Paleoliquefaction Features as Indicators of Potential Earthquake Activity in the Southeastern and Central United States

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Prehistoric earthquake-induced liquefaction features of Holocene age have been discovered in coastal South Carolina, in the epicentral area of the 1811-1812 New Madrid earthquakes, and in areas peripheral to portions to the New Madrid seismic zone. These discoveries show that areas of historic, moderate-to-strong earthquakes are likely to have been areas of strong prehistoric earthquakes in the central and southeastern United States. Locating prehistoric liquefaction features is valuable for identification of regions of potential strong earthquakes.

The central and eastern parts of North America lie within an area known to tectonic specialists as the "stable continental region" or "intraplate region" because their plate boundaries lie far away. Earthquake zones worldwide are associated chiefly with plate boundaries. Yet within central and eastern North America, some extraordinarily strong earthquakes have struck during the past 200 years. The four strongest are the 1811-1812 New Madrid earthquakes [body-wave magnitude m_b ~7.0 to 7.4; moment magnitude (**M**) ~7.8 to 8.3 (*1*)], which originated in the Mississippi Valley near Memphis, Tennessee. These events were felt as far away as Washington, D.C. A Modified Mercalli intensity of XI has been assigned to the epicentral region of several thousand square kilometers. Prominent effects of liquefaction extend over an area on the order of 10,000 km^2 and are plainly visible on the surface today (*2,3*). In 1886 another very strong intraplate earthquake [m_b ~6.7, **M** ~7.5 (*1*)] occurred near Charleston, South Carolina. Throughout much of the epicentral region, an area about 35 km wide and 50 km long, the Modified Mercalli intensity ranged from IX to X. Liquefaction effects were especially noteworthy (*4*). Other scattered strong historic earthquakes (on the order of **M**7) have taken place in southeastern Canada and the northeastern United States (*5,6*). Most of these earthquakes have also been associated with liquefaction.

To realistically assess the seismic hazard, it is necessary to know which areas of this intraplate region have the potential for future destructive earthquakes. The short historic record is not sufficient to determine if places where strong earthquakes have taken place during the past 200 to 300 years are also locales of recurring strong earthquakes. In addition, the tectonic mechanisms that cause large intraplate earthquakes are not well understood, and strong earthquakes in the intraplate region usually do not produce surface faulting that can be used to evaluate the locations and times of previous large events. For these reasons, numerous recent searches have been undertaken for secondary evidence of large prehistoric earthquakes, such as seismically induced liquefaction features (i.e., paleoliquefaction features). Paleoliquefaction features can indicate the recurrence interval of prehistoric strong earthquakes and can also be used to identify regions in which earthquake shaking has been strong enough to be of concern to engineers. The threshold for formation of liquefaction features during strong earthquakes is a horizontal acceleration on the order of 0.1 *g* (*7,8*). In addition, liquefaction data can be used in some cases to infer the magnitude of prehistoric earthquakes.

In the United States, paleoliquefaction studies have concentrated on coastal South Carolina (Figure 1), the 1811-1812 New Madrid seismic zone (Figure 2), the Wabash Valley seismic zone (Figure 2), and the northeastern United States and southeastern Canada. An overview is given here of paleoliquefaction studies in those areas except the northeastern United States and southeastern Canada, which are discussed by Tuttle and Seeber (*9*) and Tuttle et al. (*10*). Preliminary studies along the coast of the mid-Atlantic states from North Carolina to New Jersey (where no evidence of prehistoric earthquakes was found) are reported by Amick et al. (*11*).

CRITERIA FOR EARTHQUAKE ORIGIN

Earthquake-induced liquefaction in different physical settings can lead to very different manifestations of the process. For example, observers at the time of the 1886 Charleston earthquake noted the formation of great numbers of approximately circular craters along ancient beach ridges (Figure 3). Figure 4 shows how prehistoric earthquake-induced craters, now filled, appear in vertical section. In the epicentral region of the 1811-1812 New Madrid earthquakes, many thousands of more-or-less linear fissures formed through which liquefied sand vented onto the ground surface (Figure 5). In vertical section, they are now expressed as nearly vertical, planar, sand-filled fissures (dikes) that cut across the flat-lying clay and silt strata of the flood plains (Figure 6).

Because of the various expressions of earthquake-induced liquefaction, because liquefaction can have a nonseismic or-

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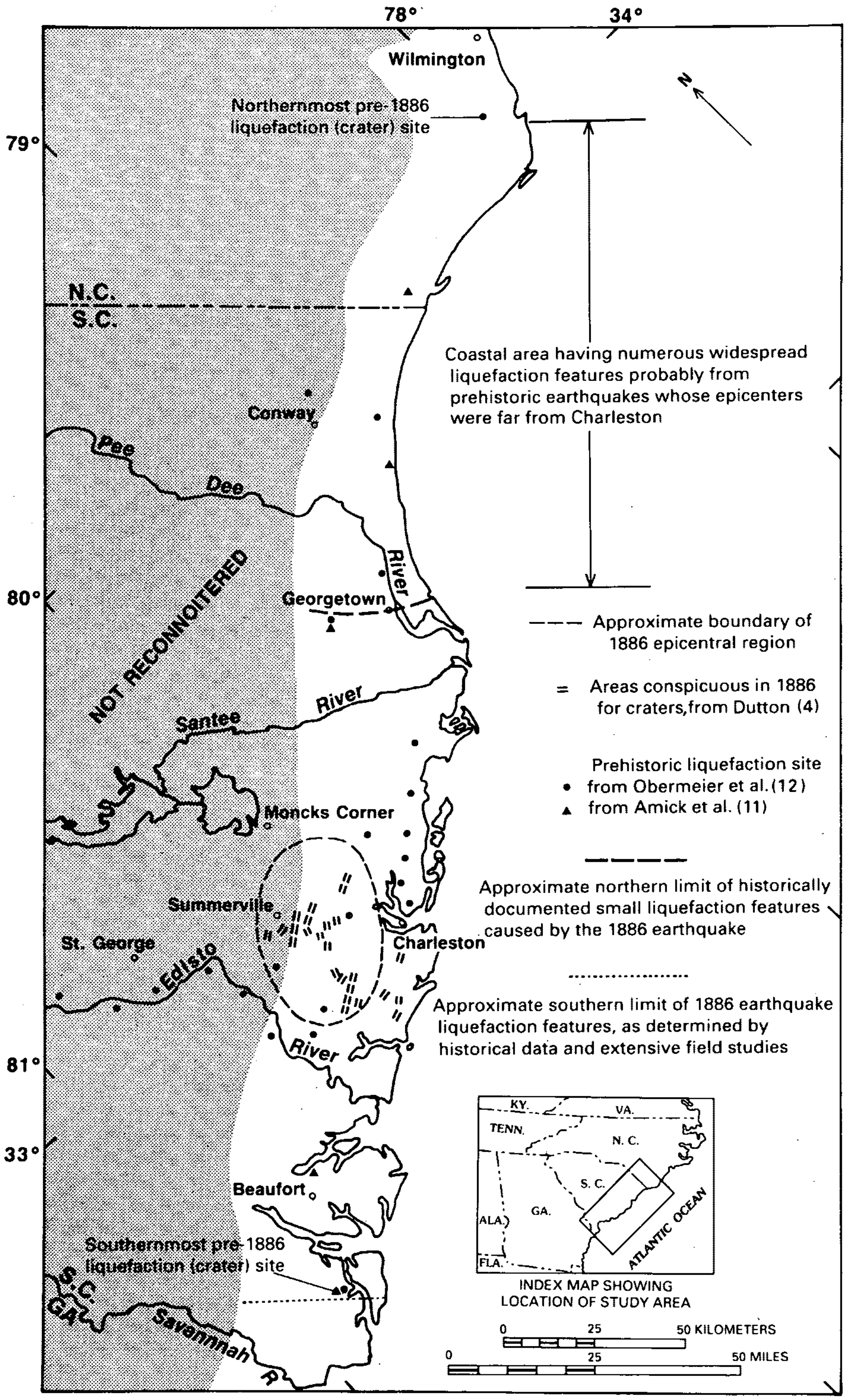

