds a single dike width because (1) it is very likely that we did not always observe the single largest dike in the vicinity of a given site (dike width is largely affected by proximity to stream banks and some of our liquefaction sites were probably far from streams), and (2) almost all sites having a large dike have numerous parallel smaller dikes nearby, so the total horizontal movement might be more closely approximated by the sum of dike widths. Alternatively, it can be argued that the dikes were widened in large part by sand and gravel abrading the clay-rich sidewalls, but that process does not explain the observation that the widths of large dikes are nearly constant in plan view, and that sidewalls are often vertically parallel.

Liquefaction susceptibility of sand is closely related to the Standard Penetration Test (SPT) blow-count number (a common geotechnical engineering test), which is largely a measure of grain packing. A greater than 1 m thickness of loose sand deposit at a shallow depth (2-10 m), located where the water table is within a few meters of the ground surface, is generally highly susceptible to liquefaction and to formation of dikes and sand blows that can be recognized as having an earthquake origin. In the Wabash Valley, our limited data show that loose sands having blow counts as low as 6 and 7 are sufficiently abundant to have a major influence on the regional pattern of sand-blow development. Blow counts of 4 or less appear to be rare. At several widely scattered paleoliquefaction sites in the Wabash Valley, the water table appears to have been within 2 m of the ground surface at the time of the earthquake, because the water table was probably at least as high as the bottoms of the dikes when they formed. Therefore we suspect that the liquefaction susceptibility was relatively high at many places when the dikes formed but not as high as sands in other sedimentary environments (sands having considerably lower blow counts, and therefore higher susceptibility, are common in beach-dune complexes such as those of coastal South Carolina).

At Wabash Valley paleoliquefaction sites the uppermost bedrock is nearly flat-lying, thick, Pennsylvanian-age indurated shale and sandstone. Thickness of flat-lying sedimentary rocks above Precambrian igneous rocks is about 3,000 to 4,000 m (Bushbach and Kolata, 1990). Sand and gravel usually less than 30 m thick lies on bedrock. We have used a stochastic simulation (using the method of Boore, 1983) of bedrock accelerations and have estimated the amplification of these accelerations in the upper part of the sand and gravel column by using the linear propagation model in the program RATTLE, which considers vertical propagation of S waves. (Our calculations are based on a moment magnitude 6.5 event; results for frequencies greater than 0.5Hz are unaffected by magnitude, and therefore the actual magnitude is of very minor importance for our purpose.) A stress drop value of 100 bars has been used in accordance with the recommendation by Boore and Joyner (1991). Amplification in the soil column is estimated for three Q values (10, 15, and 20), which are thought to encompass the range of reasonable values. Table 1 shows the input parameters. Table 1 also lists the ranges and average values of peak and root-mean-square (rms) amplification of bedrock accelerations for the six random number seeds (stochastic simulations). An amplification between 2 and 3 is shown to be most likely.

We have also used the nonlinear program SHAKE (table 3) to estimate how much the stochastic peak acceleration in bedrock is amplified in the soil column. (Representative shear-wave velocity data were provided by D.L. Eggert of the Indiana Geological Survey, and W.R. Eckhoff of Ball State University.) For the SHAKE analysis, the frequency range was restricted to a maximum value of 25 Hz, because higher frequencies in soil generally transmit a relatively small amount of energy. We initially estimated a damping factor of 10 percent for the soil column, but the procedure in SHAKE for ensuring strain compability reduced the damping values to generally less than 3 percent. The amplifications have been calculated by selecting two peak threshold accelerations at the surface, where small liquefaction features should be formed (we are concerned only with formation of small liquefaction features at the outer limits of the span of liquefaction features), and then calculating the associated bedrock accelerations. The input bedrock motions were the same set used in the RATTLE analysis (linear propagation), based on six random time series. Surficial peak accelerations of 0.08 g and 0.10 g were used. Table 3 shows that the ratio is essentially insensitive to these acceleration values and to the procedure, and an amplification of about 2 is indicated. A similar analysis showed that the RATTLE and SHAKE procedures are not very sensitive to the range of shear-wave velocity and shear modulus values that are reasonably possible in sandy alluvium.

We now compare Wabash Valley paleoliquefaction effects with those elsewhere. The areal distribution of sand blows induced by the four strongest New Madrid earthquakes ($m_b \sim 7.0$ to 7.4, $M_w \sim 7.8$ to 8.3; Nuttli, 1979; Johnston, 1992) is very poorly known, but the maximum span for the strongest of those earthquakes ($m_b \sim 7.4$, $M_w \sim 8.3$) certainly far exceeds what we have found in the Wabash Valley. The span for what we presume to have been caused by the strongest earthquake ($M_w \sim 8.3$, on Feb. 7, 1812) appears to have been on the order of 500 km on the basis that sand blows were observed on the floodplain of the Mississippi River near St. Louis, Missouri, and also in the lowermost Wabash Valley (Youd and others, 1989). We believe that it is likely that liquefaction susceptibility and bedrock amplification were relatively comparable at and near these two river valley sites during the 1811-12 and Wabash Valley earthquakes. Therefore, this comparison of spans suggests that the strongest 1811-12 earthquake far exceeded the magnitude of any earthquake that produced the paleoliquefaction features in the Wabash Valley (see table 5).

The 1895 Charleston, Missouri earthquake ($m_b \sim 6.2$, $M_w \sim 6.8$; Nuttli, 1979; Johnston, 1992), located in the New Madrid seismic zone, is the only earthquake that is known to have produced sand blows in the Central United States since the 1811-12 New Madrid earthquakes. The diameter of the region of reported sand blows and minor liquefaction effects was about 16 km (Powell, 1975); Powell describes liquefaction effects mainly in the meizoseismal region and east and south of this region, so it is likely that some liquefaction sites to the north and west were not noted. Still, because the nearby Mississippi and Ohio Rivers are bordered with sediments highly susceptible to formation of sand blows, and because thousands of people were living along these rivers in 1895 (Cairo, Illinois, is about 15-20 km from the epicenter) and did not report liquefaction features, it is unlikely that the actual diameter of distribution of sand blows much exceeded twice the reported span of 16 km, or 32 km. Our preliminary investigations using the programs RATTLE (tables 1 and 2) and SHAKE (tables 3 and 4) suggest that surface ground motions for an earthquake of given magnitude are amplified only slightly to moderately higher in the Wabash Valley relative to the 1895 Charleston earthquake epicentral region (table 5). Therefore the large, 175- by 105-km area of sand blows in the Wabash Valley, combined with the presence of very large dikes in the core area, suggests that prehistoric shaking in the Wabash Valley greatly exceeded that of the 1895 Charleston, Missouri earthquake.

A rough comparison of liquefaction effects can also be made with the 1886 Charleston, South Carolina earthquake ($m_b \sim 6.7$, $M_w \sim 7.5$; Nuttli and others, 1979; Johnston, 1992), whose epicenter was near the ocean. The Charleston area is in the stable continental region and presumably for a given earthquake magnitude has similar source dimensions and bedrock shaking characteristics to a typical intraplate earthquake (A.C. Johnston, Memphis State Univ., oral commun., 1991). Observers at the time of the 1886 earthquake noted numerous liquefaction features, notably 'craterlets,' that formed in the 30- by 50-km meizoseismal region (Dutton, 1889). Dutton also reported that craterlets formed over a region about 100 km in diameter centered about the epicenter. Widely scattered, much smaller craterlets and small sand-filled dikes may have formed much beyond the 100-km diameter. Very small, apparently liquefaction-induced features were reported up to 100 km from the epicenter, northeastward along the coast (Youd and others, 1989). Very small features that appear to have an 1886 earthquake origin have been found by Obermeier (co-author, unpublished data, 1986) along the coast at a site about 100 km southwest of the epicenter, and medium-sized features have been reported at the same site by Amick and others, (1990). No 1886-vintage liquefaction features have been found farther southwestward along the coast, despite extensive field searching. Therefore, along the coast the span of liquefaction features appears to be about 200 km or a little more. This span is very probably a maximum value, because no liquefaction features were reported very far inland from the epicenter, away from the coast, despite the presence of extensive wet lowlands underlain by loose sands that are not far inland from the epicentral area. Because there has been no direct evidence of faulting found at the surface, the location of the 1886 earthquake fault remains controversial. The principal axis of the meizoseismal region, and presumably the major rupture for the 1886 earthquake, was oriented about 30 degrees from the coast (Plate XXVII, Dutton, 1889). However, the lack of liquefaction features in fluvial sediments at large distances along the strike of the meizoseismal area indicates that the extent of liquefaction measured on the coast is not an underestimate caused by directivity or focal mechanism effects. Thus the extent of sand blows appears to be similar for the Wabash Valley and 1886 Charleston earthquakes.

The largest horizontal movement associated with a lateral spread in the 1886 Charleston earthquake epicentral region was 2.5 m (Youd and others, 1989)---which is the same as the width of the largest dike that we have found in the Wabash Valley (at Site ER). The span of lateral spread movement also appears comparable for movement of 0.15 m (6 in). Youd and others (1989), by interpreting historical accounts of liquefaction effects, have derived mathematical relations between lateral spread movements as a function of epicentral distance (LSI relations) for the 1886 Charleston earthquake and estimate a span of about 140 km for 0.15-m movements. In the Wabash Valley, movements of at least 0.15 m appear to have taken place from Sites GR to OC, a span of 160 km.

In summary, both the criteria of span of sand blows and lateral spread movement show comparable liquefaction effects in the Wabash Valley with those of the 1886 Charleston earthquake. Other factors to consider for evaluating magnitude are liquefaction susceptibility and bedrock shaking amplification. The South Carolina coastline has abundant deposits that are extremely susceptible to liquefaction and flowage. Martin and Clough (1990) found that 1-m-thick, uniformly sorted, fine sand deposits having blow counts of 2 or less, with the water table at the ground surface, are common near the coast. (In the Wabash Valley, sands are much more poorly sorted and blow counts less than 6 are not common). For loose sands (having blow counts less than about 10) there is an approximately linear, one to one relation between earthquake accelerations and blow count for initiation of liquefaction in loose sands (see, for example, fig. 4-68 in Liquefaction of soils during earthquakes, 1985). Thus the threshold acceleration is on the order of three or more times higher for Wabash Valley sands than those in coastal South Carolina.

