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Liquefaction Evidence for Two Holocene Paleo-earthquakes in Central and Southwestern Illinois

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Abstract

Two strong Holocene earthquakes in Illinois have been delineated by paleoliquefaction features such as clastic dikes, sills, and detachments of fine-grained sediment that sunk into liquefied sand. One paleo-earthquake occurred in central Illinois, about 35 km NE of Springfield, between about 5,900 and 7,400 yr BP. Dike widths are as much as 0.4 m in the presumed epicenter. Dike widths attenuate with distance from the epicenter to as far as 30 km, where they disappear.

Another paleo-earthquake centered about 65 km ESE of St. Louis, Missouri, occurred during the mid-Holocene. The epicentral region is in Illinois, probably near lowermost Shoal Creek. The epicentral region is defined by dikes as wide as 0.5 m and abundance of dikes. Dikes from this earthquake probably extend as far as 35 km from the epicenter.

Both earthquakes almost certainly exceeded **M** 6. Sufficient geologic data have been collected that, when used in conjunction with geotechnical testing, can be used to bracket more closely the likely magnitudes.

INTRODUCTION

Paleoliquefaction studies were initiated in southern Indiana and Illinois in 1990. Liquefaction features almost exclusively in the form of clastic dikes filled with sand or sand and gravel were discovered soon thereafter (Obermeier et al., 1991). The study area has since been enlarged to include most of the southern halves of Indiana and Illinois. A summary of findings current in early 1996 was reported by Munson et al. (1997). Subsequently, we have discovered much about the paleoseismic record in Illinois, and findings current in early 1997 are summarized by Obermeier (1997). Obermeier also discusses the geologic and geotechnical basis for interpretation of origin of the clastic dikes, as well as discusses the methods for estimating the magnitudes of the prehistoric earthquakes.

This report provides details of our recent findings for two paleo-earthquakes with epicenters in Illinois. One is centered about 35 km NE of Springfield, and the other is centered about 65 km ESE of St. Louis, Missouri. Evidence for the earthquake near Springfield was first discovered by R.C. Garniewicz in 1994, and was reported by Hajic et al. (1995). However, they collected insufficient data to make even a crude assessment of the magnitude of the earthquake. This prompted us to do a study to determine the limits of liquefaction of the earthquake, its epicentral region, and the depth of the water table at the time of the earthquake. All are required for geotechnical analysis of magnitude

The paleo-earthquake centered in southwestern Illinois was found as an outgrowth of previous studies. Liquefaction features along the lower Kaskaskia River were first discovered in 1992 by the second author, but the causative earthquake was unknown. The probable epicentral region has been resolved by a field search for liquefaction features over a large area in all directions around the lower Kaskaskia. Radius of the search area has exceeded 100 km.

OVERVIEW OF LIQUEFACTION STUDIES

Results of all paleo-liquefaction studies in Indiana and Illinois since the initial discovery by Obermeier are summarized in Figure 1. The map of Figure 1 is an overview showing liquefaction sites discovered in Indiana and Illinois. A liquefaction site is defined as a continuous exposure with at least one dike, but tens of dikes are also present at many sites; the exposure length ranges from a few meters to as much as 4 km. The figure also shows the maximum dike width at a site.

Almost all the sites on Figure 1 are from prehistoric seismicity of latest Pleistocene and Holocene ages. Only in extreme southern Illinois are there many sites where the features could be mostly or entirely from historic earthquakes, including the great New Madrid earthquakes of 1811-12. The most relevant, recent discussions of paleo-earthquakes represented in Figure 1 are in reports by Pond (1996), Munson et al. (1997), and Obermeier (1996, 1997).

Limits of liquefaction are shown in Figure 1 for only the six largest paleo-earthquakes. Virtually all liquefaction sites in Indiana have been associated with specific earthquakes by Munson and Munson (1996). In Illinois, incomplete limits and questionable limits are shown for most paleo-earthquakes because of the relative paucity of detailed site studies to bracket ages, and the lack of geotechnical studies.

In Indiana and Illinois, at least seven and probably eight prehistoric earthquakes have been documented during the Holocene, as well as at least one during the latest Pleistocene. The recognition of different earthquakes is based mainly on timing of liquefaction in combination with the regional pattern of liquefaction effects, but some have been recognized only by geotechnical testing at sites of liquefaction (Pond, 1996).

Ages of individual dikes are not distinguished on Figure 1. The bound of liquefaction for each of the earthquakes encompasses many dikes of the same age. Even though ages of dikes are not shown, the figure makes it apparent that the largest dikes associated with a paleo-earthquake generally lies well within the limits of the bound, thereby defining a core region of largest dikes. The figure also makes it apparent that many of the largest dikes are concentrated near the border between southernmost Indiana and Illinois. The concentration reflects liquefaction from an especially large magnitude earthquake that took place about 6,100 yr BP.

Prehistoric magnitude of the largest paleo-earthquake, the event of 6,100 yr BP, was probably on the order of moment magnitude **M** 7.5. This greatly exceeds the largest historic earthquake of **M** 5.5 centered in Indiana or Illinois. This and a **M**$\sim$7.1 prehistoric earthquake had epicenters in the vicinity of the lower Wabash Valley, where the valley borders both Indiana and Illinois. These epicenters are near where most of the strongest historic seismicity has taken place. Beyond the region of the Wabash Valley, prehistoric earthquakes on the order of **M** 6-7 and higher have occurred where there has been little or no historic seismicity.

Figure 1 also shows that large areas were not searched for paleoliquefaction features. Many of these blank areas have no liquefiable deposits or have no exposures suitable for a search. Many of the searched areas are separated as much as 75 km. Thus, even a large paleo-earthquake could have struck but left no liquefaction evidence.

Figure 2 shows epicenters of the eight largest paleo-earthquakes, superimposed on a map of historic seismicity. Epicenter locations of the prehistoric earthquakes shown on Figure 2 generally are thought to accurate within a few tens of kilometers (Obermeier, 1997). This assessment is based on the assumption that the region of strongest shaking (i.e., the meizoseismal zone) encompasses the epicenter (i.e., the point of initial rupture). Most of the prehistoric earthquakes have a reasonably well defined core region of largest, most abundant dikes, which, under similar geologic conditions, should represent the region of strongest shaking. Geotechnical analysis by Pond (1996) generally supports the interpretation of using the core as the region of strongest shaking, though this relation must always be evaluated on a case-by-case basis.

Epicenters for the two earthquakes we discuss below are on Figure 2. We refer to them as the Springfield and the Shoal Creek earthquakes.

THE SPRINGFIELD EARTHQUAKE

A map of the region of the Springfield earthquake, enlarged from Figure 1, is shown in Figure 3. Only dike locations are shown on the figure even though many other sites were discovered with other manifestations of liquefaction such as sills and detachment structures (Fig. 4). All paleoliquefaction features were discovered in banks of streams, although a very large sand-and-gravel pit was also examined. A continuous search of stream banks was made along all portions indicated in Figure 3. Searching was done when field conditions were optimal for observing clean bank exposures. Many were examined in the spring of 1995, shortly after floodwater had receded from an especially severe flood in central Illinois. The smaller streams, and especially Deer Creek and Sugar Creek, had great lengths scoured clean by the flooding, presenting an opportune occasion to search for liquefaction features. Searching along almost the larger streams (e.g., Sangamon River, Salt Creek) was done when stream levels were quite low, which for these streams was optimal. Altogether, the opportunity to observe liquefaction features that formed throughout Holocene and into latest Pleistocene time was very good throughout a large region. Results of the searches along individual streams are discussed below.