FIGURE 1 Coastal portion of South and North Carolina containing liquefaction sites. Unshaded onshore region, in which numerous ancient beach ridges lie, is predominantly marine deposits younger than about 240,000 years. Shading denotes region of older marine deposits that was not reconnoitered, except locally. Younger fluvial sediments occur locally. All liquefaction sites along the Edisto River are in fluvial sediments. Almost every liquefaction site shown represents an area where numerous liquefaction features are exposed in a network of drainage ditches several kilometers in length. Index map shows coastal region intensively searched for liquefaction features.

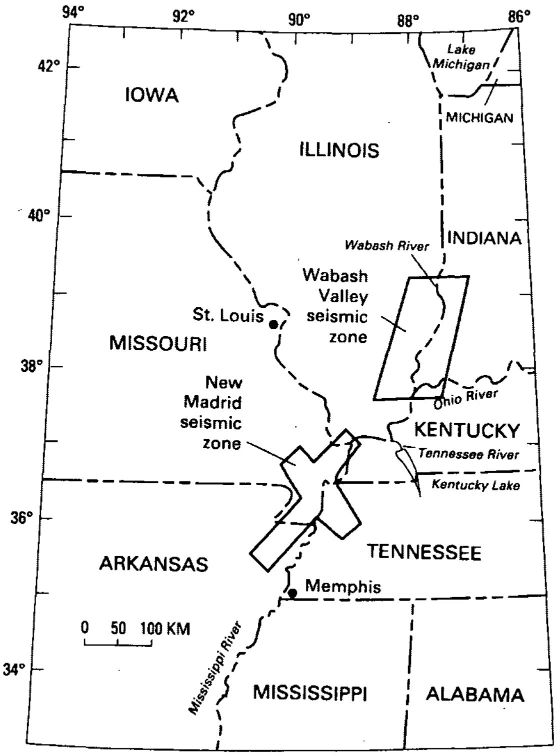

FIGURE 2 Approximate boundaries of New Madrid and Wabash Valley seismic zones. New Madrid seismic zone is the source area of 1811–1812 earthquakes and continues to have many small earthquakes and a few slightly damaging earthquakes. Wabash Valley seismic zone is a weakly defined zone of seismicity having infrequent small to slightly damaging earthquakes.

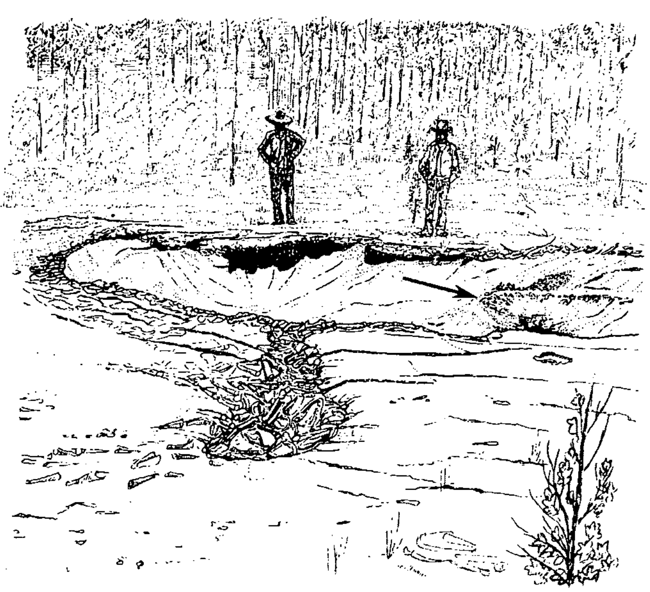

FIGURE 3 Large craterlet produced near the present Charleston airport by the 1886 earthquake. Note that the craterlet contains sand sloughing toward the lowest parts and that there is a constructional sand volcano in the lower right part of the crater (*arrow*). The craterlet is surrounded by a thin blanket of ejected sand partly veneered with cracked mud.

igin, and because nonseismic mechanisms can induce features that resemble features having an earthquake origin, it has been necessary to develop a set of interpretative guidelines for various physical settings. Criteria to interpret an earthquake origin are the following:

1. The features should have sedimentary characteristics that are consistent with an earthquake-induced liquefaction origin, that 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 consistent with historically documented observations of the earthquake-induced liquefaction processes in the same physical setting.
3. The features should occur in groundwater 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 or for landsliding.
4. Similar features should occur at multiple locations, preferably at least within a few kilometers of one another, having similar geologic and groundwater settings. The regional pattern of size and abundance of features should be consistent with a pattern of shaking reasonably associable with an earthquake. Where evidence of age 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 relatively long time periods during which no such features formed.

Emphasis has been placed on elimination of artesian conditions and landsliding as possible sources of the features. In the following sections, the application of these criteria to specific geographic-geologic settings is discussed.