Near the epicentral regional (within 50 to 100 km), earthquake accelerations in coastal South Carolina are probably attenuated as they progress upward from bedrock through the 1-km thickness of semi-lithified, pre-Quaternary Coastal Plain deposits, according to studies by Chapman and others, (1990). They estimate that the peak acceleration at the base of Quaternary deposits is on the order of two-thirds the value of bedrock acceleration at an epicentral distance of 60 km, and proportionally higher with increasing distances. (Chapman and others used a 1-km thickness of Tertiary sediments along the coast; a Q value of 20 and shear wave velocity of approximately 1 km/sec was assigned to these deposits, with a stress drop of 100 bars.) We believe that this Q value of 20 is too low for the Tertiary sediments; using a Q of 50 for these sediments suggests that there is only minor change between accelerations in bedrock and the base of Quaternary deposits. Unpublished studies by Martin (co-author, 1990) show that in the 10- to 20-m thickness of Quaternary deposits along the coast, accelerations from the underlying pre-Quaternary Coastal Plain sediments are changed either slightly or not at all. Overall, it appears that bedrock motions were not changed much at the ground surface along the coast at distances exceeding 50 km from the epicenter.

The combined factors of bedrock amplification (minor change in amplification or attenuation) and liquefaction susceptibility (extremely high) in coastal South Carolina, when compared to those which produce liquefaction features in the Wabash Valley (moderate to slight amplification and high liquefaction susceptibility), appear approximately equal for earthquakes of equal magnitudes. Therefore relatively equal spans of sand blows and lateral spread movements in the two regions suggest that earthquake magnitudes were about the same. We next make an estimate of the magnitude of the single Wabash Valley paleoearthquake by using a graphical procedure for scaling to the outer bound of sand blows. A theoretical and philosophical basis for the technique developed by Youd and Perkins (1978) shows that a unique bound of liquefaction effects should exist for a given tectonic setting, if other factors are fixed. Data from the 1895 Charleston, Missouri earthquake and the 1811-12 New Madrid earthquakes, presented in figure 11, are used for our analysis.

Figure 11 is a plot (modified from Ambraseys, 1988) comparing moment magnitude versus epicentral distance to farthest liquefaction features, with the bound by Ambraseys for shallow-focus earthquakes. According to Youd (1991, p. 129-130), the data apparently includes all effects of liquefaction, including minor fissures and small sand blows, and "Ambraseys' points for intermediate depth earthquakes generally lie well beyond the bounds for shallow-focus events, indicating that intermediate-depth earthquakes may generate liquefaction to larger distances than shallow events." Figure 11 contains data mostly from interplate and crustal earthquakes in the Western United States and Japan but also includes data from areas of lower attenuation. The farthest distance to sand blows for the intermediate-depth, 1988 Saguenay earthquake is seen to extend beyond Ambraseys' bound.

Figure 11 shows, in addition, the data points for the farthest reported sand blows of the 1811-12 earthquakes. These liquefaction features formed during the month of February, which is normally in the season when the water table is very high (and therefore most likely to produce sand blows), although we have no weather data for that time. Epicentral distance data points for the 1895 Charleston, Missouri earthquake are shown as 16 and 20 km. The 16-km distance represents what is thought to be an upper limit from the epicenter on the basis of reported effects; 20 km is the distance from the epicenter to the town of Cairo, Illinois, located along the banks of the Ohio River where no sand blows were reported, and therefore is an absolute upper limit.

We now address the question of the relationship of the 1895 Charleston, Missouri liquefaction data to the 1811-12 New Madrid liquefaction data and to the Wabash Valley paleoliquefaction data. Wabash Valley seismicity tends to originate at a greater depth than it does in the New Madrid seismic zone, but hypocentral depths of strongest earthquakes in both the New Madrid seismic zone and in the Wabash Valley are less than about 10 to 20 km (Gordon, 1988). On this basis, both areas qualify as sources for shallow-focus earthquakes. Regional stress fields (NE-SW compression) and major fault zones are oriented similarly in the Wabash Valley and in the New Madrid seismic zones (W.L. Ellis, U.S. Geol. Survey, oral commun., 1992), although locally there are significant variations in stress orientation. Therefore it is reasonable to assume that earthquakes in both regions have similar shaking characteristics at the source and that liquefaction effects will be bounded by the same line, providing that an accounting is made for the factors of amplification of bedrock motions and liquefaction susceptibility. Bedrock shaking is amplified less in the Charleston, Missouri area than in the Wabash Valley according to our analyses using RATTLE and SHAKE (shaking is amplified less by factors of about 1.25 and 1.7, respectively). Where farthest liquefaction takes place, bedrock shaking amplitude decays inversely proportional to distance from the earthquake source as a result of geometric spreading. Because of the high Q of the crust, anelastic and scattering losses are small over this distance range. Therefore an earthquake in the Wabash Valley of equivalent magnitude to the 1895 Charleston, Missouri earthquake would cause equivalent shaking (and farthest liquefaction, for the condition of equal liquefaction susceptibilities) at epicentral distances 1.25 and 1.7 times greater (according to RATTLE and SHAKE, respectively) than around the Charleston, Missouri area. In the Wabash Valley, the equivalent distance from the 1895 Charleston epicenter to Cairo, Illinois is 25 km (20 km x 1.25, RATTLE analysis) and 34 km (20 km x 1.7, SHAKE analysis). These data points are shown on Figure 11.

We previously have argued that the susceptibilities of the most liquefiable sediments are reasonably comparable in the Charleston, Missouri and Wabash Valley areas. The most susceptible sediments in both regions are recent river deposits. In addition to similar depositional processes, the grain-size gradations of the most susceptible sediments are about the same, thicknesses of capping sediments are commonly comparable, and the water table is always extremely shallow at many places. Therefore, the susceptibility of the most liquefiable deposits is approximately the same for our purpose of evaluating the relations between earthquake magnitude and the span of sand blows.

The next concern is the shape of the line on figure 11 connecting the corrected 1895 Charleston, Missouri earthquake data to the 1811-12 earthquake data point (the 250-km distance). A straight line connecting the points is probably an extreme upper limit. Most likely, the shape is similar to Ambraseys' bound. The straight line intersects the epicentral distance to the farthest Wabash Valley paleoliquefaction sand blows (89 km) at magnitudes M_w 7.5 and 7.7. Curved lines yield magnitudes of about M_w 7.4 to 7.5.

This graphical analysis leads us to the same conclusion that we arrived at by our comparison of the span and lateral spreading movements of Wabash Valley liquefaction features with those of the 1886 Charleston, S.C. earthquake--namely, that it is likely that a paleoearthquake having a magnitude of about M_w 7.5 struck the Wabash Valley. Thus, completely independent methods of evaluation yield the same result. We emphasize, though, that these estimates of magnitude assume a normal intraplate stress drop (100 bars) and typical focal depth (10 to 20 km) and are therefore best viewed as tentative and subject to change with future studies.

Conclusions

1. The dikes in the Wabash Valley are interpreted to be of earthquake origin, on the basis of the following evidence:

a) The dikes have characteristics that are generally consistent with dikes produced by earthquakes elsewhere in a similar geologic setting, and, in particular, with the meizoseismal region of the 1811-12 New Madrid earthquakes.

b) We have found no field evidence, of the sort that should be commonplace, to support nonseismic origins for dikes in the Wabash Valley, such as artesian conditions or landslides.

c) The field settings in which the dikes formed at almost all sites shown in figure 2 are not conducive to formation of significant artesian conditions that can induce nonseismic lateral spreading landslides. In addition, there are only rare, localized occurrences of small dikes in the Ohio River valley, just south of the lower Wabash Valley, and the ability to produce landslides and liquefaction features appears comparable in the Wabash and Ohio River valleys.

d) Mechanisms such as sudden lowering of the river level, weathering, or frost action do not explain the characteristics and distribution of dikes in the Wabash Valley.

2. It is highly possible that virtually all the dikes were formed by a single large earthquake that took place between 2,500 and 7,500 years ago.

3. The epicenter of the strongest earthquake(s) appears to have been in the general vicinity of Vincennes, Indiana.

4. The strength of earthquake shaking that formed the dikes in the Wabash Valley far exceeds historic levels of shaking in this area and far exceeds the level of shaking and magnitude of the 1895 Charleston, Missouri earthquake ($m_b \sim 6.2$, $M_w \sim 6.8$).

5. If all the dikes in the Wabash Valley are from a single earthquake, the magnitude appears to have been on the order of that of the 1886 Charleston, South Carolina earthquake ($m_b \sim 6.7$, $M_w \sim 7.5$).

6. More field research should provide more insight into the origin of the dikes, should clarify whether the liquefaction features could be the result of a single earthquake or multiple events, and could provide a better

estimate of the magnitude(s) of the earthquake that are believed to have caused the features.

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Figure 1. Map showing areas searched for liquefaction features and locations of sites where paleoliquefaction features (dikes) were discovered. Sites having dikes are labeled with capital letters, followed by a classification of dike widths. A continuous search of Wabash River banks was made from the confluence with the Ohio River northward to the limit shown on the map; a continuous search of White River banks was made from the confluence with the Wabash River eastward to the limit shown on the map. The banks along the Wabash River and White River in most places overlie moderately liquefiable sediments. Outcrop quality was highly variable but was generally good along the Wabash River except for the 25-km-long portion shown on the map. Outcrop quality was generally very poor along the White River because of extensive bank slumping. Sites of localized searching are denoted by symbols in the explanation. Outcrop quality at sites of localized searching along the Ohio River was excellent, and even small dikes would have been detected. Sites in the southern part of the study areas, where dikes might have been induced by the 1811-12 New Madrid earthquakes, are designated with question marks. Dike width shown on the figure is the width measured at least 1 m above the base of the dike; where the base of the dike was not exposed, the listed width was the maximum observed.

Figure 2. Map showing generalized locations of major fluvial and slackwater deposits near the Wabash and Ohio Rivers, within the study area. Dotted areas show locations of late Wisconsinan outwash sand and gravel and Holocene alluvial silt, sand, and gravel, with subordinate amounts of clay. Shaded areas show locations of late Wisconsinan slackwater deposits, which are mainly clay and silt, and locally sand. Map units taken from Gray and others (1991).

Figure 3. Diagrammatic vertical section showing general characteristics of buried sand- and gravel-filled dikes along the Wabash River. Source beds are Holocene point-bar deposits or late Wisconsinan braid-bar deposits overlain by much finer overbank sediment. The sediments in source beds beneath dikes show evidence of flowage into dikes. The gravel content and size decreases upward in dikes at many places. The extreme upper portion of a dike is widened and shows evidence of ground shattering at many places. The column on right side of the figure contains pedological descriptions.