Results of the Field Study

<u>Sangamon River</u> The search on Sangamon River extended upstream to as far as Big Creek (Fig. 3) and included about 2 km of that stream. In general, upstream from Lake Decatur, only exceptionally were there exposures as old as about 5,900 to 7,400 yr BP, the age of the Springfield earthquake. Some of the oldest exposures were in situations very favorable for liquefaction features to have developed throughout Holocene time, which causes us to us to conclude that probably no strong seismic shaking has occurred there in Holocene time.

Downstream from Lake Decatur, numerous exposures are old enough to record the Springfield event on the basis of stratigraphic and weathering relations, supplemented with radiocarbon data. Fine-grained deposits of early to mid-Holocene typically are at higher elevations and are more severely weathered than younger sediments (Fig. 4). The levels of the base of the older fine-grained deposits are generally 1 to 2 m above deposits younger than about 6,000 yr BP. The older deposits appear to have been laid down mainly by braided streams, whereas younger deposits were laid down by meandering streams with deeper channels. The combined thickness of Bt and Bw horizons is typically three to four meters in deposits older than 7,000 yr BP. These relations between age and level of fine-grained cap are very evident along the portion of the Sangamon shown boxed in Figure 4. Very long sections as old as 5,900 yr BP (radiocarbon site 1, Table 1) had no dikes or other, more sensitive, indicators of seismic liquefaction, such as sills and detachment structures. Older deposits had sensitive indicators, however, within the bound indicated for liquefaction. Thus, the lower age limit for liquefaction in the region is taken to be 5,900 yr BP.

Dikes as much as 30 cm in width occur at radiocarbon site 2 (Fig. 3). A schematic depiction of part of the site is shown in Hajic et al. (1995, Fig. 13). Dikes associated with lateral spreading occur throughout a 300 m exposure. Gravel-filled, pinching up dikes as much as 5 cm in width also occur in the area, on the streambank opposite from the wide dikes. Dikes vented onto the paleosurface at two locales, but no material suitable for radiocarbon dating was found along the paleosurface. Host materials as young as 7,870 yr BP were cut by dikes at this site (Hajic et al., 1996).

Dikes and sills are present at radiocarbon site 3 (Fig. 3). A log at the base of the cap, directly beneath a dike, had a radiocarbon age of 7,380 yr BP. This age provides the upper bound limit for the Springfield earthquake.

Downstream from radiocarbon site 3, exposures were very limited and stream banks were low, likely because of a small dam or shallow bedrock. Thus the opportunity to find liquefaction effects from the earthquake were poor.

The water table depth is thought to be relatively shallow along the Sangamon when the earthquake struck. This deduction is based on the premise that for the highly permeable sands in the region, the liquefied zone must be at least as high as the base of the fine-grained cap. Otherwise the excess pore-water pressure would dissipate in the sand beneath the cap. Levels of the bases of dikes at two widespread sites, and the levels of detachments beneath the cap at widespread sites, indicate the water table was probably less than 2 to 2.5 m deep when the earthquake struck.

Lake Fork All searching along the Lake Fork was done by walking in a ditched portion of the stream during a period of very low flow. Even though Lake Fork is a small stream, it is in an exceptionally good physiographic situation to have recorded liquefaction from any earthquakes since the deposits were laid down, in late Pleistocene time. The Lake Fork traverses a broad valley filled with glaciofluvial sand that has been capped with a thin silt veneer (3 to 4 m) throughout the Holocene and into latest Pleistocene. The valley has had a persistent high water table as indicated by the unoxidized base of the cap, and the radiocarbon age of a wood fragment in the cap, near the base (radiocarbon site 4, Fig.3., Table 1).

Wide dikes were found at two sites on Lake Fork. One dike at each of the two sites was in excess of 30 cm wide. The widest dike was at least 37 cm, and may have been in excess of 50 cm. The ground was so severely disrupted that definite assessment was not possible. Also, at the widest dike, more than one episode of intrusion appears to have occurred at widely spaced times. Whether there was venting could not be determined because of bank conditions.

All the smaller dikes on Lake Fork pinched together upward. The small dikes at radiocarbon site 4 were accompanied by extensive development of sills.

Salt Creek Numerous exposures on the uppermost portion were searched, but the great majority were younger than mid-Holocene in age. Still, a few of the exposures revealed glaciofluvial deposits, but most seemed so gravelly the very strong shaking would have been required for any liquefaction.

Only a very small portion of lowermost Salt Creek was searched (less than one km), even though conditions are excellent for searching through this part. Two small, pinching together dikes were found in a terrace that is slightly higher and older than other exposures. No evidence of liquefaction was found in the lower levels. The field relations showing levels where dikes were found are depicted in Figure 4. As was the case along the Sangamon River, the water table was at least relatively high when the earthquake struck, being less than 2.5 m deep.

Deer Creek Conditions for forming liquefaction features along most of the searched portion of Deer Creek clearly have been excellent throughout Holocene time. Deer Creek is a small stream that flows across a broad valley filled with glaciofluvial sand. The sand is capped by few meters of silt, which is unoxidized in the basal portion. A small stick taken from the contact of the silt cap and sand yielded a radiocarbon age of 9,860 yr BP (radiocarbon site 6, Table 1). At least two km of exposures revealed clean sand overlain by a thin silt cap, in which a water table has persisted within 2 to 3 m of the surface through Holocene time. One very small, possible dike was discovered in the most downstream portion of the searched part.

Kickapoo Creek Two sections of Kickapoo Creek were searched. The upstream section greatly resembled the physiographic setting of Deer Creek. Conditions were clearly excellent for forming liquefaction features for most of Holocene time. Dikes were discovered only in the lower section of the search area. Three small, pinching together dikes were discovered in an exposure where a log at the base of one dike (radiocarbon site 6) yielded an age of 7,730 yr BP. Many other exposures of such great age, in settings of persistent high water tables, were in the vicinity of the site with the dikes, but none contained evidence of liquefaction.

Sugar Creek Conditions along Sugar Creek were outstanding, and were basically the same as along upper Kickapoo Creek and Deer Creek. Strong shaking from any earthquake through almost all Holocene time should have developed dikes that would have been discovered.

South Fork, Sangamon River Numerous exposures revealed sediments old enough to have liquefied from the Springfield earthquake. The depth and severity of weathering of the fine grained cap was extraordinary at many places, indicating ages in excess of Holocene. In addition, polygons in plan view, at a depth of a few meters, were extensive in caps of silt and sandy silt; we suspect these polygons reflect structures caused by severe frost or permafrost in a periglacial environment. Such a severe environment would have occurred only in earliest Holocene or older time.

The only liquefaction site along the South Fork of the Sangamon has numerous closely spaced, small dikes that cut into and pinch out in a mat of sticks, twigs, leaves, and other organic matter. The mat is decomposed so completely that it can be torn apart by hand.