SOUTHEASTERN U.S. STUDIES

The most thorough studies have been conducted in a strip of South Carolina 30 km wide that parallels the coast for about 300 km. The Charleston area is centrally located in this strip (Figure 1). Studies were concentrated here because of concern about a repetition of the 1886 earthquake (**M**~7.5). The Charleston area is also the only part of coastal South Carolina to have significant recurrences of seismicity (albeit earthquakes of small magnitude) in this century. In addition, there is an abundance of sand layers in ancient beach ridges that are especially susceptible to liquefaction and formation of craterlets. Results of the searches for paleoliquefaction features (*11,12*) show that the Charleston area and other South Carolina areas far from Charleston have been the epicentral regions of repeated strong earthquakes throughout Holocene time (i.e., the past 10,000 years).

Charleston, South Carolina, Epicentral Region

The geologic setting most commonly associated with craters is the crest or flank of Pleistocene beach ridges, where a thin surficial cover of clay-bearing sand or humate-rich sand overlies clean sand. According to first-hand observations of effects of

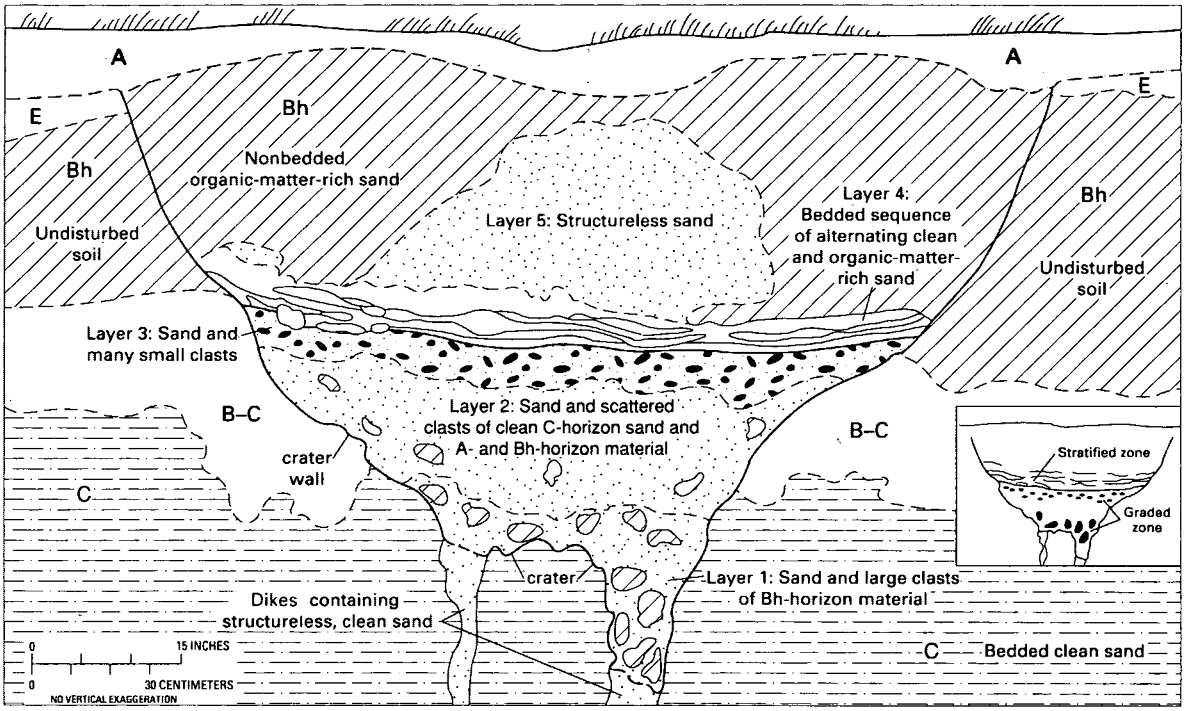

FIGURE 4 Schematic vertical section of filled, liquefaction-induced craterlet. Letters correspond to agronomical soil horizon designations. This filled crater much predates the 1886 earthquake on the basis of the thickness of the Bh horizon.

the 1886 earthquake by Sloan, "these craterlets are found in greatest abundance in belts parallel with (beach) ridges and along their anticlines" (*13*, p. 68). A schematic cross section through a beach ridge of coastal South Carolina, which is typical of the ridges described by Sloan, is presented in Figure 7.

Prehistoric craters are more abundant and tend to be larger in the vicinity of Charleston than elsewhere. Near Charleston, an earthquake origin is thought to be unequivocal for many of the prehistoric craters because (*a*) their size, shape, and sedimentary characteristics are entirely consistent with historic observations of effects of the 1886 earthquake; (*b*) some of the prehistoric craters occur at the same sites where swarms of craters were reported during the 1886 earthquake, and (*c*) alternative possible sources for the prehistoric craters have been eliminated. A complete discussion of the various possible sources for craters has been given by Obermeier et al. (*3*). For example, artesian springs are suspected to be a nonseismic mechanism that might produce features similar to those induced by seismicity. However, the presence of craters on the tops and flanks of beach ridges, where artesian springs are impossible, eliminates that mechanism. The possibility of ground disruption by thrown trees is eliminated in part because the craters contain minerals transported from deeper sources upward into the crater. Dikes that feed into the base of the craters can also be seen in some places. Engineering studies (*14*) also show that the loosest sands at depth are the same sands that were transported up in the dikes and into the craters, which is what would be expected from an earthquake-induced liquefaction origin.

The time of formation of some prehistoric craters can be estimated with high accuracy. Some craters contain bark from trees and small twigs that fell into the open crater soon after its opening. Radiocarbon dating of these materials shows that prehistoric craters in the Charleston area are approximately 600, 1,250, 3,200, 5,150, and more than 5,150 years old (*15*).

An estimate of the magnitude of the prehistoric earthquakes is provided by both historic worldwide and local observations of liquefaction. Data from the 1886 earthquake furnish a basis for comparison of crater distribution along the coast and size and abundance of the craters. Worldwide data have shown that features that have a liquefaction origin can be developed at magnitudes as low as **M**~5, but that a magnitude of about 5.5 is the lower limit at which liquefaction effects are relatively common (*16*). The source sands that produced craters in coastal South Carolina commonly are extremely susceptible to liquefaction and flowage, and this susceptibility might be interpreted to suggest that an exceptionally low magnitude earthquake could have produced the craters. However, the numerous large prehistoric craters (many having diameters as much as 3 m at a depth of 1 m below the ground surface) in the Charleston area clearly did not result from marginal liquefaction; the earthquake that produced them probably was much larger than **M**~5. In addition, the zones containing prehistoric craters with radiocarbon ages of 600 and 1,250 years extend at least as far from Charleston as the zone containing craters produced by the **M**~7.5 earthquake of 1886 (which formed over a distance of about 200 to 250 km up and down the coast, centered about Charleston).