Figure 4. Grain-size curves for samples from suspected coarsest source stratum observed in the Wabash Valley (at Site RF) and for samples from coarsest source stratum (at Whiskey Springs) that liquefied and formed sand blows in response to the 1983 M_s7.3 Borah Peak, Idaho earthquake (Andrus and others, 1991). The stratum at Whiskey Springs appears to have the coarsest deposits, worldwide, that are documented to have liquefied, flowed, and formed sand blows.

Figure 5. Vertical section showing schematic relations for largest (widest) dikes and associated vented sand materials at three sites, ranging from frequently flooded (Site VW) to infrequently flooded (Site PB) to rarely flooded (Site GR). Also shown are locations and tentatively estimated ages of paleosurfaces and soil descriptions. Width of vented sediments is as much as 20 m and is much larger than depicted. (Sketch and soil interpretations provided by Leon R. Follmer and Wen-June Su, Illinois Geological Survey).

Pedo-mix zones have sand-rich cores of vented sediments containing minor silt and clay, surrounded by a zone of increasingly lower sand content. Highest concentration of sand and pebbles is on the paleosol surface. Presence of the pedo-mix zone represents passage of time before burial by overbank deposits. Paleosol surface onto which sediments vented has an estimated age of 4 to 7 ka, primarily on the basis of radiometric and archaeological data. At Site VW, the contact having the age of 1-3 ka is estimated on the basis of archeological and pedological data. At Site PB, the inceptisol below the sand blow is estimated to be 7.5 ka on the basis of radiometric data. At Site GR, the age of the present surface is estimated to be 10.5 to 12 ka on the basis of geological and archaeological data.

Soil designations are described below:

B	B horizon, zone of alteration below topsoil or main root zone in soil profiles showing color and morphological changes in comparison to original material (parent material). B-horizon soil normally appears as a relatively uniform zone of blocky aggregates in loose or compact form.
Bg	The gleyed variation of B horizon that is dominated by gray colors and indicates seasonal or permanent wetness.
Bt	One of the B horizon variations that has evidence of clay accumulation (clay skins).
Bx	One of the B horizon variations that is brittle and very hard when dry and softens upon wetting.
B(ox)	B horizon that shows evidence of oxidations; other features such as Bt or Bx are usually weak or absent, or are not designated.

Figure 6. Vertical section showing anticipated relation of dikes and vented sediments from recurrent earthquake-induced liquefaction at an alluviating site. (No comparable relations were observed in the Wabash Valley.)

Figure 7. Vertical aerial photograph of a portion of the Manila, Arkansas, 7.5-minute orthophotographic quadrangle. The photograph shows long fissures through which sand vented (light-colored linear features) and also shows individual sand blows (light-colored spots) formed by liquefaction during the 1811-12 New Madrid earthquakes. These features formed in latest Pleistocene braid-bar deposits and younger Holocene point-bar sediments. Note how fissures formed parallel to the scrolls of point-bar deposits.

Figure 8. Aerial photograph (A) and topographic map (B) of Site VW, and photographs (C and D) of the widest dike at the sites. Aerial photograph (A) shows meander scrolls of point-bar deposits. Topographic map (B) (a portion of USGS Vincennes, Ind.-Ill. 7.5-minute quadrangle, 10-ft contour interval) shows locations and strikes of dikes. On the topographic map, observed lengths of dikes have been exaggerated to clearly illustrate trend; meander scrolls are indicated by dashed lines. Note that the dikes form a 350-m wide zone that parallels the scrolls of point-bar deposits, similar to those associated with the 1811-12 New Madrid earthquakes (fig. 7). Photograph (C) shows oblique view of stream bank and straight-on view of 75-cm wide dike. Photograph (D) shows perpendicular view of bank and oblique view of dike. (Scale is meters).

Figure 9. Aerial photograph, topographic map, and vertical section showing location and geologic setting of dikes at Site PB. Aerial photograph (A) shows meander scrolls of point-bar deposits in which dikes formed. Topograph map (B) (a portion of USGS Grayville, Ill.-Ind. 7.5 minute quadrangle, 10 ft contour interval) shows location and strike of largest dikes (as much as 0.6 m wide) at the site and the location of a braid-bar terrace; lengths of dikes are exaggerated. The vertical section (C) shows location and elevation of paleosols, point-bar sediments, dikes, and sand blow that are exposed in river bank.

Note orientation of point bars in paleomeander and similar orientation of dikes.

Figure 10. Aerial photograph, topographic map, and plan view of pit showing location of dikes in Site GR. Aerial photograph (A) shows braid-bar terrace surface, meander scrolls of point-bar deposits, and bedrock (sandstone and shale) upland. Topographic map (B) (a portion of USGS New Harmony, Ind.-Ill. 7.5-minute quadrange, 10-ft contour interval) shows locations of braid-bar deposits, point-bar deposits, region of pit with numerous dikes, and map in C. Plan view of corner of pit (C) shows location and strike of dikes in pit wall.

Note NE-SW orientation of braid bars on terrace, NE-SW orientation of Black River, and similar orientation of dikes.

Figure 11. Relationship between earthquake moment magnitude and distance from earthquake epicenter to the farthest liquefaction feature. (Modified from Ambraseys, 1988.)

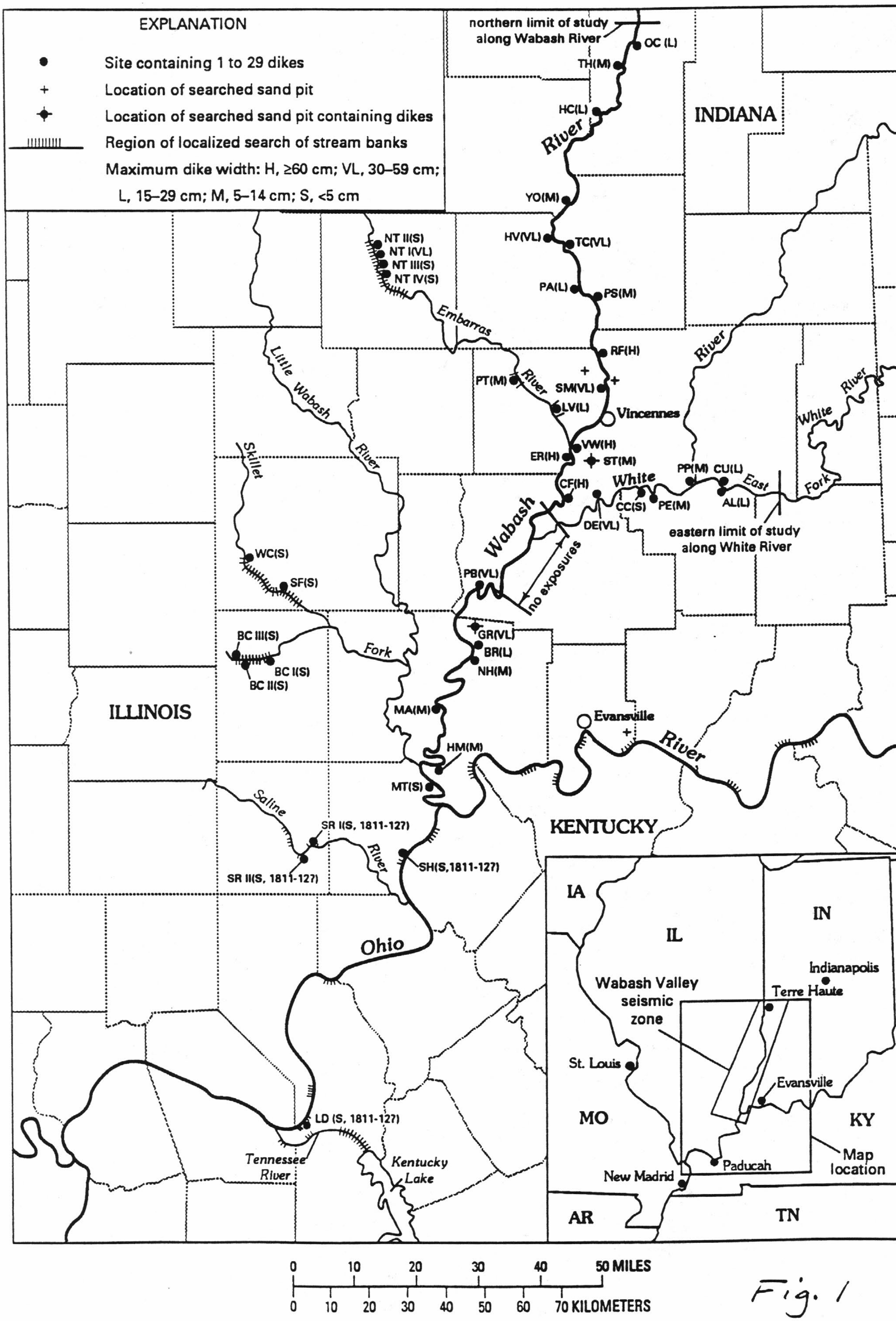

EXPLANATION
Site containing 1 to 29 dikes
Location of searched sand pit
Location of searched sand pit containing dikes
Region of localized search of stream banks
Maximum dike width: H, ≥60 cm; VL, 30–59 cm; L, 15–29 cm; M, 5–14 cm; S, <5 cm
northern limit of study along Wabash River
OC (L)
TH(M)
HC(L)
INDIANA
River
YO(M)
HV(VL)
TC(VL)
PA(L)
PS(M)
NT II(S)
NT I(VL)
NT III(S)
NT IV(S)
Embarras
River
RF(H)
PT(M)
SM(VL)
LV(L)
Vincennes
Little Wabash River
VW(H)
ER(H)
ST(M)
CF(H)
White
CC(S)
PE(M)
PP(M)
CU(L)
AL(L)
East Fork
White River
DE(VL)
eastern limit of study along White River
Wabash
no exposures
Skillet
WC(S)
SF(S)
Fork
PB(VL)
GR(VL)
BR(L)
NH(M)
BC III(S)
BC I(S)
BC II(S)
ILLINOIS
MA(M)
Evansville
River
HM(M)
MT(S)
KENTUCKY
Saline
River
SR I(S, 1811-12?)
SR II(S, 1811-12?)
SH(S,1811-12?)
Ohio
LD (S, 1811-12?)
Tennessee River
Kentucky Lake
IA
IL
IN
Indianapolis
Wabash Valley seismic zone
Terre Haute
St. Louis
Evansville
MO
KY
Map location
Paducah
New Madrid
AR
TN
0 10 20 30 40 50 MILES
0 10 20 30 40 50 60 70 KILOMETERS