Radiocarbon age of the mat is 25,240 $\pm$ 240 yrs BP (radiocarbon site 8, Table 1). The dikes cut across the sticks and twigs, so the mat must have been decomposed when the dikes intruded. The site with the dikes was the only exposure suspected to be of such great age along the South Fork. Whereas the dikes in the mat may be from the earthquake northeast of Springfield, the paucity of dikes along the South Fork suggests otherwise. As a minimum, shaking could not have been very strong along the South Fork.

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

<u>Flat Branch</u> Flat Branch flows through a valley filled with glaciofluvial sand, which is capped with a thin veneer of silt and clay. Water table in the region is very high. Even though the region is ideal for forming liquefaction features, Flat Branch is such a lethargic stream that the banks were never clean enough to permit observing even any very large liquefaction features that may have been present.

<u>Sand and Gravel Pit</u> About 300 m of bank exposures were examined in a large sand and gravel pit (Buckhart Sand & Gravel) located 10 km east of Springfield (Fig. 3). Thick (tens of meters) glaciofluvial sand is capped with several meters of silt, in a field setting where the water table is normally quite high. The silt cap is severely weathered in at least the uppermost 2 meters, including a strongly bleached E-horizon. The cap is likely at least earliest Holocene in age, and certainly is old enough to record the Springfield earthquake. In summary, the field situation for forming liquefaction features in response to the Springfield earthquake was very good, especially considering that the water table was relatively high at the time of the earthquake.

The lowermost part of the cap could not be observed during the paleoliquefaction search, because it extended to a depth of about 2 m below water level. Thus, any sills, detachments, or very small dikes that might have been present would not have been observed. Still, any medium sized or large dikes would have been visible. The lack of any such dikes indicates that seismic shaking from the Springfield earthquake could not have been especially strong in the vicinity of the pit.

Discussion of Results for the Springfield Earthquake

The regional pattern of dikes shows a well-defined cluster ("core") of widest dikes about 35 km northeast of Springfield. This core region likely identifies the epicentral area because the ability to form liquefaction features is probably relatively uniform throughout the area, on the basis of thickness of alluvium, and character of sands and overlying capping material.

Unconsolidated sediment is relatively thin as shown by our field observations, supplemented with map information by Soller (in press). Bedrock generally is less than 30 m deep, and infrequently is as shallow as 5 m. Such a thin alluvial cover does not permit large amplification of bedrock shaking (Obermeier et al., 1993; Pond, 1996). As a maximum, bedrock peak accelerations were probably amplified by a factor of less than X 1.3.

Clean sands that typically are medium sized occur throughout the study area. The sands were laid down by fluvial processes, and the fine-grained cap above the sands is generally relatively thin, on the order of 2 to 4 m; thus, at least regionally, the ability of the sands to liquefy is likely about the same. In addition, at the time of the Springfield earthquake, the water table was relatively shallow. In summary, factors relating to liquefaction susceptibility were probably relatively uniform, and therefore the core region of largest dikes probably identifies the locale of strongest shaking. We take this locale to approximate the epicenter.

The farthest dike from this inferred epicentral region is probably on the order of 35 km. An upper bound estimate of the prehistoric magnitude is provided by using the distance of 35 km in conjunction with a curve developed for the study area of southern Indiana-Illinois, which relates distance of the farthest liquefaction effect from the epicenter to the magnitude (Obermeier et al., 1993; Pond, 1996). Use of the curve yields moment magnitude **M** 6.8. We emphasize that we suspect this magnitude is an upper limit, because the curve was developed for higher bedrock amplification than likely occurred in the study area, and in addition, the water table at the time of the Springfield earthquake was likely higher than normal. A lower limit magnitude is about **M** 6.2, using the lower bound relations for earthquakes that have occurred worldwide (see Obermeier et al., 1993). Site-specific geotechnical testing will be required in the study area before a better estimate of magnitude can be made.

THE SHOAL CREEK EARTHQUAKE

The vicinity of the Shoal Creek earthquake is shown in Figure 5, which is an enlargement of part of Figure 1. All dikes sites were discovered in banks of streams. Even though sand and gravel pits were searched in the area of the figure, all pits had sediments too young to show evidence of liquefaction from the Shoal Creek earthquake, which almost certainly occurred during mid-Holocene time. Thus pit locations are not shown.

Searching was done by continuous examination of all portions of streams indicated in Figure 5. Stream levels were very low when the stream banks were searched, presenting optimal conditions for finding liquefaction features. Results of the searches along individual streams are discussed below.

Results of the Field Study

<u>Shoal Creek</u> Only the lowermost 15 km of Shoal Creek were searched, because elsewhere bank conditions were very poor for revealing liquefaction from an earthquake approximately mid-Holocene in age. Within the searched portion a 0.45 m wide dike (lateral spread) was discovered, and all exposures revealing potential hosts of sufficient age contained dikes. No evidence of venting of sediment onto a paleosurface was discovered. Most bracketing of when the earthquake occurred has been done by bracketing the age of the hosts, and by comparison of weathering profile of sediment in dikes with the profile of the hosts.

Relative ages of potential hosts were based on severity and depth of weathering of the fine-grained cap. Dikes were found only in fine-grained, very clay-rich silt hosts that had weathered (oxidized to Bw condition) continuously to a depth of about 2 meters below modern stream level, at lowest flow (i.e., all hosts deposits are oxidized above the 2 meter depth). Such a depth of the Bw shows that the hosts have experienced a long-term episode of drying when the water table was much deeper than now. This great depth of the Bw in combination with other excellent evidence indicates antiquity of the hosts; these indicators include depth and thickness of the Bt horizon above the Bw, the presence of a thick, well developed E horizon above the Bt, and the presence of caliche-like nodules throughout the Bt and in some of the Bw. Altogether, these weathering indicators show that the hosts had experienced the "hypsithermic," which ended about 6,000 yr BP and was a time when drying lowered the water table significantly (Knox, 1983). The radiocarbon age of the least weathered host with dikes was found to be 6,690 yr BP (site 10 on Fig. 5).

The Shoal Creek earthquake is believed to be mid-Holocene in age not only because of the antiquity of all hosts, but also because of severity of weathering in the filling in the large lateral spread. The filling is very similar to the laterally adjoining host throughout the uppermost 2 m, in terms of grain sizes and severity of weathering. In both, the Bt horizon is about 2 1/2 m thick, and the E is more than 1 1/2 m thick. Thus the ages of the host and the lateral spread must be close to one another.

Kaskaskia River Great lengths of potential host deposits were exposed along the portion of the Kaskaskia shown of Figure 5, especially in the lowermost half. The search terminated at the upstream end of the portion that has been channelized to the Mississippi River. The channelized portion has been covered with rip-rap on both banks, thereby concealing the deposits from inspection. Upstream from the channelized portion, though, the Kaskaskia is severely eroding laterally and is also downcutting. The erosion is so severe that clean banks are almost continuous in the lowermost 15 km of the searched portion. Erosion decreases upstream, but conditions were very good for revealing paleoliquefaction features all the way to Lake Carlyle (Fig. 5).

Figure 5 shows that many sites with dikes were discovered along the Kaskaskia. As was the case along Shoal Creek, though, no evidence of venting onto a paleosurface was found, and no cross-cutting relations could be used to bracket closely when any individual dike was formed. Only radiocarbon ages of hosts, in combination with severity of weathering of hosts and of the largest dikes provide guidance to ages. Fortunately, the recent downcutting of the Kaskaskia revealed the unoxidized, basal portion of the cap at many places, which made it easy to collect samples for radiocarbon dating of the cap.