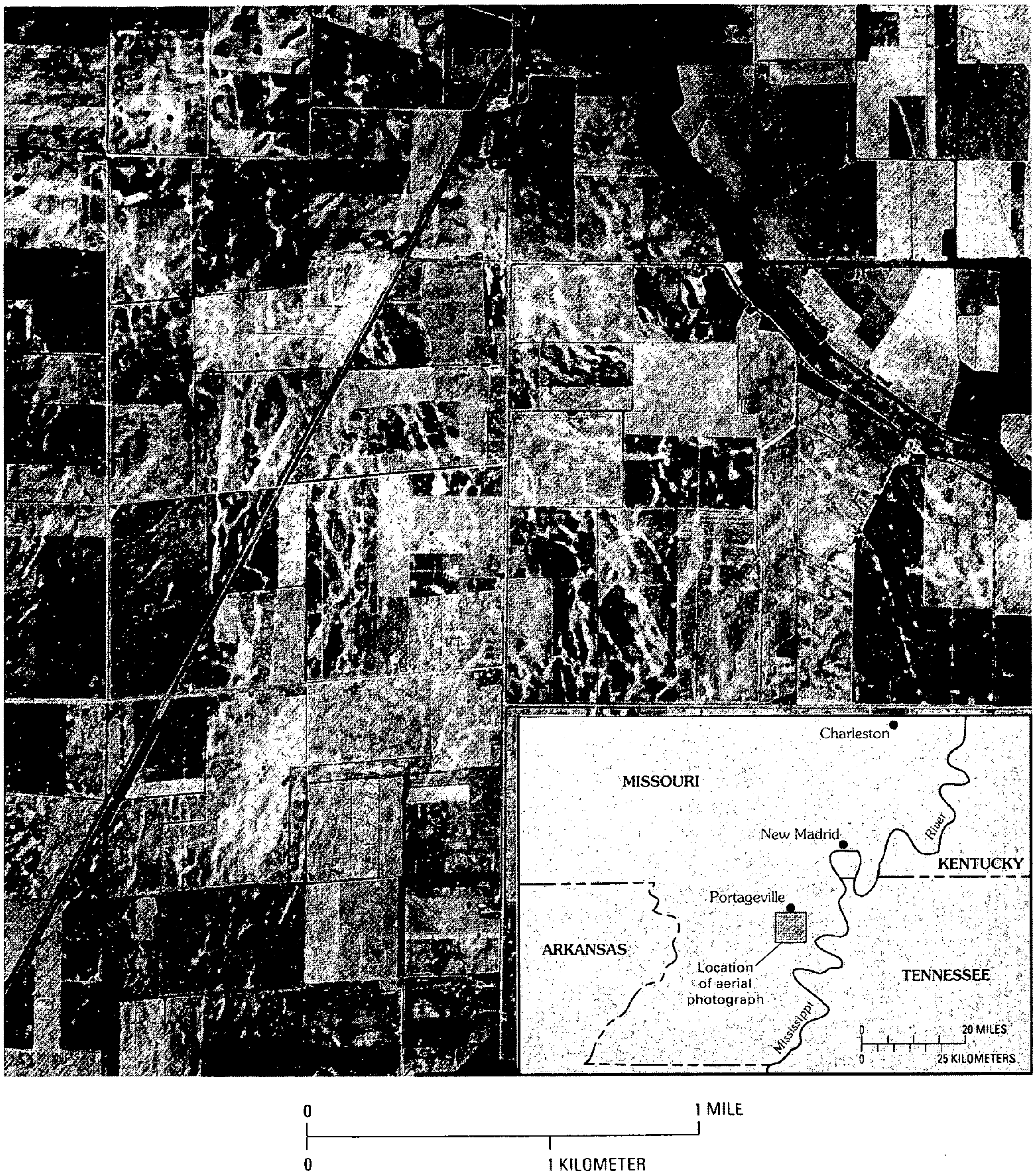

FIGURE 5 Aerial photograph showing vented sand caused by liquefaction and flowage during the 1811–1812 New Madrid earthquakes. Vented sand is light-colored and contrasts with the dark-colored silt and clay overbank (flood) deposits of the Mississippi River. The lineations were caused by ground cracks that were due largely to lateral spreading. Lineations are underlain by steeply dipping, planar, sand-filled fissures (dikes) that cut across the overbank deposits.

Interpretations of prehistoric earthquake magnitudes must account for other local factors, including water-table location and the degree of compactness of the source sands. The water table is presently very shallow (<1 m below ground surface) and probably has been essentially unchanged for the past few thousand years (*15*) at many of the sites where the craters formed. Just prior to the 1886 earthquake, the Charleston area was experiencing an extraordinarily wet period, and so the water-table conditions were optimal for production of liquefaction features (*17*). Standard Penetration Test (STP) data also show that the source sands are so loose as to be optimal for liquefaction; it is not unusual that sand deposits (fine sand and silty sand) in coastal South Carolina have STP blow counts as low as 2 or less (*14*). Thus, these sands are about as loose as possible, and it is difficult to conceive of any mechanism that would have made the sands significantly