Fig. 1

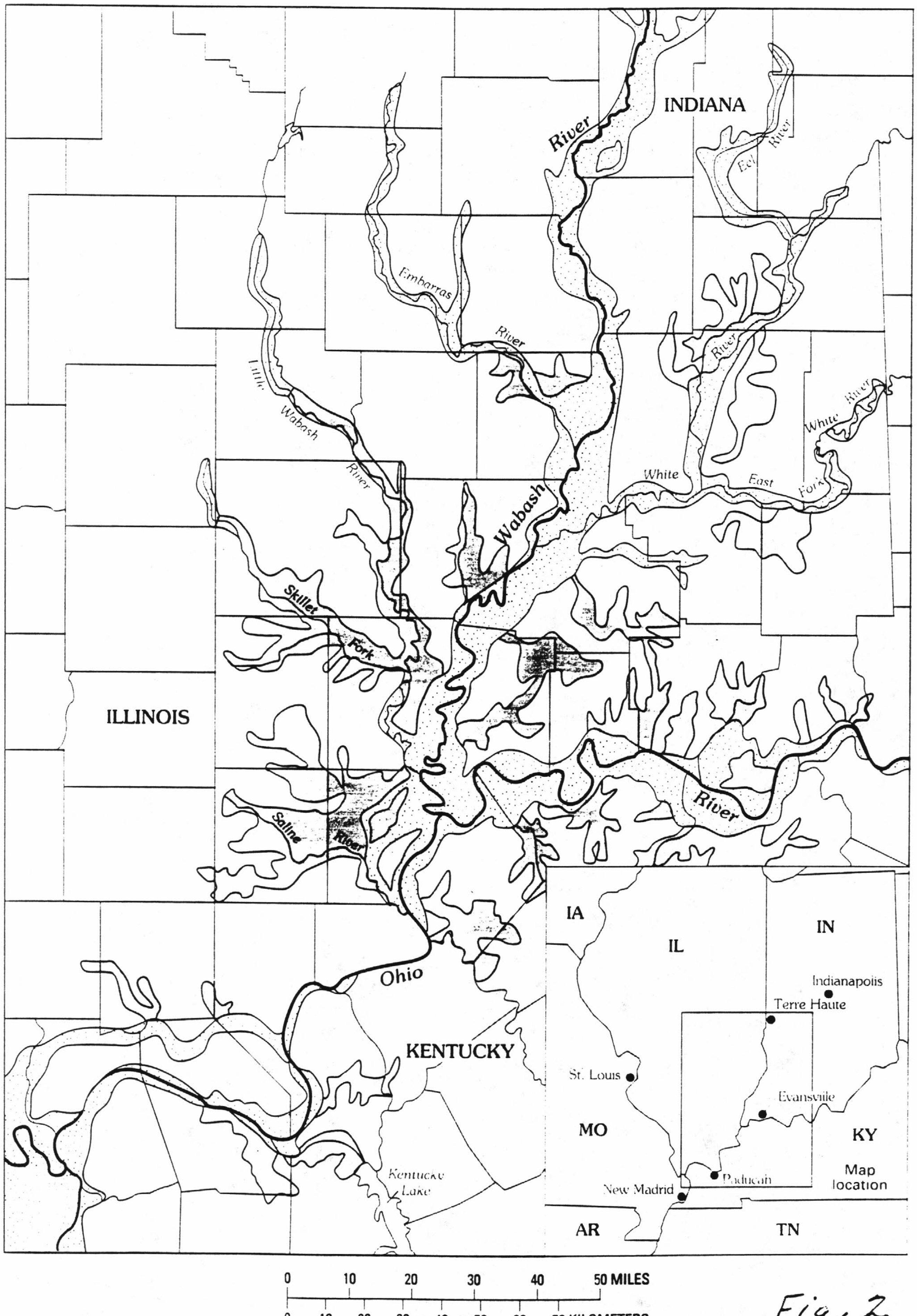

INDIANA
River
Eel
River
Embarras
River
Little
Wabash
River
White
River
White
East
Fork
White River
Wabash
Skillet
Fork
ILLINOIS
Saline
River
River
Ohio
KENTUCKY
Kentucky
Lake
IA
IL
IN
Indianapolis
Terre Haute
St. Louis
Evansville
MO
KY
Paducah
New Madrid
Map
location
AR
TN
0 10 20 30 40 50 MILES
0 10 20 30 40 50 60 70 KILOMETERS

Fig. 2

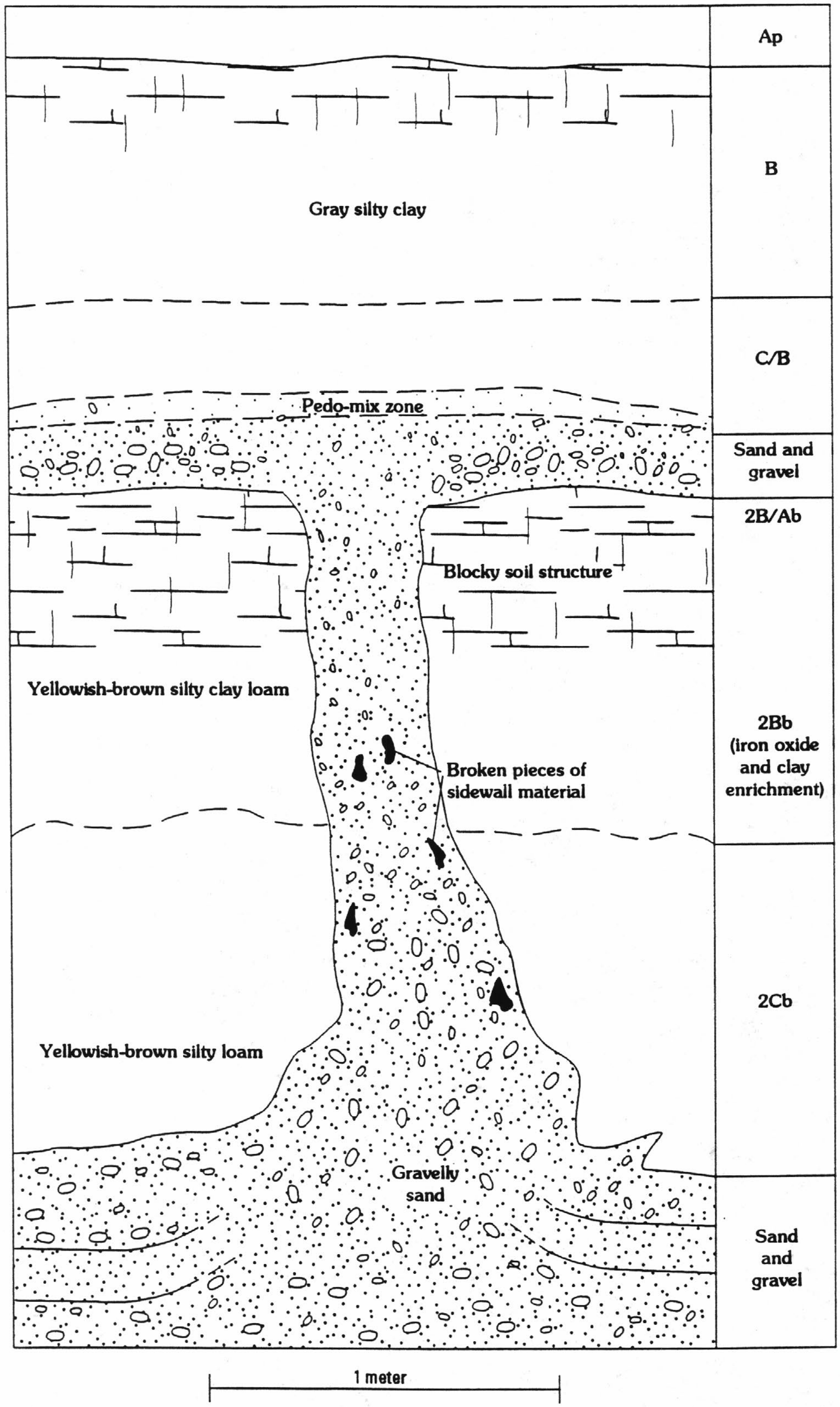

Ap
B
Gray silty clay
C/B
Pedo-mix zone
Sand and gravel
2B/Ab
Blocky soil structure
Yellowish-brown silty clay loam
2Bb (iron oxide and clay enrichment)
Broken pieces of sidewall material
2Cb
Yellowish-brown silty loam
Gravelly sand
Sand and gravel
1 meter