It was obvious from even superficial field examination that at least two ages of earthquakes, widely spaced in time, are represented along the part of the Kaskaskia on Figure 5. A very young event is represented by the dike at site 12. The dike is small and pinches together about 2 m beneath the modern surface. The host is virtually unweathered to the surface, making unlikely an age of more than several hundred years. Sand in the dike shows no evidence of weathering and is very loose, indicating youth. Possibly the dike was caused by the great 1811-12 New Madrid earthquakes, which at the time of the earthquake caused small liquefaction effects to be observed as far north as the Cahokia Plains on the Illinois side of the Mississippi River, across from St. Louis (Donnely, 1949).

Near site 12 with the very young dike are two other sites (both shown as being at radiocarbon site 14) with intrusions cutting into much older dikes. Indeed, several of the larger dikes downstream have evidence of multiple intrusions into older dikes, likely widely spaced in time, but no effort was made to catalog them because of the inability to be certain if more that one earthquake is represented by many of the intrusions.

Except for the very small dikes, the paleoliquefaction data indicate an absence of strong shaking since the mid-Holocene. Only in mid-Holocene and older deposits are there many and much larger dikes. The youngest of the mid-Holocene generation is at site 11, with an age of 5,840 yr BP. Three sites (sites 13, 16, 17) are in the 8,000 yr BP range.

The largest dike, a 30 cm wide lateral spread, cuts into a host that has an age of 13,480 yr BP (site 15). The dike cuts into a cap 7 m in thickness; the dike could be traced within 2 1/2 to 3 m of the paleosurface, where the dike becomes so severely weathered that it cannot be traced upward. Such severity strongly indicates that the dike is mid-Holocene or older.

Further downstream from site 14 are two other sites (18 and 19) in which the hosts are latest Pleistocene to earliest Holocene in age, on the basis of a thick stratum of montmorillonite clay that caps the hosts; montmorillonite was last introduced in the region by flooding of the Mississippi during meltdown of glaciers, during latest Pleistocene (Leon Follmer, Ill. Geol. Survey., oral commun., 1996). The dikes at one site cut the montmorillonite cap and are strongly weathered, and thus could possibly be latest Pleistocene in age.

Figure 5 seems to indicate an especially high abundance of dike sites in about the lowermost 15 km of the searched portion of the Kaskaskia. The apparent high concentration is an artifact of the figure, however, because of the extraordinary amount of exposure along that portion of the Kaskaskia. Overall, the concentration per unit of exposure is probably higher in the vicinity of the 30-cm-wide dike.

The level of the base of all the dikes in the older hosts (i.e., older than mid-Holocene) is far beneath the tops (deeper than about 3-4 m) of the hosts, even though sand susceptible to liquefaction extends to higher levels at many places. This depth indicates the water table was relatively deep when the ancient earthquake(s) struck.

In summary, dikes from at least two earthquakes occur along this part of the Kaskaskia River. One generation of dikes, all quite small, is very young and perhaps from the great 1811-12 New Madrid earthquakes. The second generation formed during a mid-Holocene earthquake(s). Many of these dikes could have been induced at the same time as those on Shoal Creek. The largest dike on the Kaskaskia, the 30 cm wide dike at site 14, is relatively close to the 0.5 m wide dike on Shoal Creek. Still, the 30-cm-wide dike and others on the Kaskaskia may have resulted from a latest Pleistocene-earliest Holocene earthquake. Other possible earthquakes that may be represented are discussed below.

Silver Creek Two sections were searched along Silver Creek. The most relevant is the lowermost section, about 5 km in length. Numerous, very long exposures were examined that are at least as old as the exposures on Shoal Creek with the dikes, on the basis of radiocarbon data (site 20) and severity of weathering. As on Shoal Creek, the older sediments are weathered at least 2 m below the modern water table, even during dry periods.

An upper section of 3 km in length was also searched. Sparse outcrop in the upper section (~75m total) was virtually identical to larger exposures searched on Cahokia Creek (discussed below). Weathering characteristics, bank elevation, and soil development indicate an age far less then the exposures hosting liquefaction on Shoal Creek.

No dikes were observed on Silver Creek. However, any liquefiable sand is probably thin and in patches on the basis of data from engineering borings for bridges along Silver Creek. Six hand borings that we made to depths of 6-7 m below the paleosurface encountered only sandy clay and possibly clayey sand in the lowermost meter of the borings, and silt and clay above. Such thin, dirty sand deposits would probably have liquefied only in the event of extremely strong seismic shaking.

<u>Cahokia Creek</u> No dikes were observed on about 10 km of Cahokia Creek that were searched. However, it is unclear whether significant lengths of exposures were as much as mid-Holocene in age. Radiocarbon data show that large sections were as old as 3,000 yr BP, but that age much post-dates the dikes on Shoal Creek.

<u>Big River</u> The lowermost 15 km of the Big River were searched. Only about 500 meters, in several widely scattered locales, were clearly of sufficient age to record a mid-Holocene earthquake. At one site (site 21) there was evidence of ancient landsliding, possibly accompanied by a small sand dike and sills. Age of the host is at least earliest Holocene (M. Tuttle, oral commun., 1996), on the basis of age of an Indian artifact within the host.

Exposures of very young to mid-Holocene sediments are very common in this portion of the Big River. The physiographic setting is that of a rapidly broadening flood plain in response to merging with the Meramec River. Such a field setting is very favorable for having high liquefaction susceptibility through time. Thus the absence of liquefaction features probably indicates a lack of strong shaking since at least mid-Holocene time.

Even if the possible older dike is seismic in origin, it is unlikely that very strong shaking has taken place in Holocene time; this interpretation is supported by observations nearby on the Meramec River.

<u>Meramec River</u> A length of some 75 km was searched upstream from the confluence with the Big River. Radiocarbon data and weathering observations show that there were very few exposures more than 3-4,000 years old, in situations favorable for liquefaction. There were adequate exposures, though, to have recorded any strong seismic shaking in the region the past several thousand years.

Just upstream from the confluence with the Big River is an extraordinary exposure in terms of length (approaching 1 km) and age. This exposure should have recorded very strong seismic shaking since at least latest Pleistocene time. The exposure is approximately 8 to 10 m in height above low flow of the river. The cap is weathered to strong red in the upper parts, providing evidence for Pleistocene age. The cap overlies sandy gravel and gravelly sand at various levels. The sizes of the granular deposits are too coarse to be sensitive indicators of seismic shaking, but any very strong shaking probably should have caused some liquefaction features to have formed, throughout Holocene time. No indications of liquefaction were found.

Big Muddy River Two sections of the Big Muddy River were searched. No evidence of liquefaction was found in the upper section, where about 3 km of stream banks were searched. Exposures in the river banks were commonplace, yet no liquefacion features were found. Sediments examined were dominantly early Holocene-late Pleistocene, on the basis of geologic map information (Lineback, 1979). According to map information by Soller (in press), part of the searched region should be underlain by sand deposits, but the total thickness of sand-rich deposits should be relatively thin, less than 15 m. This portion of the Big Muddy is poorly drained, and large areas were clearly very swampy before deep drainage ditches were excavated in recent years. Considering all factors relevant to liquefaction susceptibility, the sand deposits in this portion of the searched area are probably so thin and patchy that very strong bedrock shaking would have been required to form liquefaction features. Still, very strong shaking should have induced some features that we would have discovered.