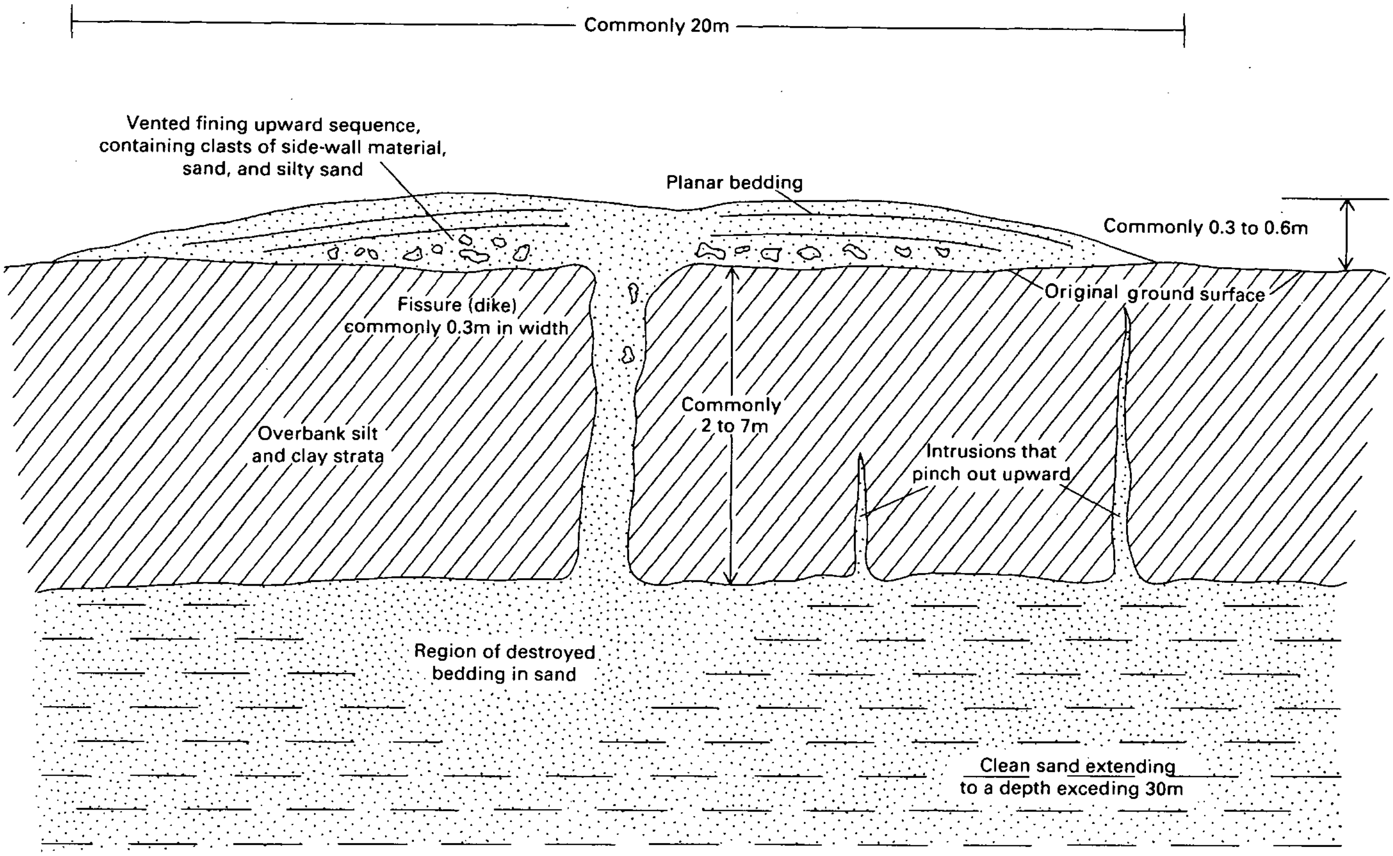

FIGURE 6 Schematic vertical section of sand-filled fissure cutting through overbank silt and clay. Situation shown is encountered at many places in epicentral region of the 1811–1812 New Madrid earthquakes.

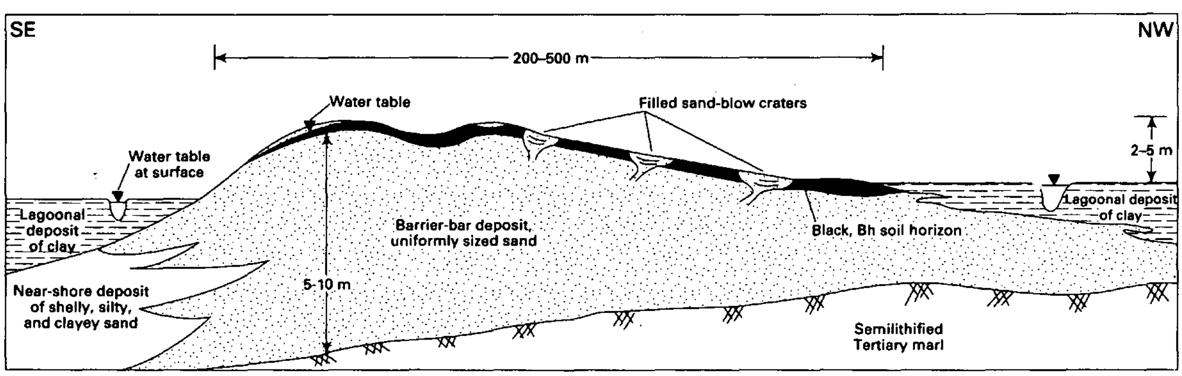

FIGURE 7 Schematic vertical cross section of representative barrier in coastal Carolinas showing sediment types, water-table locations, filled craters, and Bh (humate-rich) soil horizons. Modern shoreline is to the southeast. Lagoonal clay deposit at left is younger and lower in elevation than the barrier-bar (beach) deposit.

more compact some thousands of years ago, when the prehistoric earthquakes occurred. In summary, the geotechnical characteristics relevant to formation of craters were as favorable as possible when the 1886 earthquake struck.

It was noted above that the area along the coast having craters with ages of 600 and 1,250 years is at least equal in size to the area having craters induced by the 1886 earthquake. In addition, a comparison of the size (diameter) of the craters shows that those of the 600-year and 1,250-year events are much larger than the 1886 craters in the vicinity of Charleston and that craters for these prehistoric events in the vicinity of Charleston are larger than craters a distance away. This relation indicates that earthquakes at least as strong as the 1886 event (**M**~7.5) have taken place. (Again, some of the sands that liquefied in 1886 are still extremely loose, so progressive densification from prehistoric earthquakes could not have greatly affected liquefaction potential in 1886.)

Paleoliquefaction evidence for the event that took place 3,200 years ago has been found only in the vicinity of Charleston. Abundant craters for this event are exceptionally large, which might suggest that the earthquake was exceptionally large, but the limited size of the affected area suggests otherwise. The absence of craters far from Charleston might alternatively be explained by a lower water table caused by a lower sea level and a generally drier climate earlier in the Holocene (*15*). Absence of the 3,200-year-old craters far from Charleston might also be explained by an exceptionally shallow earthquake. The event of 5,150 years ago may have affected an area that exceeds that of the 1886 earthquake, but radiometric data are not sufficiently constrained to provide trustworthy evidence of synchronous ages of widespread craters. Craters for the oldest event (>5,150 years) in the Charleston area seem to be restricted to the immediate vicinity of Charleston. For the older events (more than several thousand years old), there is a greatly diminished chance for preservation of organic material that can be dated with accuracy. This makes it difficult to evaluate their regional distribution and causative earthquake magnitudes.