Fig. 3

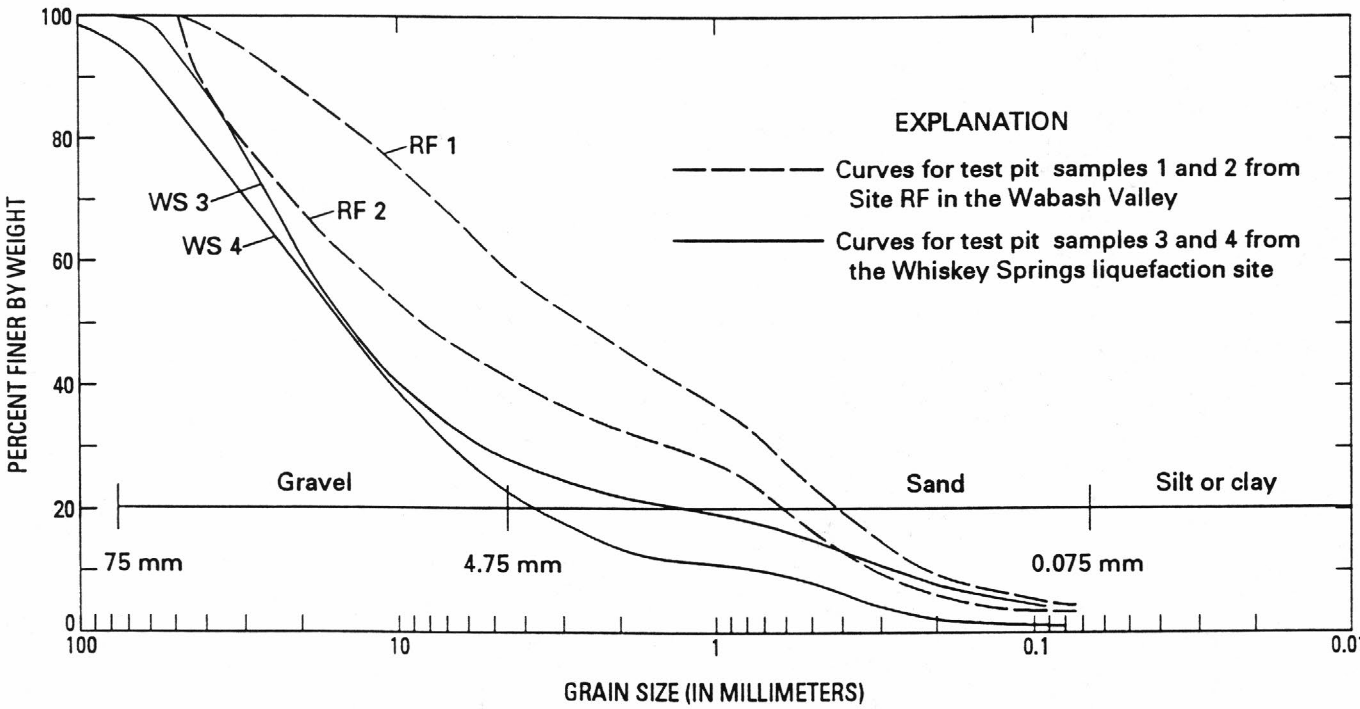
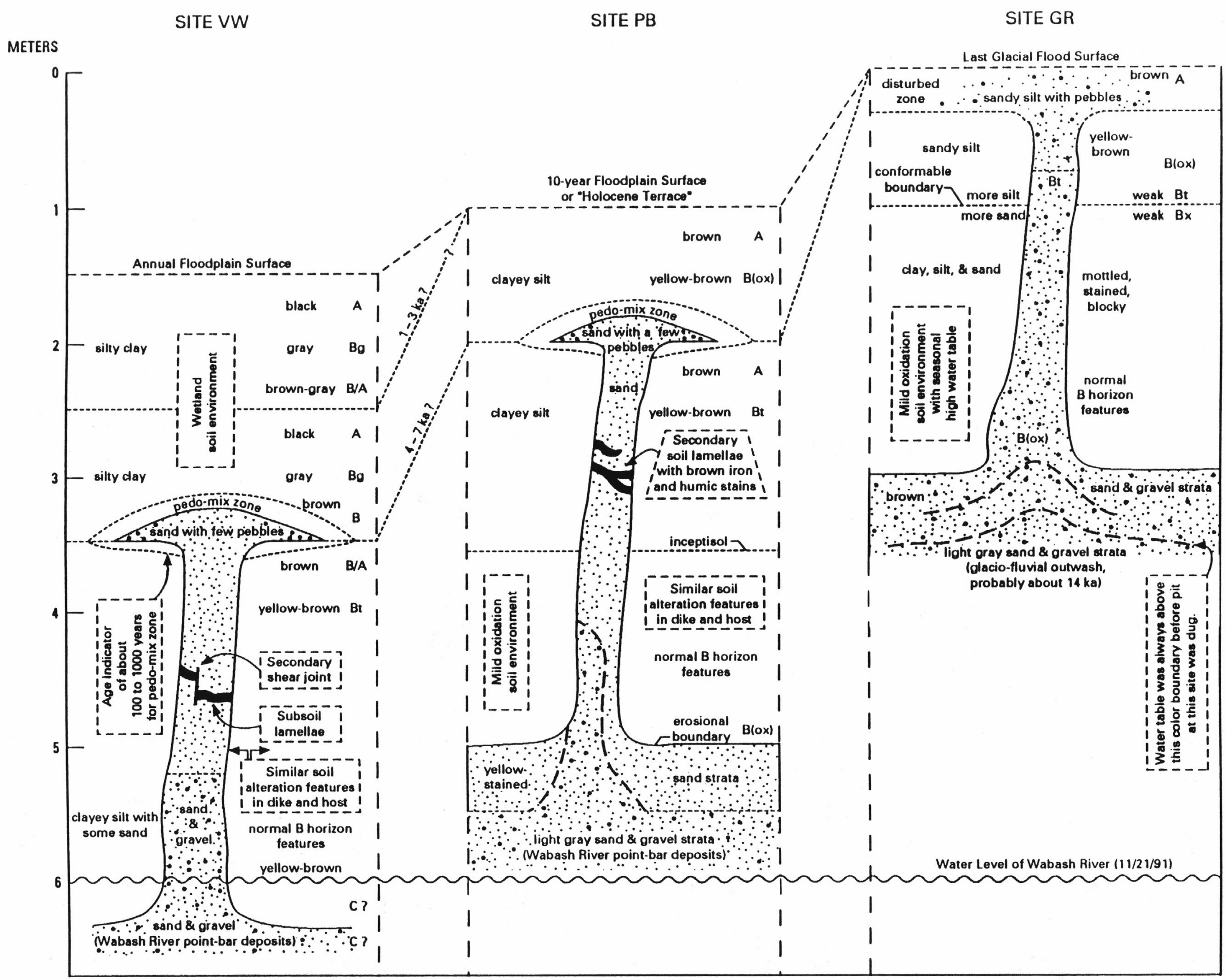

EXPLANATION
Curves for test pit samples 1 and 2 from Site RF in the Wabash Valley
Curves for test pit samples 3 and 4 from the Whiskey Springs liquefaction site
RF 1
RF 2
WS 3
WS 4
Gravel
Sand
Silt or clay
75 mm
4.75 mm
0.075 mm
PERCENT FINER BY WEIGHT
100
80
60
40
20
0
100
10
1
0.1
0.01
GRAIN SIZE (IN MILLIMETERS)

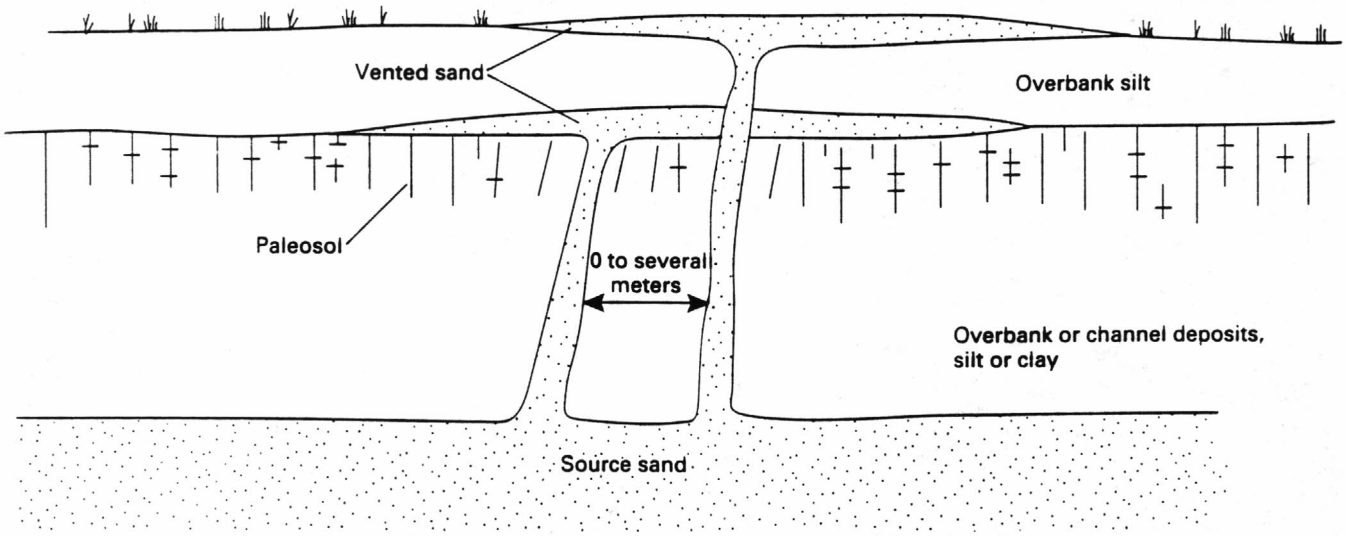
Fig. 4



SITE VW
SITE PB
SITE GR
METERS
0
1
2
3
4
5
6
Annual Floodplain Surface
black A
silty clay
gray Bg
brown-gray B/A
Wetland soil environment
black A
silty clay
gray Bg
pedo-mix zone
brown B
sand with few pebbles
brown B/A
yellow-brown Bt
Age indicator of about 100 to 1000 years for pedo-mix zone
Secondary shear joint
Subsoil lamellae
Similar soil alteration features in dike and host
clayey silt with some sand
sand & gravel
normal B horizon features
yellow-brown
C ?
sand & gravel
(Wabash River point-bar deposits)
C ?
1–3 ka ?
?
4–7 ka ?
10-year Floodplain Surface or "Holocene Terrace"
brown A
clayey silt
yellow-brown B(ox)
pedo-mix zone
sand with a few pebbles
brown A
sand
clayey silt
yellow-brown Bt
Secondary soil lamellae with brown iron and humic stains
inceptisol
Mild oxidation soil environment
Similar soil alteration features in dike and host
normal B horizon features
erosional boundary
B(ox)
yellow-stained
sand strata
light gray sand & gravel strata
(Wabash River point-bar deposits)
Last Glacial Flood Surface
disturbed zone
brown A
sandy silt with pebbles
sandy silt
yellow-brown
B(ox)
conformable boundary
Bt
more silt
weak Bt
more sand
weak Bx
clay, silt, & sand
mottled, stained, blocky
Mild oxidation soil environment with seasonal high water table
normal B horizon features
B(ox)
brown
sand & gravel strata
light gray sand & gravel strata
(glacio-fluvial outwash, probably about 14 ka)
Water table was always above this color boundary before pit at this site was dug.
Water Level of Wabash River (11/21/91)

Fig. 5

Fig. 6



Vented sand
Overbank silt
Paleosol
0 to several meters
Overbank or channel deposits, silt or clay
Source sand