The lowermost portion that was searched on the Big Muddy was as a joint study with M. Tuttle. About 20 km of the Big Muddy was examined. Only small dikes were found at a few widespread sites (Tuttle et al., 1996), even though exposures were plentiful that should have revealed evidence for any very strong seismic shaking throughout the Holocene. Conditions for forming liquefaction features have probably been very good throughout the Holocene, on the basis of the very thick, clean sands throughout much of the study area and the likelihood of a persistently high water table in the broad alluvial floodplain traversed by the Big Muddy. In summary, the relative paucity of liquefaction features indicates a lack of very strong seismic shaking throughout the Holocene.

Big Creek Ditch and Auxier Creek Dikes in both drainages are exposed in glacial slackwater deposits that almost certainly are latest Pleistocene in age (Lineback, 1979). The slackwater deposits are dominantly silt and clay (Soller, in press), locally intercalated with thin lenses of clean medium and fine sand (Illinois DOT bridge borings). The slackwater deposits cover extensive, very flat regions, which were swampy and persistently wet before deep drainage ditches were excavated. Thus it is very likely that conditions for liquefaction have persisted throughout Holocene time, but the lack of thick sand deposits would have prevented large liquefaction features from ever forming, irrespective of strength of seismic shaking.

The dikes along these two drainages all pinch together upward in the fine-grained cap of slackwater deposits, which prevents meaningful bracketing of when the causative earthquake(s) struck. The size and abundance of liquefaction features along these drainages seems consistent with two very large paleo-earthquakes ($M > 7$) whose epicenters were farther east (Fig. 1), near Vincennes, Indiana.

Skillet Fork Only in the uppermost part of the searched portion of Skillet Fork are there sand deposits thick enough to readily liquefy and form large dikes. Downstream from the upper 10-15 km of the searched portion, the fine-grained cap becomes so thick that it would be very difficult for any liquefaction dikes to penetrate up to levels observable in the banks of the stream, irrespective of level of shaking. The entire portion of Skillet Fork was very wet and swampy before large man-made drainages were excavated, and likely was swampy through Holocene time.

The absence of large liquefaction features in the uppermost searched part, in conjunction with scattered occurrences of small features, indicates that extremely strong seismic shaking has not struck this area. The liquefaction effects in the region seem consistent with the proximity to the epicenters of the two very large earthquakes (M>7) that were farther east (Fig. 1).

Discussion of Results for the Shoal Creek Earthquake

Alluvial deposits along Shoal Creek are relatively thin (Soller, in press), presenting little opportunity for amplification of bedrock shaking. In contrast, along nearby Kaskaskia River, both alluvium and clean deposits are much thicker, presenting a much greater opportunity to form large and abundant liquefaction features. Yet the widest dike (0.5 m) and a higher abundance occurs along Shoal Creek. Every exposure of sufficient age (i.e., predating the end of hypsothermic time) on Shoal Creek hosted dikes. Such an abundance is typically found only in the meizoseismal region of an earthquake, and such a width is typically found only in the meizoseismal region.

The possibility has also been considered that the M~7.5 earthquake that struck about 6,100 yr BP, with epicenter near Vincennes, Indiana (Fig. 1), is the source of the dikes on Shoal Creek. However, the size of the widest dike is too large, the abundance of dikes is too high, and conditions for amplifying bedrock motions are too poor for the dikes on Shoal Creek to be reasonably associated with the earthquake at Vincennes.

Field searches nearly encircled Shoal Creek. Yet no evidence was found for another candidate as the source region of the mid-Holocene liquefaction features on Shoal Creek. Only due north of the Shoal Creek sites is there a very large area that has not been searched. We recommend that further searching be done in this region. In the meantime, the best candidate for the epicenter is the vicinity of lower Shoal Creek.

Most likely, many of the dikes along the portion of the Kaskaskia on Figure 5 were caused by the same earthquake that created the Shoal Creek dikes. The dikes are too large and too abundant on Shoal Creek to have not come from an earthquake affecting a large region.

Even though more field searching needs to be done, a geotechnical assessment of the strength of shaking required to form the dikes on Shoal Creek could now be done profitably. The water table was likely quite deep at the time of the earthquake, on the basis of observations along the Kaskaskia.

The magnitude of the earthquake cannot yet be realistically bracketed within close limits. However, the fact that historic **M** 5.5 earthquakes have not even been observed to have caused liquefaction in the study area indicates a significantly stronger event was necessary. We believe that **M** 6 is a reasonable lower limit, especially considering that the water table was likely relatively deep at the time of the earthquake.

CONCLUSIONS

1. A strong earthquake struck in central Illinois between 5,900 and 7,400 yr BP. The epicenter was probably about 35 km NE of Springfield. Dikes are as much as 0.4 m in width near the presumed epicenter. Moment magnitude almost certainly was in excess of **M** 6, and was less than **M** 6.8.

2. A strong earthquake struck in southwestern Illinois during the mid-Holocene. The epicenter was likely about 65 km ESE of St. Louis, Missouri, in the vicinity of lower Shoal Creek. Dikes as wide as 0.5 m occur in the epicentral region. Dikes probably extend as far as 35 km from the epicenter or this earthquake. Moment magnitude almost certainly was in excess of **M** 6.

3. Geotechnical testing can probably provide a better estimate of the magnitudes of these two paleo-earthquakes, and especially for the earthquake near Springfield. For both paleo-earthquakes, an adequate number of sites is available for geotechnical testing.