The three most recent crater-producing events have an average recurrence interval of about 600 years. The passage of only 100 years since the 1886 earthquake might suggest a low likelihood for a large earthquake within the next hundred years or so. For example, Amick and Gelinas (*15*) used a statistical procedure based on modern seismicity to determine that the probable occurrence of an event similar to the 1886 earthquake during the next two decades is less than 5 percent. Although this low likelihood seems intuitively appealing, it must be kept in mind that the causative fault (or faults) for the Charleston earthquakes has never been located despite extensive studies using geophysical, seismological, and deep bore-hole data (*18,19*). Possibly the region has a myriad of faults, each with a different potential for earthquakes (*20*), so a definitive assessment of return periods cannot be made. All that can be stated with confidence is that the paleoliquefaction data show that the Charleston area has been seismically active in the recent geologic past, and there is reason to expect that the area will occasionally experience strong earthquakes in the future.

Other Epicentral Regions

Some craters far from Charleston have an age of formation different than the ages of craters caused by the prehistoric earthquakes near Charleston. Numerous craters about 1,700 years old are present in the coastal region that extends from about 75 to 150 km northeast of Charleston toward North Carolina. There are also some very old craters (probably >5,000 years) in North Carolina, as much as 50 km north of the South Carolina state boundary. Current data do not suggest that the areal distribution of craters centered northeast of Charleston approaches the span of craters about Charleston. In addition, these craters are not as large as those in the Charleston area, yet they are found in similar physical settings. It seems likely that smaller-magnitude earthquakes were responsible for their formation. Clearly more work is needed in this area. For example, at numerous crater sites in the 1886 epicentral region near Charleston, various types of engineering tests (*14*) and geologic tests (*21*) have been performed to verify that the prehistoric craters have an origin entirely consistent with an earthquake-induced liquefaction. Outside the 1886 epicentral region, though, no such assemblage of tests has yet been performed, which places an earthquake origin in doubt at some of these sites. Still, an earthquake origin is probable at these sites far from Charleston.

CENTRAL U.S. STUDIES

The great New Madrid earthquakes of 1811–1812 took place in a rift complex (Figure 8), which is suspected to be the source of strong earthquakes in the New Madrid seismic zone (*22*). The presence of the rift, now deeply buried, is interpreted mainly from indirect forms of evidence such as seismic reflection, gravity, and magnetic surveys. The rift is thought to have formed hundreds of millions of years ago as a result of tensile stresses associated with continental breakup. With time, the regional stresses changed from extension to east-west compression. The region around the rift has subsided for the past tens of millions of years, producing a basin (including the Mississippi embayment) in which sediments now have deeply buried the rift. In the New Madrid seismic zone, the correlation of the buried rift with contemporary seismicity (Figure 9) suggests that the earthquakes result from slippage along zones of weakness associated with the ancient rift structures (*22*). Hundreds of small earthquakes, and some damaging events, one as large as M6.8 (*23*), have taken place in the New Madrid seismic zone since the 1811–1812 earthquakes. This zone is one of the most seismically active in the United States.

Whereas association of seismicity with an ancient rift seems generally accepted in the New Madrid seismic zone, there is considerable doubt about the existence of a branch of the rift that projects northwestward from the confluence of the Mississippi and Ohio rivers (Figure 8) and also some doubt about the existence of a branch in the Wabash Valley seismic zone

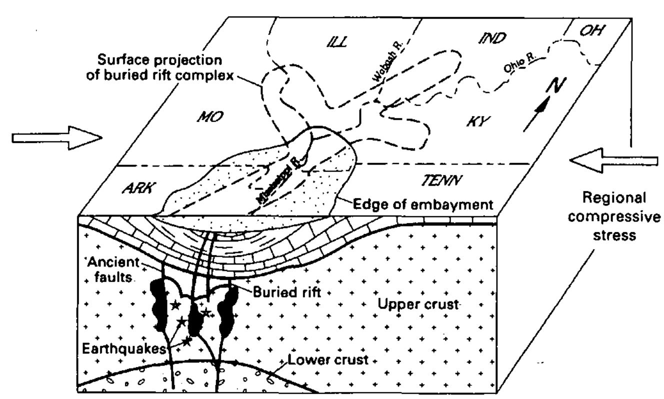

FIGURE 8 Block diagram illustrating configuration of the buried New Madrid rift complex. Branches of the rift extending northwestward along the Mississippi River and northeastward into the Wabash Valley have questionable existence. Dark areas indicate igneous intrusions near the edge of the buried rift. Hypocenters of stronger earthquakes that took place in 1811–1812 and in 1895 are in the ancient rift. Modified from Braile et al. (22).

(T. G. Hildenbrand, U.S. Geological Survey, unpublished data, 1992). Still, this model, in conjunction with the mapped distribution of faults and epicenters of modern earthquakes (Figure 9), makes these proposed branches suspect as potential sources of modern strong earthquakes. For example, six damaging earthquakes (M~5) have taken place in this area according to the historical record (*23*).

Concern about a repeat of an earthquake event approaching the strongest of the 1811–1812 New Madrid earthquakes has served as the impetus for several recent paleoliquefaction studies in the central United States, some of which were ongoing in 1992. These studies have concentrated on and very near the New Madrid seismic zone (Figure 2). Studies were also initiated in 1990 in the Wabash Valley of Indiana-Illinois. Although these studies in both seismic zones are ongoing, important preliminary results have been reported.

