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# THE REPEAT TIME OF THE 1811 AND 1812 NEW MADRID EARTHQUAKES: A GEOLOGICAL PERSPECTIVE

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ABSTRACT

**The great New Madrid earthquakes of 1811 and 1812 were accompanied by extensive liquefaction within the meizoseismal zone. We examined tens of kilometers of freshly excavated ditch banks within the southern limb of the New Madrid Seismic Zone for evidence of prehistoric liquefaction events. Radiocarbon dates indicate that the exposures studied provide a record of the last 5000 to 10,000 years. Analyses of the statistics of historical seismicity imply a relatively short 550- to 1100-yr repeat time for 1811- to 1812-type earthquakes. In contrast, our search did not reveal definitive evidence of widespread paleoliquefaction events and, hence, provides no independent support for the relatively short 550- to 1100-yr return time implied by statistics of historical seismicity.**

## INTRODUCTION

The New Madrid sequence of earthquakes consisted of four principal ($M_s \geqq 8$) events occurring on the days of 11 December 1811 and 23 January and 7 February 1812. The distribution of isoseismals (Nuttli, 1973, 1979; Hopper, 1985), the recognition of a distinct zone of seismicity within the region of largest isoseismals (Stauder *et al.*, 1976; Stauder, 1982), and the association of extensive liquefaction features that indicate severe ground motion proximal to that zone of seismicity (Fuller, 1912; Heyl and McKeown, 1978; Obermeier, 1984) support the assertion that the now well-known New Madrid Seismic Zone was the source of the 1811 and 1812 earthquakes (Fig. 1). Understanding the recurrence characteristics of such events is important to understanding both the seismic hazard and rate of intraplate deformation in the New Madrid region.

Johnston and Nava's (1985) recent analysis of the statistics of historical seismicity within the New Madrid Seismic Zone places the return time of 1811- and 1812-type earthquake sequences at between about 550 and 1100 yr. The same authors also note the significant uncertainty attendant to interpreting the long-term behavior of the zone based on the limited historical record. Russ' (1979) geological study of Reelfoot scarp and Saucier's (1991) study of archaeological sites about 30 km north of New Madrid also point to a return time for large earthquakes of about 450 to 600 yr. However, each also notes that the estimates may reflect the recurrence of earthquakes of smaller size than occurred in 1811 and 1812. Thus, although arguably the largest historical earthquakes within the conterminous United States, data bearing on the expected repeat time of 1811- and 1812-type events remain few and are generally equivocal.

The New Madrid Seismic Zone is not expressed as a clear and unambiguous fault trace (Schweig and Marple, 1991). It is not known if the 1811 and 1812