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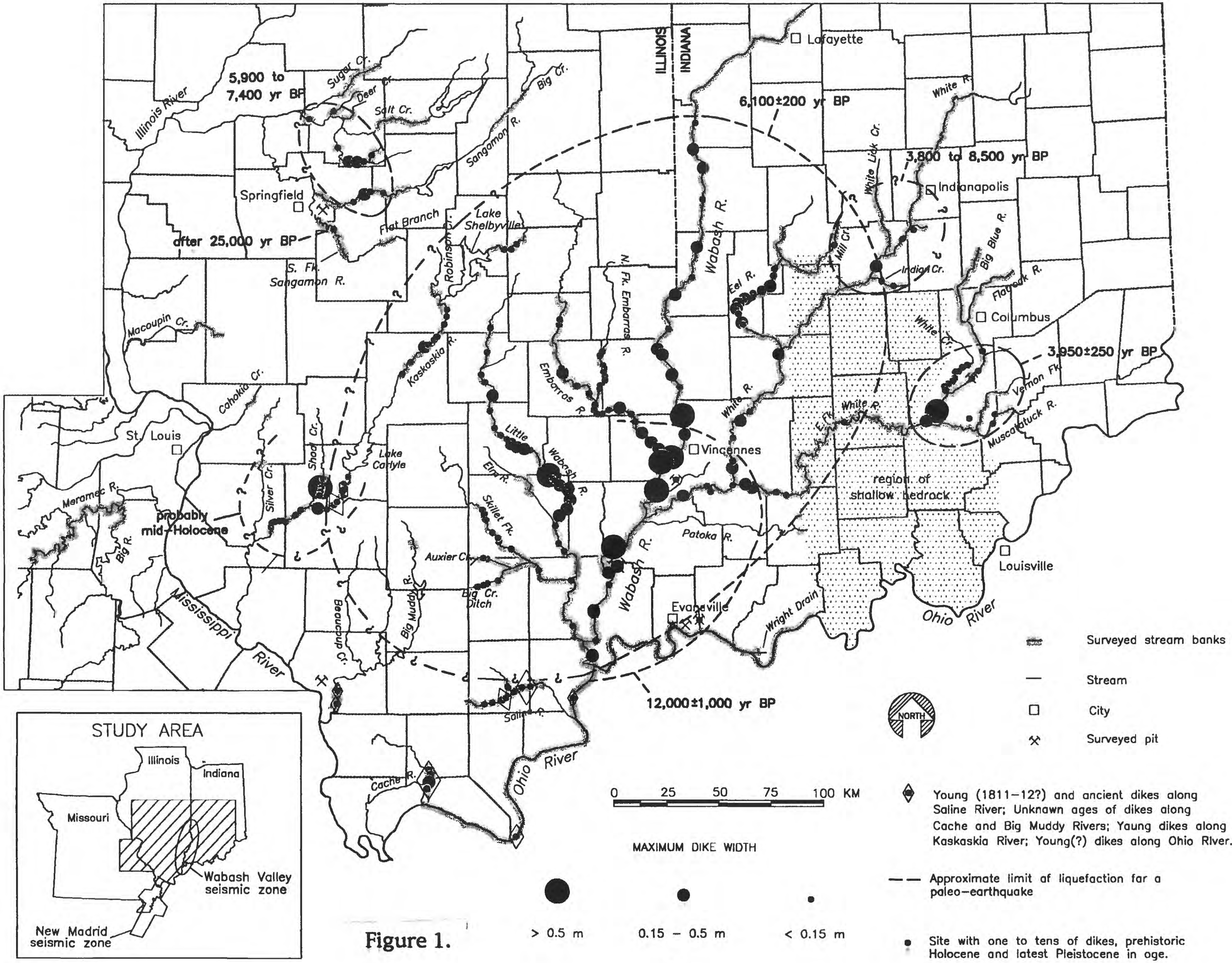
Table 1. Radiocarbon ages relevant to the Springfield earthquake

Site No.	*^{14}C age*	*Comment*
1.	5,960±60 yr BP	Leaf mat at base of cap, at stratigraphic level younger than cap with dikes.
2.	7,870 yr BP	Sample from host cut by dikes (from Hajic et al., 1996).
3.	7,380±90 yr BP	Log at base of cap, directly beneath dike.
4.	13,900 ±140 yr BP	Wood chip (cut by paleo-beavers?) in lower part of cap at dike site; region of persistent high water table.
5.	8,770 ±60 yr BP	Pine needles at base of cap, at dike site.
6.	7,730 ±80 yr BP	Log at base of cap, at dike site; region of persistent high water table.
7.	9,860 ±90 yr BP	Age of log at base of cap; large region of no dikes and persistent high water table.
8.	25,240±230 yr BP	Age of peat mat cut by dikes.

Table 2. Radiocarbon and weathering ages relevant to the Shoal Creek earthquake

Site No.	*Age* (from weathering severity and ^{14}C data)	*Comment*
10.	6,690 ±60 yr BP	Hickory shell fragment, at base of cap, at dike site.
11.	5,840 ±110 yr BP	Hickory shell fragment, at base of cap, at dike site.
12.	< 1,000 yr BP	Age of cap (basis of weathering), containing virtually unweathered dike; dike very young.
13.	8,280 ±70 yr BP	Hickory nut, at base of cap, at dike site.
14.	Early to mid-Holocene	Age of cap (basis of weathering), containing dikes from two earthquakes widely spaced in time.
15.	13,480±70 yr BP	Leaves from base of cap. Site of 15 cm wide lateral spread and many dikes. Lateral spread severely weathered in upper 3 m.
16.	7,960 ±50 yr BP	Log at base of cap, directly beneath dikes; multiple intrusions in dikes.
17.	7,770 ±80 yr BP	Log at base of cap, beneath dikes.
18.	Latest Pleistocene	Dikes cut in to thick montmorillonite layer of Pleistocene age. Lateral spread10 - 15 cm wide; severly weathered in upper 2 m.
19.	Latest Pleistocene - early Holocene	Dike cuts through host into thin montmorillonite layer at top.
20.	7,440 ±50 yr BP	Nut shell at base of cap, in large region of no dikes.
21.	8,600 to 9,000 yr BP	Indian spear point in upper part of cap (from M. Tuttle, oral comm., 1996); site of ground disruption
22.	Early Holocene or older	Age of cap (basis of weathering), in region of no dikes.
23.	Variable ages, many early Holocene	Age of cap (basis of weathering), in region of very infrequent, small dikes.
24.	Early Holocene or older	Age of cap (basis of weathering), in region of infrequent, small dikes.

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



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

Figure 1.