New Madrid Seismic Zone

Figure 10 shows the area of extensive liquefaction caused by the 1811–1812 earthquakes. The epicentral region for the 1811–1812 earthquakes almost certainly lies in the center of the area of extensive liquefaction. Isolated instances of venting of liquefied sand were reported as far to the northwest as St. Louis, Missouri (Figure 2), on the flood plain of the Mississippi River, and as far to the northeast as the lowermost

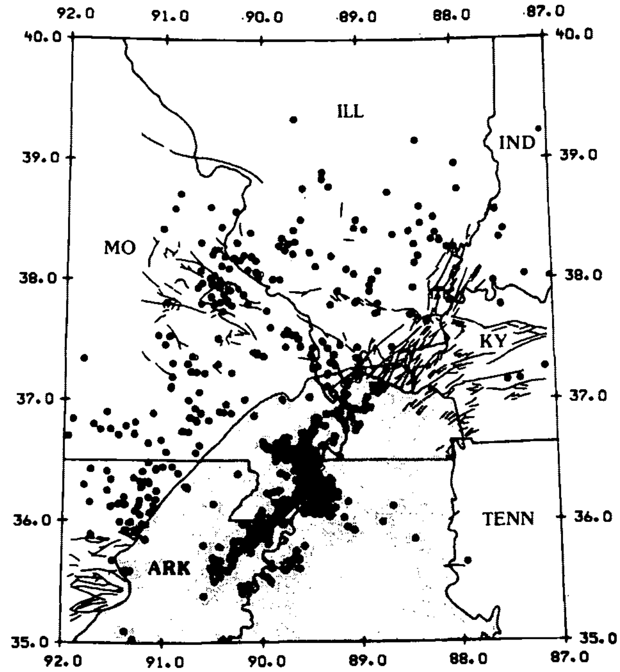

FIGURE 9 Map view of the area shown in the block diagram in Figure 6, showing major faults in bedrock and epicenters of modern earthquakes. Pattern indicates the Mississippi embayment.

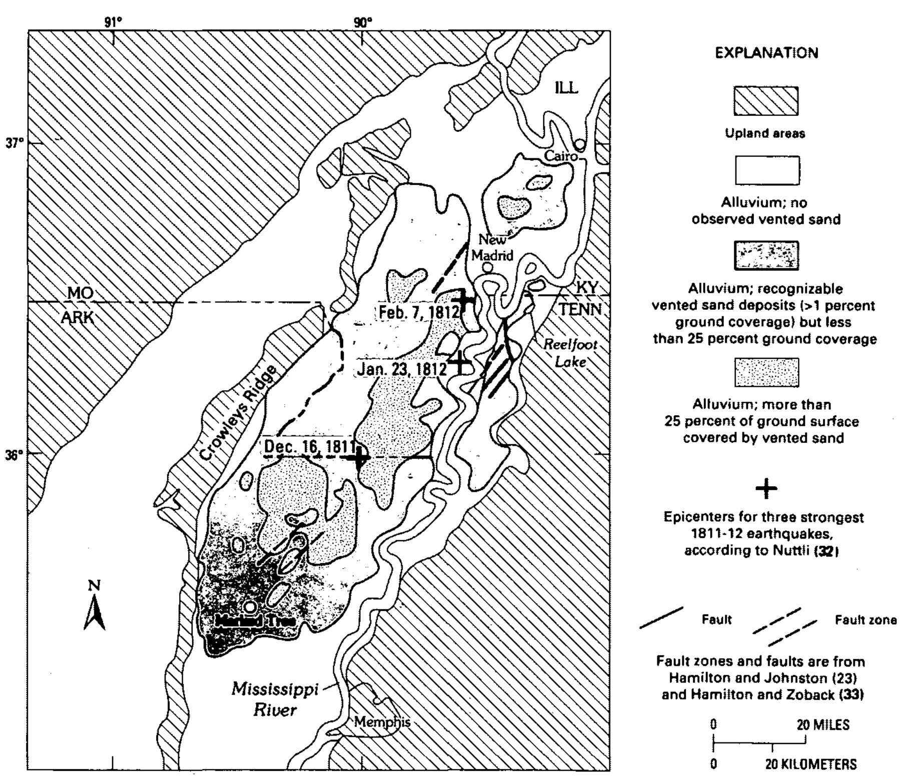

FIGURE 10 Regions having abundant vented sand, excluding modern flood plains, in the New Madrid seismic zone [from Obermeier et al. (*3*)]. Sand was presumably vented in response to 1811–1812 earthquakes. Severe liquefaction occurred locally beyond the areas shown on the map, especially along streams west of Crowleys Ridge, according to Fuller (*2*). Also shown are the approximate epicenters for the three strongest 1811–1812 earthquakes and major faults and fault zones.

Wabash Valley (*24*). These farthest sites are about 250 to 275 km from the presumed epicenter (near the town of New Madrid) for the strongest earthquake of the series, the event of February 7, 1812 (**M**~8.3).

The epicentral region lies in low-relief alluvial lowlands that have thick strata of fine and medium sand at shallow depth and a very high water table. Therefore the lowland area is well suited for production of earthquake-induced liquefaction features. The area is made up largely of braid-bar terraces of late Wisconsinan age, which formed in response to high-discharge streams carrying great quantities of sand in glacial meltwater. Sand beneath the terraces generally is thicker than 30 m. At most places the sand is capped with clay- and silt-rich strata a few meters thick. The water table appears to have been very shallow at many places since the terraces were formed (*25*). Thus, it seems reasonable that if very strong earthquakes occurred during the Holocene, the geologic record should have liquefaction features such as the dikes shown in Figures 5 and 6.

Terraces in the lowlands are exposed in vertical section by a network of hundreds of kilometers of drainage ditches that traverse the area. Wesnousky and Leffler (*25*) recently completed an extensive search of 50 km of ditch banks for pre-1811–1812 liquefaction features, mainly in the vicinity of the Missouri-Arkansas border near where the epicenter for the December 16, 1811, earthquake is shown in Figure 10. In a more limited search, they examined about 15 km of ditches southwest of the town of New Madrid. Ages of sediments that they searched ranged from about 5,000 to 10,000 years. They observed many hundreds of sand-filled fissures (dikes) caused by the 1811–1812 earthquakes but no pre-1811–1812 liquefaction features. About 10 years ago, Obermeier searched about 10 km of ditches near the southern end of the region of extensive liquefaction shown in Figure 10 and found only equivocal evidence for a small liquefaction-producing event in the early Holocene. Rodbell and Schweig (*26*) recently completed excavations in a terrace where 1811–1812 earthquake liquefaction was extensive and found no evidence of activity before 1811–1812. The terrace, about 20 km south of Reelfoot Lake, has an age exceeding 20,000 years. In the epicentral region of the 1811–1812 earthquakes (Figure 2), definitive evidence for pre-1811–1812 liquefaction has been found only near Reelfoot Lake (*27*) and at a site about 30 km northeast of Reelfoot Lake (*28*). Russ (*27*) interpreted the evidence to indicate the occurrence of three earthquakes sufficiently large to induce liquefaction during the past 2,000 years, and on that basis he suggested a recurrence interval of 600 years for liquefaction-producing events. Saucier (*28*) estimated an average recurrence interval of 470 years for liquefaction-producing events in the past 1,300 years.