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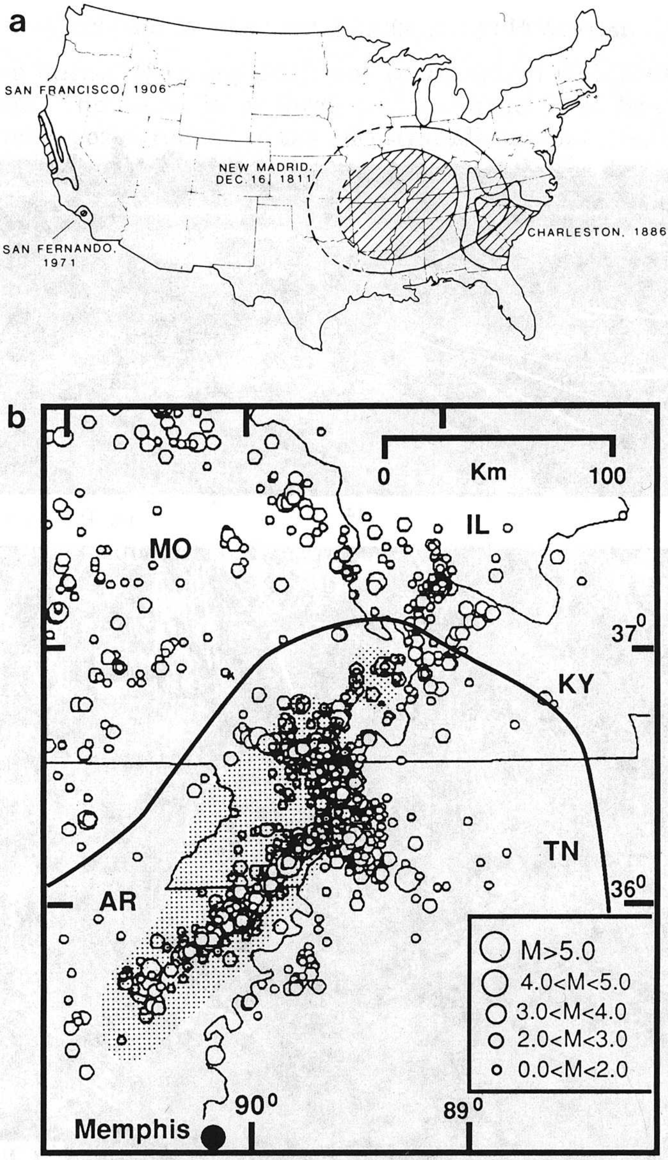
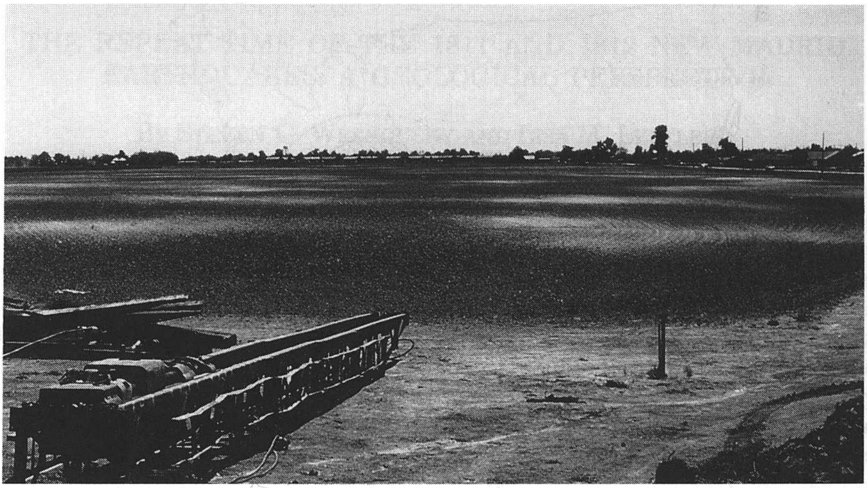
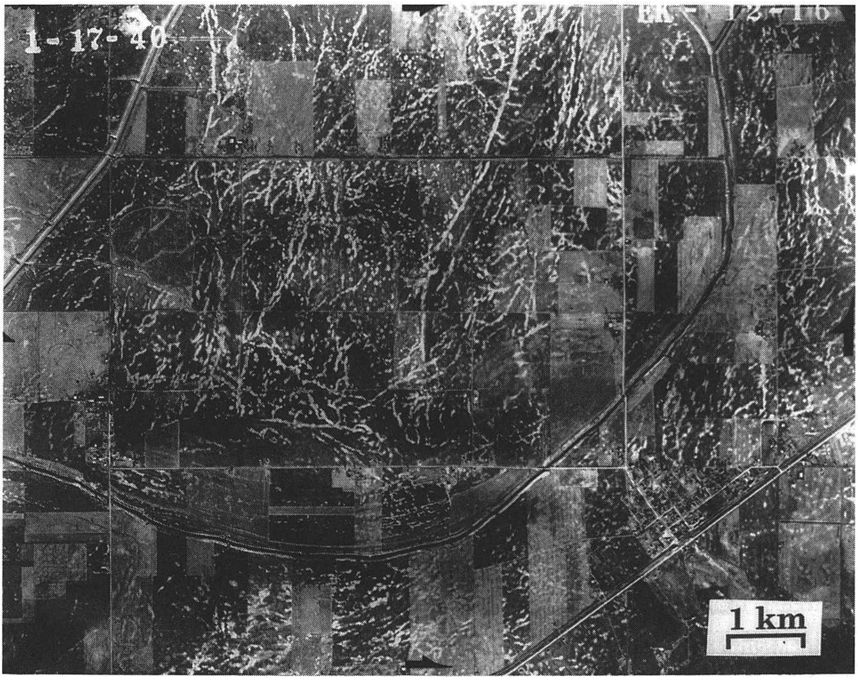



FIG. 1. (a) Modified Mercalli (MM) VI and VII (hachured) isoseismals for the 1811 and 1812 earthquakes compared to other major U.S. earthquakes (modified from Hamilton and Johnston, 1990). (b) The New Madrid Seismic Zone is defined by alignment of earthquake epicenters recorded between 1974 and 1990, which extends southwestward from near Illinois (IL) to northwest of Memphis, Tennessee (TN). The stippled area was characterized by extensive liquefaction during the 1811 and 1812 New Madrid earthquakes (Heyl and McKeown, 1978; Obermeier, 1984). The curved solid line marks the northern extent of the Mississippi Embayment.