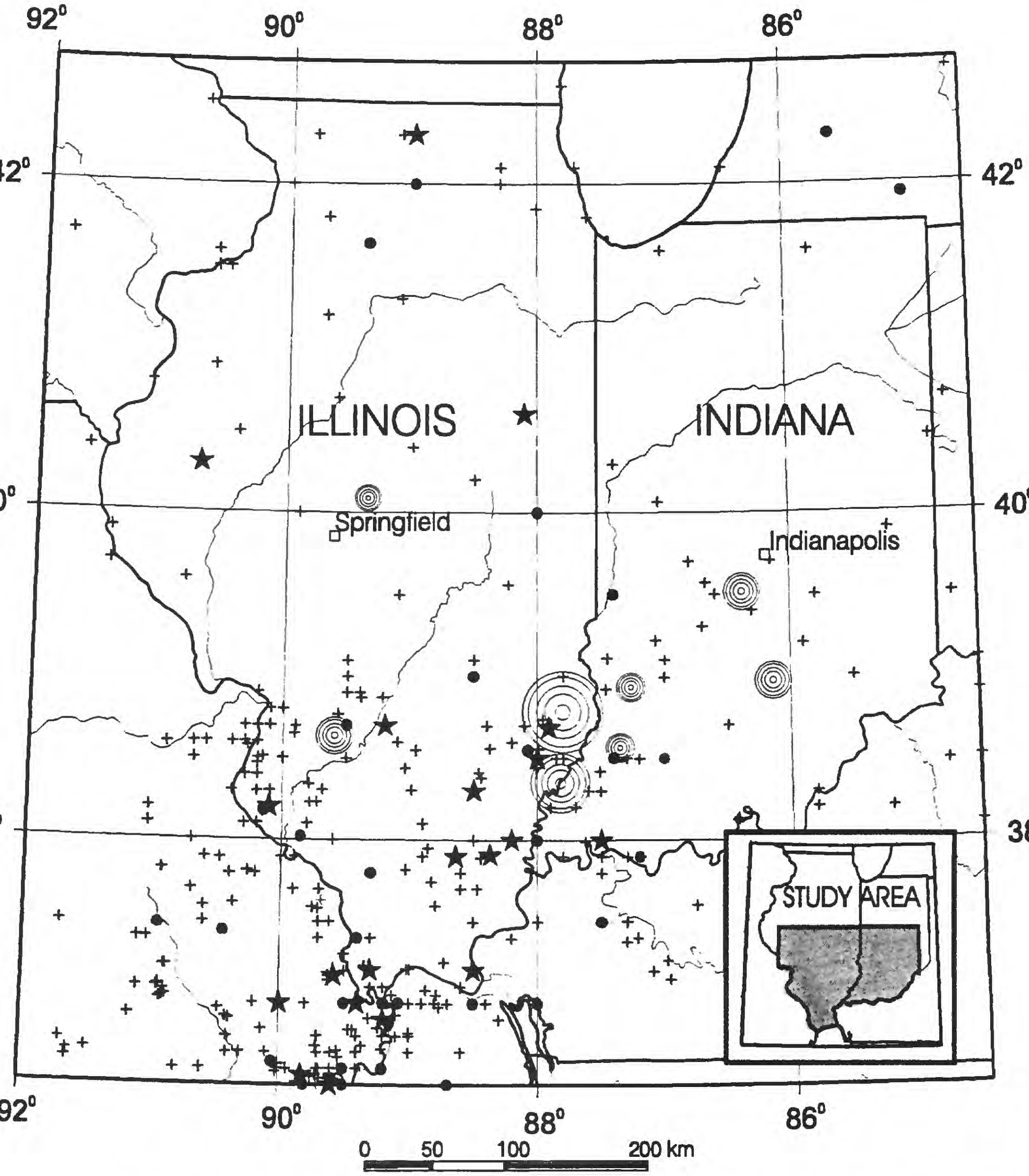


Figure 2. Epicenters of historic earthquakes in the study area for the time period 1804-1992. A star represents magnitude of 5 or higher. A solid circle represents magnitude between 4.5 and 5. Plus represents magnitude between about 2.3 and 4.5. Data from USGS/NEIC Global Hypocenter Data Base CD-ROM (Version 3.0).

Concentric circles show estimated epicenters of large prehistoric earthquakes. Diameters of the circles are scaled to indicate their moment magnitudes. Magnitude of the largest paleo-earthquake was about M 7.5, and magnitude of the smallest shown was on the order of M 6 or higher. Liquefaction effects associated with the paleo-earthquake are shown in Fig. 1. Prehistoric epicenters mainly from information in Munson and Munson (1996), Pond (1996), Hajic et al. (1995), Obermeier et al. (1993,1997), and this report.

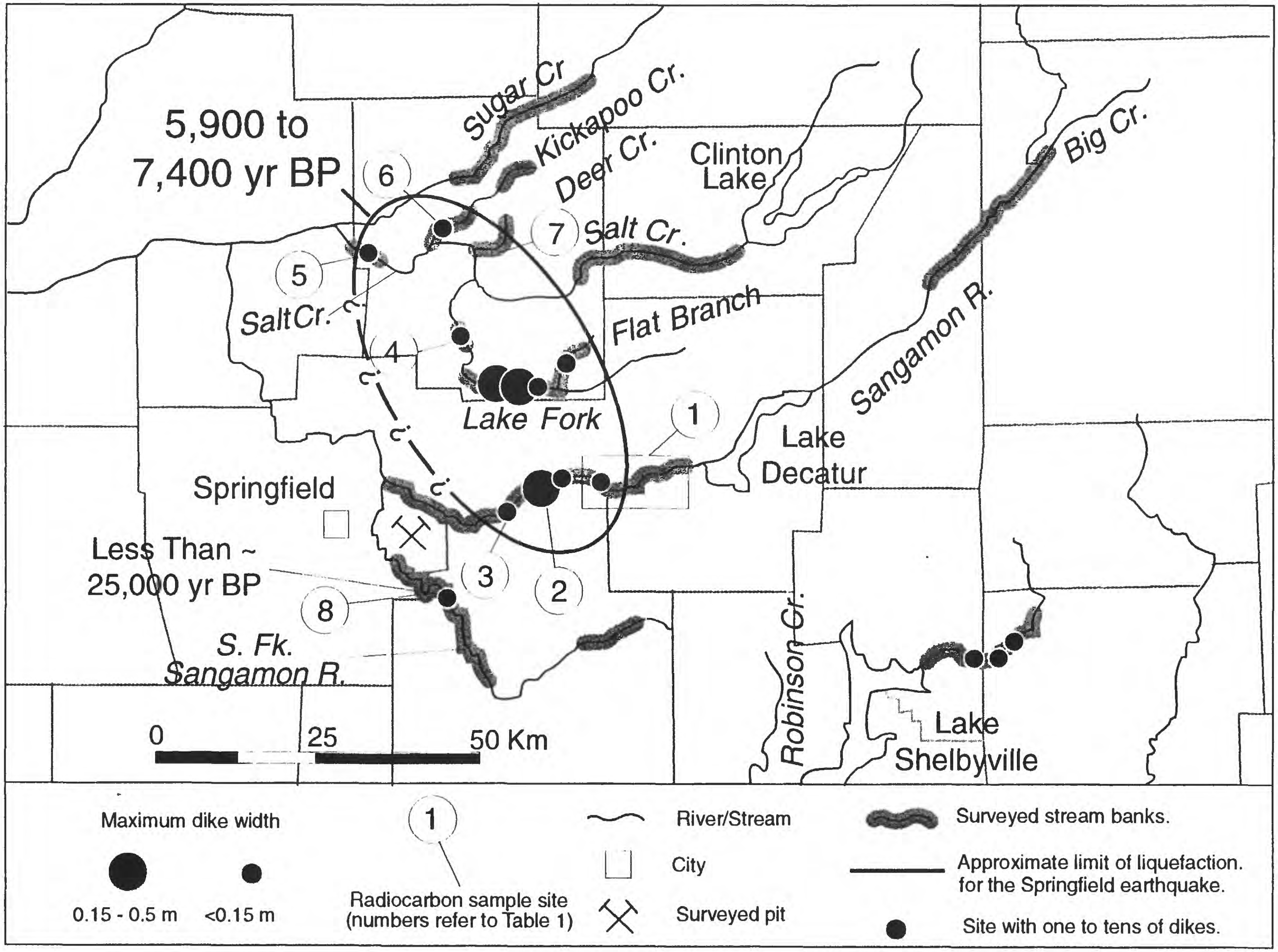


Figure 3. Map of the vicinity of the Springfield earthquake, showing approximate limit of liquefaction for the earthquak