It is probable that the magnitudes of the earthquakes that produced the prehistoric liquefaction features reported by Russ and Saucier did not approach the strengths of the strongest of the 1811–1812 earthquakes, as indicated by the limited areal distribution of the prehistoric liquefaction features (again, no prehistoric liquefaction features were found by Wesnousky and Leffler to the west and southwest of Reelfoot Lake or by Rodbell and Schweig to the south of Reelfoot Lake). The threshold magnitude for producing liquefaction features in the region is about m_b 6.0 to 6.2 (**M**6.4 to 6.8) on the basis of historical observations of liquefaction-producing events in the New Madrid seismic zone (*29*). Therefore, the prehistoric earthquakes were probably stronger than **M**~6.4, but because of the limited span of liquefaction, they did not approach the strength of any of the four strongest 1811–1812 events (m_b ~7.0 to 7.4; **M**~7.8 to 8.3).

Good evidence for prehistoric liquefaction in the form of sand-filled dikes has also been found about 50 km west of the epicenter for the February 7, 1812, earthquake (Figure 10). The dikes are west of Crowleys Ridge in an alluvial lowland in which the physical setting and liquefaction susceptibility are comparable with those in the lowland region east of Crowleys Ridge where such extensive development of liquefaction features took place in 1811–1812. Large portions of the lowlands west of Crowleys Ridge are a few tens of thousands of years old (*28*).

The features west of Crowleys Ridge are small to medium-sized scattered dikes. Ages of dike formation are not well constrained. However, Vaughn (*30*) suggested that there have been three or four prehistoric liquefaction-producing earthquakes during approximately the past 20,000 years. These prehistoric liquefaction episodes have not yet been recognized east of Crowleys Ridge, suggesting either that the earthquakes that produced the features were local events originating west of Crowleys Ridge or that the features may represent pre-Holocene earthquakes in the epicentral region of the 1811–1812 earthquakes.

Obermeier has made a limited search for liquefaction features in the banks of the lowermost Ohio River downstream from the confluence with the Wabash River (Figure 8) as well as a search of the banks of the Tennessee River downstream from Kentucky Lake. At least 20 km of exposed banks were examined in sediments that are at least as old as 4,000 years in most places. No evidence of pre-1811–1812 liquefaction was found beyond the immediate vicinity of the Wabash Valley (discussed in the next section). There is no reason to suspect that the liquefaction susceptibility has changed greatly through middle to late Holocene time. Thus, it is unlikely that very strong shaking (more than about 0.2 *g*) or a very strong earthquake (much higher than about **M**7) has occurred in the immediate vicinity of the lowermost Ohio Valley in the past 4,000 years.

Wabash Valley Seismic Zone

Good liquefaction evidence shows that at least one very strong prehistoric earthquake has struck the lowermost Wabash Valley (*31*). Sand-filled dikes occur near the confluence of the Wabash with the Ohio River and northward about 200 km in the Wabash Valley. Most of the dikes are exposed in banks of the Wabash River and tributary streams. Present data indicate that almost all the dikes formed in response to an earthquake between about 5,000 and 7,500 years ago.

Because almost all the sand-filled dikes in the Wabash Valley were found in the banks of rivers, and therefore possibly were very near the rivers when they formed, a special effort was required to determine that the dikes were not caused by nonseismic mechanisms such as landsliding or artesian conditions. The criteria discussed above for verifying an earthquake origin were used as the guide.

The sand-filled dikes in the Wabash Valley have formed in a physical setting very similar to the area of extensive liquefaction in the epicentral region of the 1811–1812 New Madrid earthquakes (Figure 10). An earthquake origin for the Wabash Valley dikes is thought to be highly probable because (*a*) the sand dikes have the same characteristics as those in the 1811–1812 epicentral region, (*b*) artesian conditions that could have produced dikes were extremely unlikely at many sites, and (*c*) modern landsliding in the Wabash Valley region (or anywhere else in a similar physical setting) has not been shown to produce dikes similar to those of the Wabash Valley (*31*).

The earthquake magnitude for the largest event has been estimated by comparing the span of liquefaction features (exceeding 200 km) in the Wabash Valley with the span of other historic liquefaction-producing earthquakes in the central and eastern United States (*31*). Calibration was provided by effects of the 1811–1812 New Madrid earthquakes; the 1895 Charleston, Missouri, earthquake; and the 1886 Charleston, South Carolina, earthquake. Such a comparison yields an earthquake having an estimated moment magnitude on the order of 7.5; the epicenter was approximately in the center of the Wabash Valley seismic zone shown in Figure 2.

Intensive ongoing studies are widening the study area much beyond the limits of the Wabash Valley seismic zone and are providing engineering data (such as minimum accelerations) to refine preliminary interpretations of the magnitude of the large prehistoric event. Whatever the magnitude, it appears that the potential exists for very strong earthquakes whose magnitudes are much larger than any in the historic record to strike the Wabash Valley on a rare, infrequent basis.

SUMMARY

Not only have paleoliquefaction studies proven to be valuable for interpreting recent prehistoric earthquake activity, but this method is one of the most important for assessing hazardous zones in intraplate portions of central and eastern North America. Interpretations of an earthquake origin and magnitude for suspected liquefaction features are best made by geologic field studies in combination with geotechnical engineering field studies and calculations.

Earthquake-magnitude prediction models used by seismologists are based on measurements of very recent earthquakes; this record is far too limited in time to be meaningful. A good example of the inherent error in this method is provided by comparison of results of paleoliquefaction studies in the 1811–1812 New Madrid epicentral region with predictions using the seismological approach of statistical mechanics. The discussion by Wesnousky and Leffler (*25*) points out that the seismological approach predicts a recurrence about every 600 years for the great 1811–1812 earthquakes in the New Madrid seismic zone. In contrast, the absence of widespread paleoliquefaction features indicates that no earthquakes as strong as those of 1811–1812 occurred in the last 5,000 to 10,000 years.

Many fundamental issues need to be resolved before seismological statistical measurements on modern earthquakes can be used as the basis for predictions. These issues include determining whether strong earthquake activity in a local area is time dependent or time independent and determining the tectonic causes of earthquakes in the intraplate region of central and eastern North America. Paleoliquefaction studies can serve an important role in resolving these issues.

Paleoliquefaction studies show that very strong earthquakes have struck in some unexpected places but that earthquakes weaker than expected have struck in other places. The studies also show that strong intraplate earthquakes have a tendency to recur at or very near a given region but at widely spaced time intervals.

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