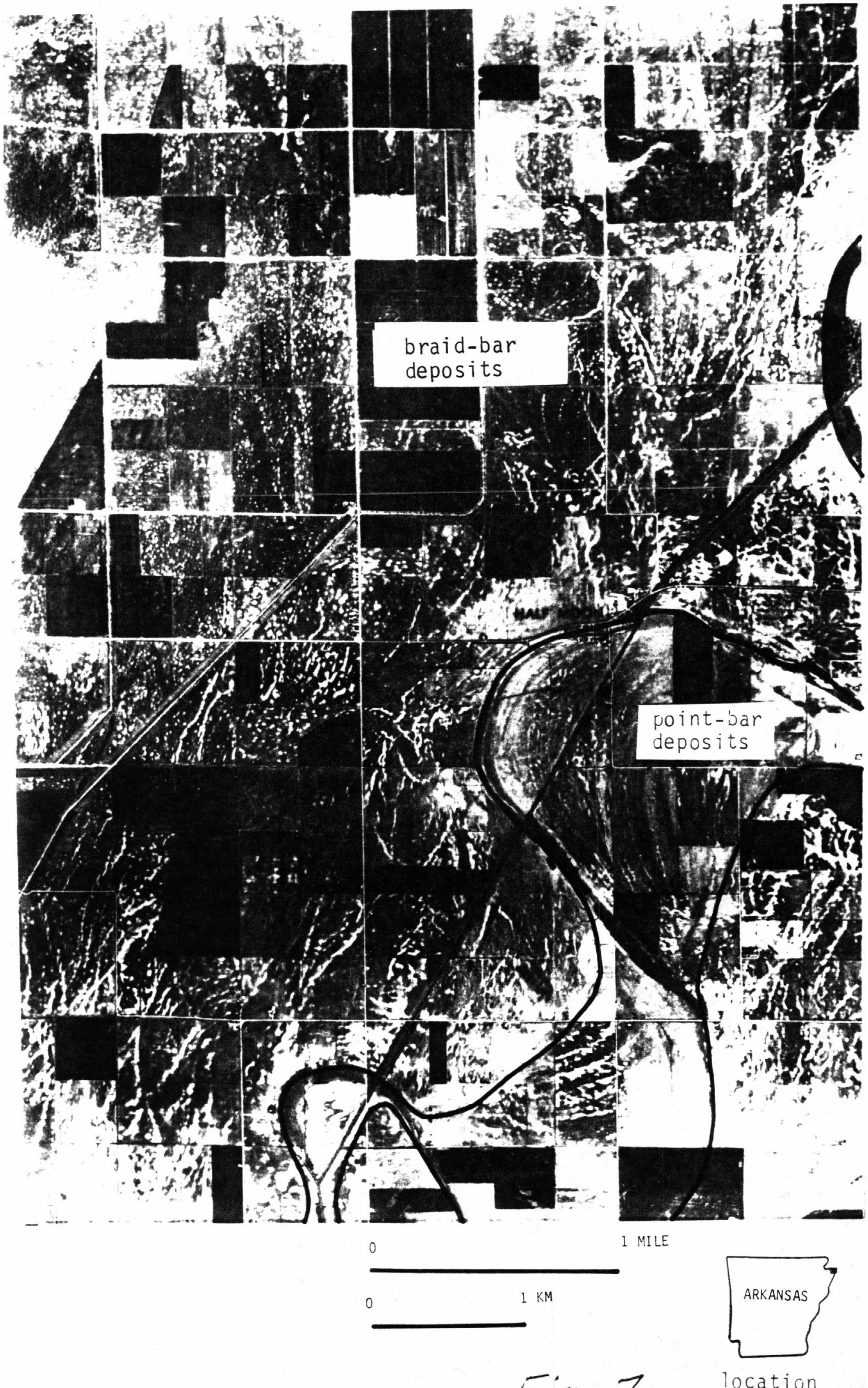
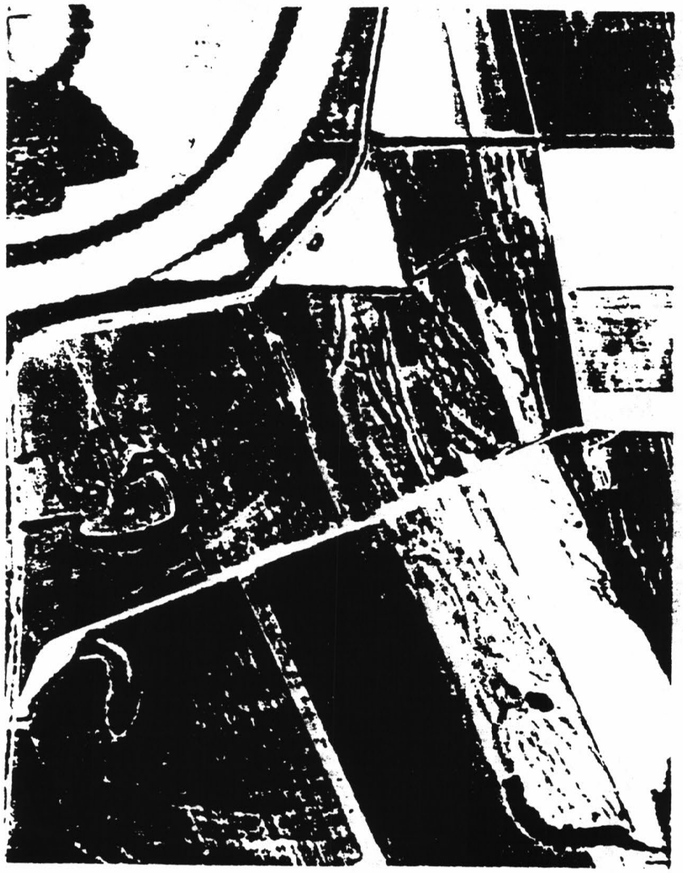
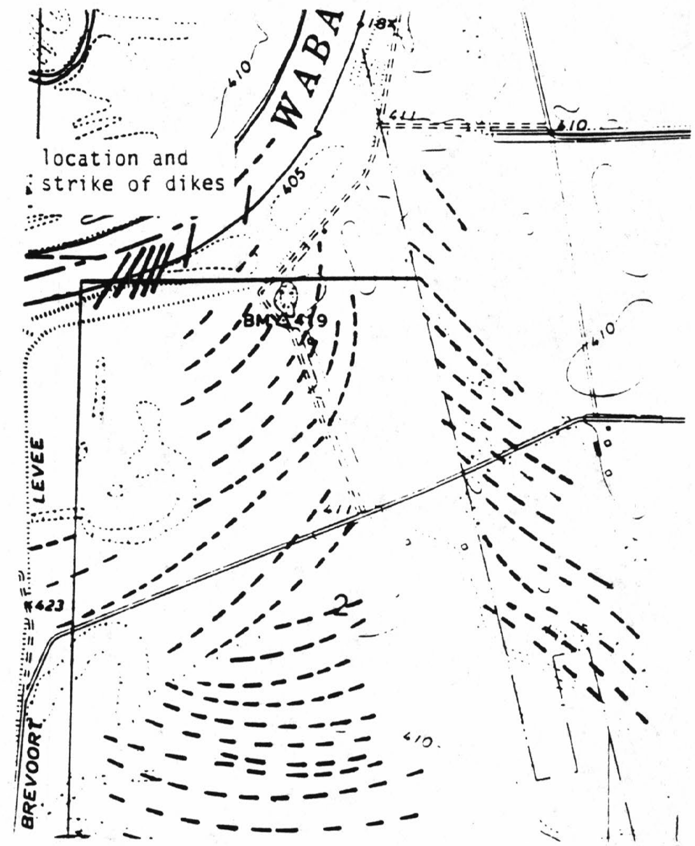

braid-bar deposits
point-bar deposits
0
1 MILE
0
1 KM
ARKANSAS
location

Fig. 7

(A)



(B)

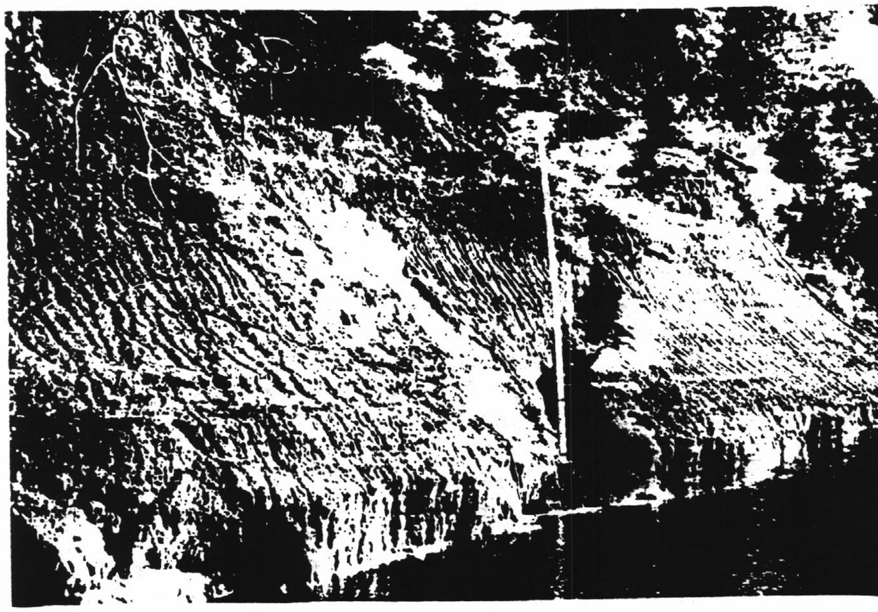


0 — 1 MILE

0 — 1 KILOMETER

Fig. 8

(C)



(D)