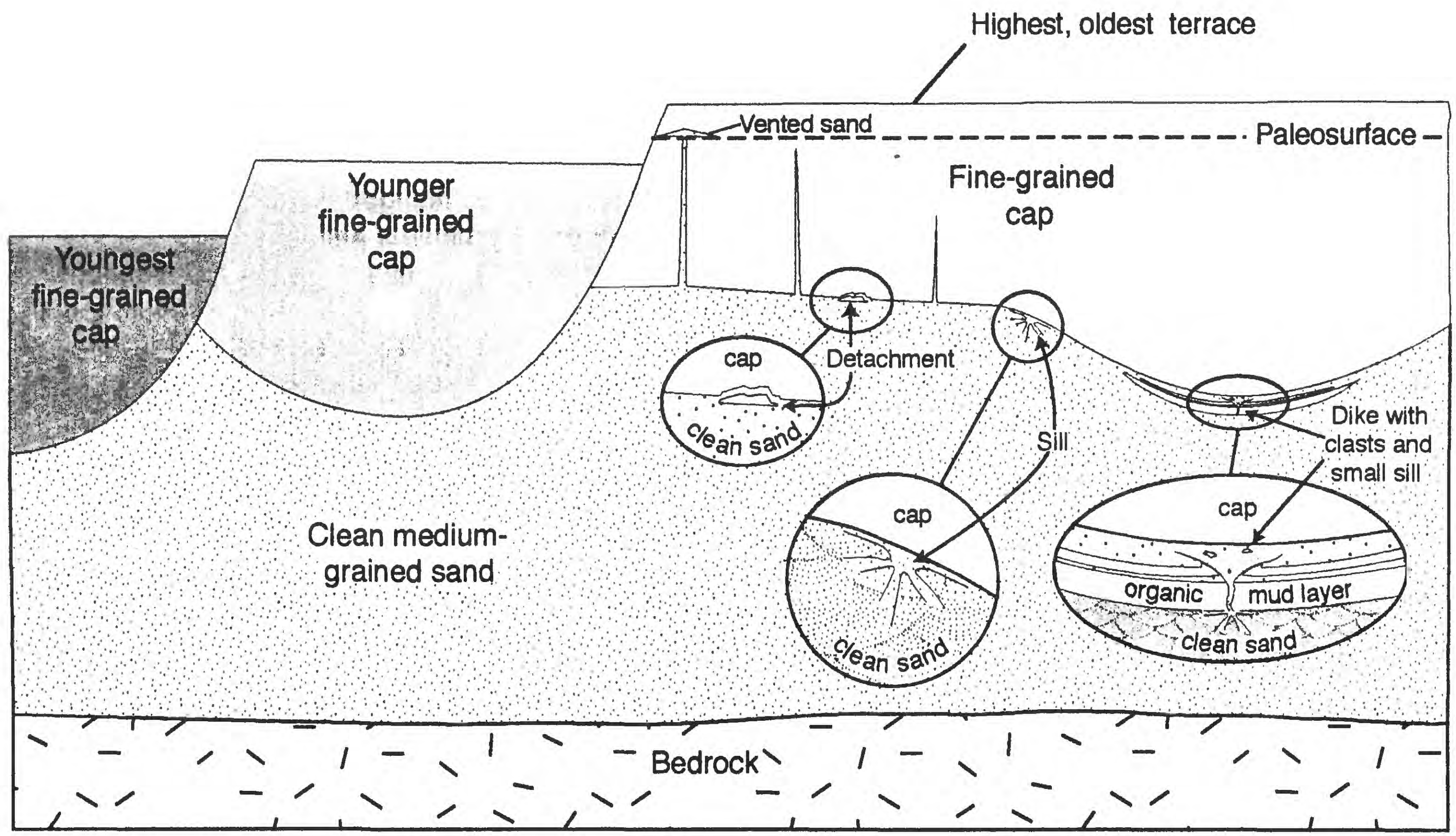


Figure 4. Vertical section showing relations between sediments of various ages along the Sangamon River. Schemaic locales of liquefaction features such as dikes, sills, and detachments are also shown.

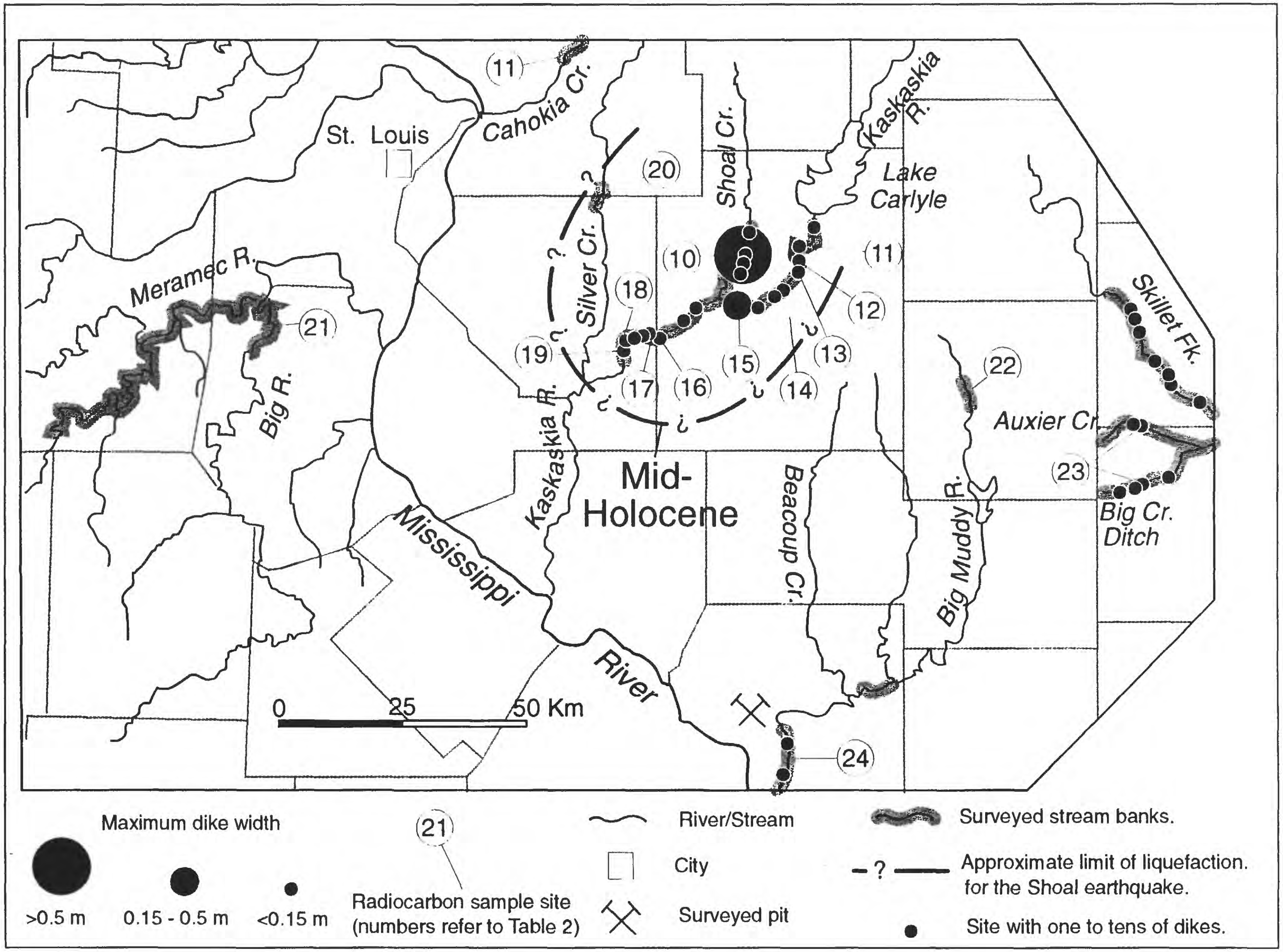


Figure 5. Map of the vicinity of the Shoal earthquake, showing approximate limit of liquefaction for the earthquake.