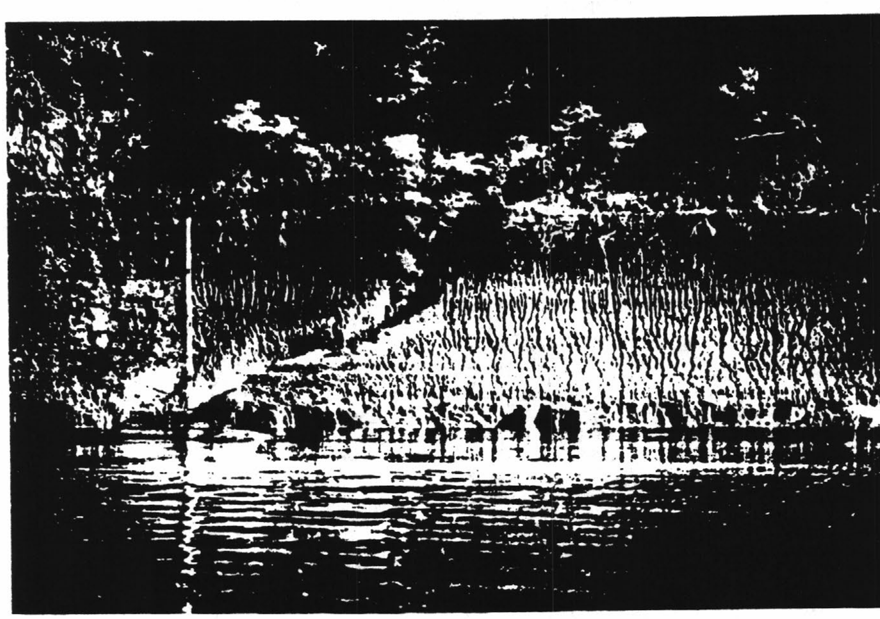


Fig. 8

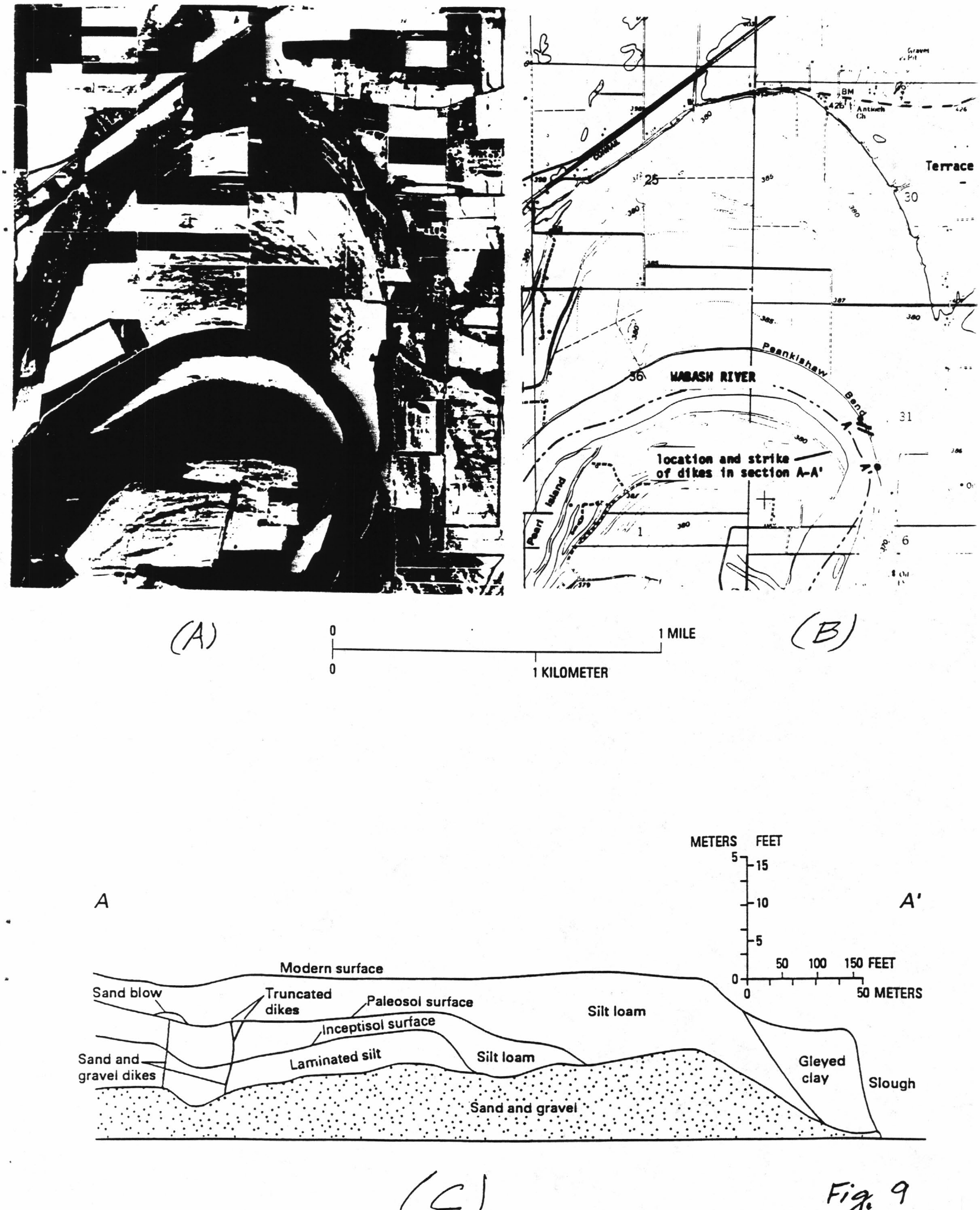
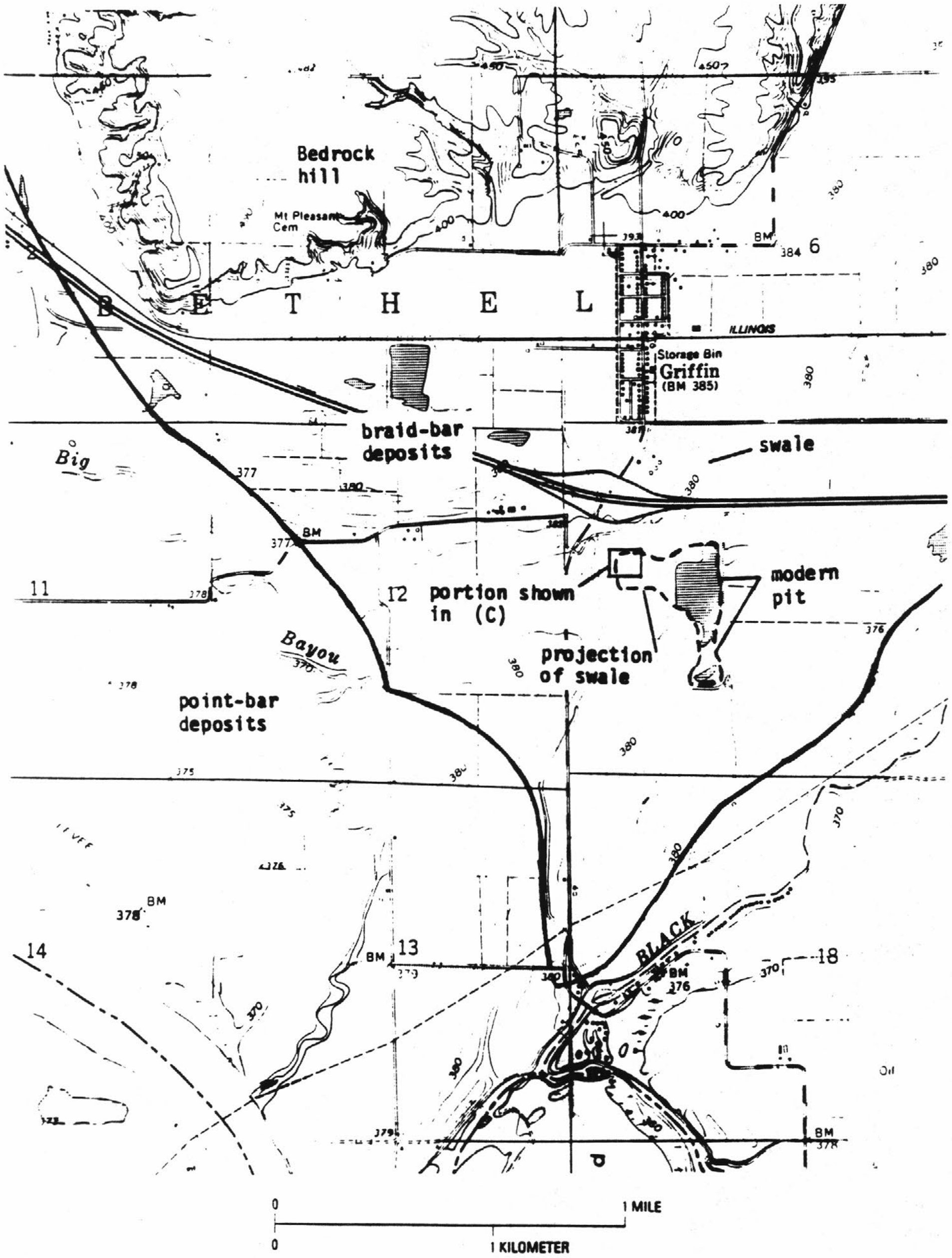

(A)
(B)
0
1 MILE
0
1 KILOMETER
Terrace
25
30
WABASH RIVER
Peankishaw Bend
31
A
A'
location and strike
of dikes in section A-A'
Pearl Island
1
6
METERS
FEET
5
15
10
5
0
0
50
100
150 FEET
50 METERS
A
A'
Modern surface
Sand blow
Truncated
dikes
Paleosol surface
Silt loam
Inceptisol surface
Sand and
gravel dikes
Laminated silt
Silt loam
Gleyed
clay
Slough
Sand and gravel
(C)

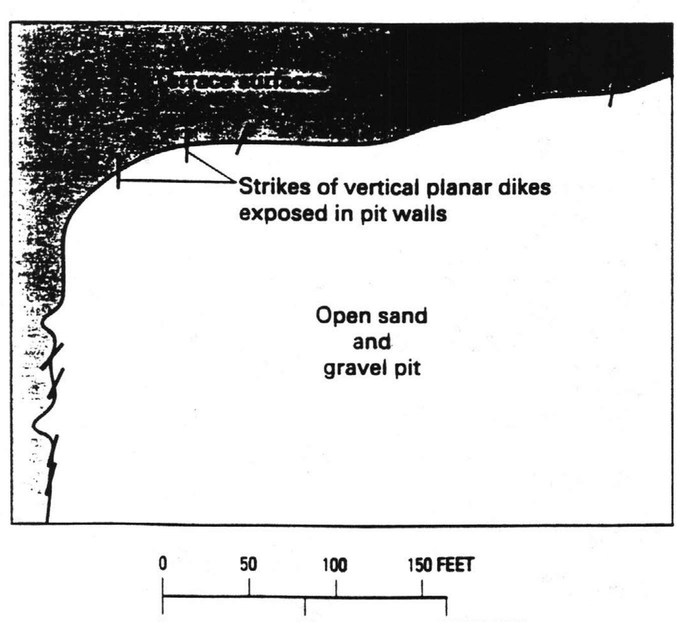
Fig. 9

(A)

Fig. 10

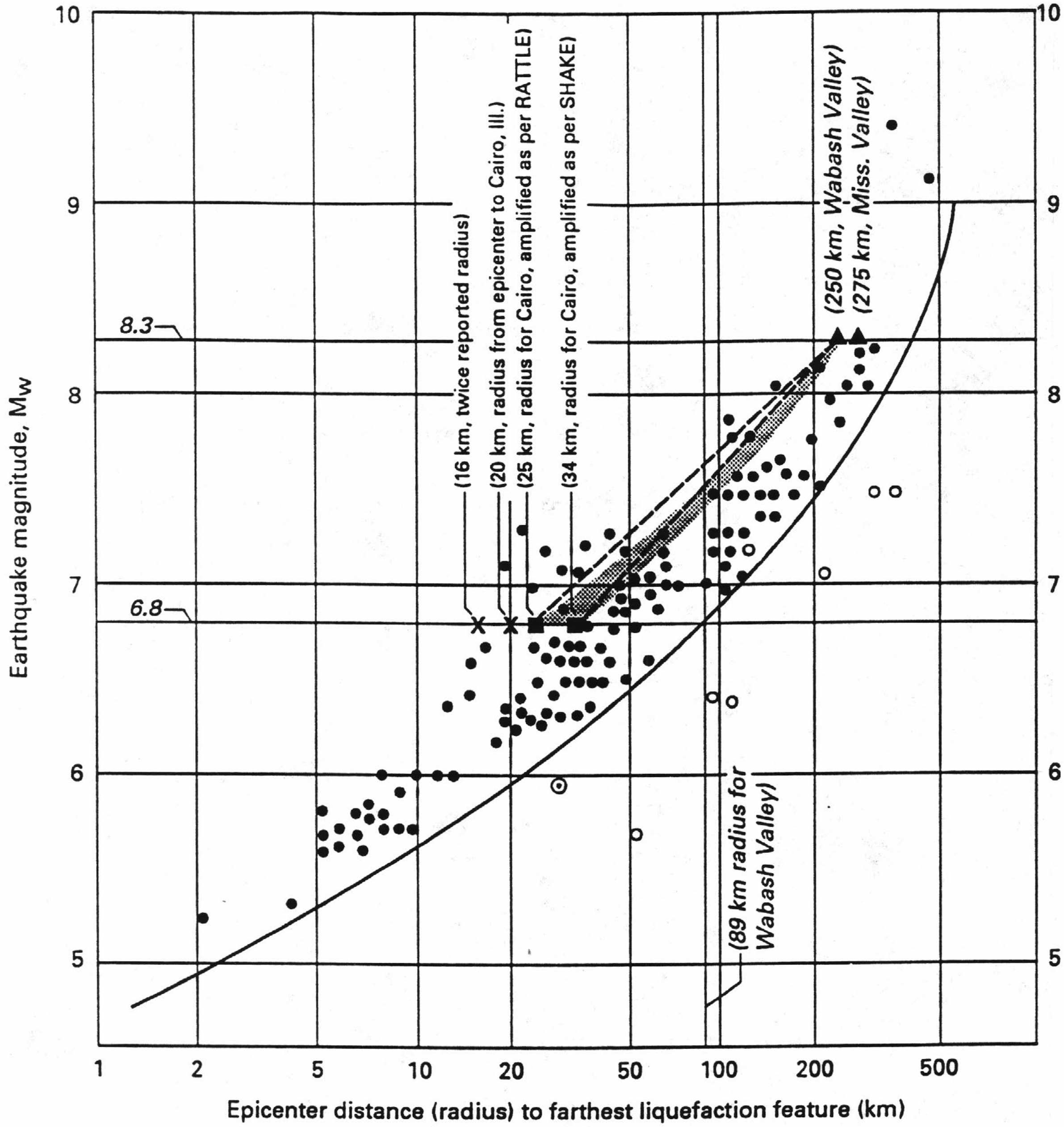

Bedrock
hill
Mt Pleasant
Cem
B E T H E L
ILLINOIS
Storage Bin
Griffin
(BM 385)
braid-bar
deposits
swale
Big
Bayou
portion shown
in (C)
modern
pit
projection
of swale
point-bar
deposits
BLACK
11
12
13
14
18
6
0
1 MILE
0
1 KILOMETER

(B)


Strikes of vertical planar dikes
exposed in pit walls
Open sand
and
gravel pit
0
50
100
150 FEET
0
25
50 METERS

(C)

Fig. 10



EXPLANATION

- ● Farthest liquefaction effect for shallow-focus earthquakes
- ○ Farthest liquefaction effect for deep-focus earthquakes (>50 km)
- ▲ Farthest sand blows reported for 1811-12 New Madrid earthquakes
- X Farthest sand blows for 1895 Charleston, Mo. earthquake
- ■ Farthest sand blows for 1895 Charleston, Mo. earthquake, corrected for bedrock amplification in Wabash Valley
- ⊙ Farthest sand blows for 1988 Saguenay, Quebec earthquake
- —— Bound suggested by Ambraseys (1988)
- – – – Upper bounds for Wabash Valley, using our analysis
- ▒ Most reasonable bound for Wabash Valley, using our analysis

Fig. 11

5/12/92

Table 1. RATTLE results for amplification of horizontal acceleration in soil with respect to bedrock, in Wabash Valley. (M_w = 6.5, hypocentral distance = 15 km, frequency band = 0.05-50 Hz, $\Delta\sigma$ = 100 bars, bedrock t* (travel time over Q for near-surface bedrock) = 0.01)

Material properties

stratum and depth(m)	density gm/cc	shear wave velocity (m/sec)	quality factor, Q
sand, 0-10	2.0	150	10, 15, 20
sand, 10-30	2.0	300	10, 15, 20
bedrock, >30	2.5	3,000	2,000

Amplification factors obtained by using 6 random no. seeds for each Q value

Q (sand)	peak acceleration amplification	rms acceleration amplification
10	1.9-2.9 (avg. = 2.1)	2.0-2.6 (avg. = 2.3)
15	2.0-3.5 (avg. = 2.4)	2.4-2.9 (avg. = 2.6)
20	2.2-3.9 (avg. = 2.7)	2.6-3.2 (avg. = 2.9)

D/1414A

Table 2. RATTLE results for amplification of horizontal acceleration in soil with respect to bedrock, in Charleston, Mo. area. (M_w = 6.5, hypocentral distance = 15 km, frequency band = 0.05-50 Hz, $\Delta\sigma$ =100 bars, bedrock t* (travel time over Q for near-surface bedrock) = 0.01)

Material properties

stratum and depth (m)	density (gm/cc)	shear wave velocity (m/sec)	quality factor , Q
sand, 0-10	2.0	150	10, 15, 20
sand, 10-38	2.0	300	10, 15, 20
sand & clay 38-148	2.0	330	20
sand & clay 148-258	2.0	667	50
bedrock, > 258	2.5	3,000	2,000

Amplification factors obtained by using 6 random no. seeds for each Q value in the upper 38 m of sand

Q (sand)	peak acceleration amplification	rms acceleration amplification
10	1.2-1.9 (avg. = 1.5)	1.5-2.0 (avg. = 1.8)
15	1.4-2.1 (avg. = 1.7)	1.7-2.1 (avg. = 1.9)
20	1.5-2.2 (avg. = 1.8)	1.7-2.2 (avg. = 2.0)

5/6/92

Table 3. SHAKE results for amplification of horizontal acceleration in soil with respect to bedrock, in Wabash Valley. (M_w = 6.5, f_{max} = 25 Hz, $\Delta\sigma$ = 100 bars)

Material properties

stratum and depth (m)	density (gm/cc)	shear wave velocity* (m/s)	shear modulus* (kg/cm^2)
sand, 0-10	2.0	150	460
sand, 10-30	2.0	300	1,835
bedrock, >30	2.5	3,000	-

*Value for 10^{-4}(%) shear strain.

Amplification factors for 6 random no. seeds, for peak acceleration at ground surface = 0.08 g

seed no.	peak acceleration at top of bedrock (g)	peak acceleration at ground surface (g)	amplification ratio
1	0.047	0.080	1.7
2	0.038	0.083	2.2
3	0.048	0.085	1.8
4	0.044	0.085	1.9
5	0.034	0.078	2.3
6	0.037	0.079	2.1
		average:	2.0

Amplification factors for 6 random no. seeds, for peak acceleration at ground surface = 0.10 g

seed no.	peak acceleration at top of bedrock (g)	peak acceleration at ground surface (g)	amplification ratio
1	0.047	0.100	2.1
2	0.057	0.098	1.7
3	0.052	0.098	1.9
4	0.059	0.095	1.6
5	0.050	0.106	2.1
6	0.049	0.098	2.0
		average:	1.9

2/18/92

Table 4. SHAKE results for amplification of acceleration in soil with respect to bedrock, in Charleston, Mo. area (M_w = 6.5, f_{max} = 25 Hz, $\Delta\sigma$ = 100 bars)

Material properties

stratum and depth (m)	density (gm/cc)	shear wave velocity* (m/s)	shear modulus*
sand, 0-10	2.0	150	460
sand, 10-38	2.0	300	1,835
sand & clay, 38-148	2.0	330	2,220
sand & clay, 148-258	2.0	667	9,065
bedrock, >258	2.5	3,000	-

*Value for 10^{-4}(%) shear strain.

Amplification factors for 6 various random no. seeds, for peak acceleration at ground surface = 0.08 g

seed no.	peak acceleration at top of bedrock (g)	peak acceleration at ground surface (g)	amplification ratio
1	0.060	0.082	1.4
2	0.064	0.083	1.3
3	0.086	0.084	1.0
4	0.086	0.084	1.0
5	0.074	0.082	1.1
6	0.068	0.076	1.1
		average:	1.2

Amplification factors for 6 various random no. seeds, for peak acceleration at ground surface = 0.10 g

seed no.	peak acceleration at top of bedrock (g)	peak acceleration at ground surface (g)	amplification ratio
1	0.081	0.104	1.3
2	0.084	0.100	1.2
3	0.112	0.098	0.9
4	0.098	0.103	1.1
5	0.100	0.097	1.0
6	0.106	0.098	0.9
		average:	1.1

5/6/92

Table 5. Comparison of liquefaction effects and factors controlling liquefaction, for earthquakes in the central and eastern United States

Earthquake source	Maximum span of sand blows (diameter about epicenter)	Maximum span for lateral spread movement of 0.15 m	Liquefaction susceptibility (A)	Amplification of bedrock acceleration (B)	Combined effect of (A) and (B) relative to Wabash Valley	Earthquake magnitude relative to single Wabash Valley paleo-earthquake
Wabash Valley	>175 km	probably >160 km	locally high (SPT blow counts as low as 6-7)	likely moderate amplification (factor of 2-3 as per RATTLE; or 2 as per SHAKE)	--	--
Feb. 7, 1812 New Madrid (m_b~7.4, M_w~8.3)	probably about 500-550 km	?	locally high	same as above along Mississippi and Wabash River valleys	about same along these valleys	much higher
1895 Charleston, Mo. (m_b~6.2, M_w~6.8)	probably <40 km (16 km reported)	?	locally high, especially along rivers	likely moderate amplification (factor of 1.5-2 as per RATTLE; or 1.15 as per SHAKE)	likely slightly to moderately higher	much lower
1886 Charleston, S.C. (m_b~6.7, M_w~7.5)	probably on the order of 200-250 km (100 km reported)	~140 km (calculated from (Youd et al., 1989)	locally extremely high near coast (SPT blow counts as low as 0-2)	likely slight amplification or attenuation	likely slightly higher	likely same order of magnitude