earthquakes produced a single through-going zone of surface faulting, as commonly observed for large earthquakes in the western United States. However, the 1811 and 1812 earthquakes induced pervasive liquefaction in a zone approximately 20 to 50 km wide trending southwestward for a distance of about 150 km through portions of Missouri, Arkansas, and Tennessee (Fig. 1). Sand extruded in 1811 and 1812 covered as much as 25% of the land surface, is still



(a)




(b)

FIG. 2. (a) Liquefied sand that was extruded onto the surface in 1811 and 1812 is still clearly visible as light-colored, circular patches on the dark brown soil of this farm field at the intersection of Stateline (Main) Ditch and State Hwy. 151 in northeastern Arkansas. Lack of significant relief seen here is characteristic of the entire study region. (b) Abundant sandblows (isolated white spots) and sand-filled fissures (linear white features) seen in this 1940 aerial photograph further attest to the pervasive occurrence of liquefaction in 1811 and 1812. Dell, Arkansas, in the lower right-quarter of the photograph, sits above the New Madrid Seismic Zone. Up is North on the photo.

readily visible today, and is expressed as light-colored and commonly irregular shapes on the dark brown soils of the Mississippi Embayment (Fig. 2). Here we report on our search for evidence of a widespread paleoliquefaction event and, hence, evidence bearing on the repeat time of great 1811 and 1812 earthquakes.

## Geologic Setting and Liquefaction Potential

Liquefaction during 1811 and 1812 was concentrated within the St. Francis drainage basin. The basin is in large part constructed of late Wisconsinan braided stream deposits related to the ancestral Mississippi river system and is now characterized by low relief, a high water table, and poor drainage. Near the latitude of Memphis, deposition of braided stream deposits is estimated to have ceased about 9500 yr ago (Saucier, 1974). Hence, the majority of vented sand deposits rest upon abandoned late Wisconsinan braided stream terraces (Fig. 3), which have been stable surfaces with only minor localized sedimentation since the formation of the Holocene Mississippi river meander belt. The braided stream terrace deposits generally consist of loose, water-saturated sand overlain by clay and silt-rich strata that effectively form a topstratum of low permeability. The topstratum is generally $\geqq 1$ to 2 m thick. The relatively thin topstratum and associated high water table were responsible for the tremendous liquefaction effects reported for the 1811 and 1812 earthquakes (e.g., Fuller, 1912; Obermeier, 1988).

The occurrence of liquefaction features over a 16-km diameter resulting from the moderate $m_b = 6.2$ Charleston, Missouri, event during the dry season of October 1895 illustrates the high level of liquefaction susceptibility in the region (Obermeier, 1988). We further suggest that seasonal or relatively brief climatic fluctuation should not significantly affect the liquefaction susceptibility of the region. Even during record low stages of the Mississippi river, which occurred during the period of our study, the water table remained relatively high, as seen by the persistent flow in local drainage ditches that was maintained by springs along the ditch margins. Radiocarbon and pollen analysis of cores near Big Lake, Arkansas (Fig. 4), also provide evidence that much of the area of our study has been characterized by backswamp depositional processes and backswamp and bottomland arboreal vegetation through the Holocene (Guccione, 1987) and, by inference, a relatively high water table. It then seems reasonable to expect that, if 1811- and 1812-type earthquakes occurred during the Holocene, a signature of paleoliquefaction would be preserved in the geologic record.

## Opportunity and Approach

The U.S. Army Corps of Engineers maintains a large network of major drainage ditches throughout the St. Francis drainage basin for flood control and land reclamation (Fig. 4). Two factors provided us with an unusual opportunity to search for evidence of paleoliquefaction along these ditches. The Mississippi Embayment and associated drainages were subject to an unusual drought during the late 1980s, with the lowest recorded stage of the Mississippi River during the summer of 1988. Simultaneously, the Corps of Engineers embarked on a program to re-excavate and widen several of the existing ditches. During re-excavation, the vegetation on one side of the ditches is removed, resulting in fresh exposures of 2- to 3-m height (Fig. 5). The combination of drought and excavation provided tens of kilometers of vegetation-free exposures. We searched the length of the ditches, marked by heavy solid lines in Figure 4, for evidence of sand-blow deposits and sand-filled vents and fissures within the topstratum, which might record evidence of prehistoric liquefaction. We limit our discussion here to ditch exposures within the limits of Figure 6, which are generally representative of the other ditches studied (Leffler, 1991).

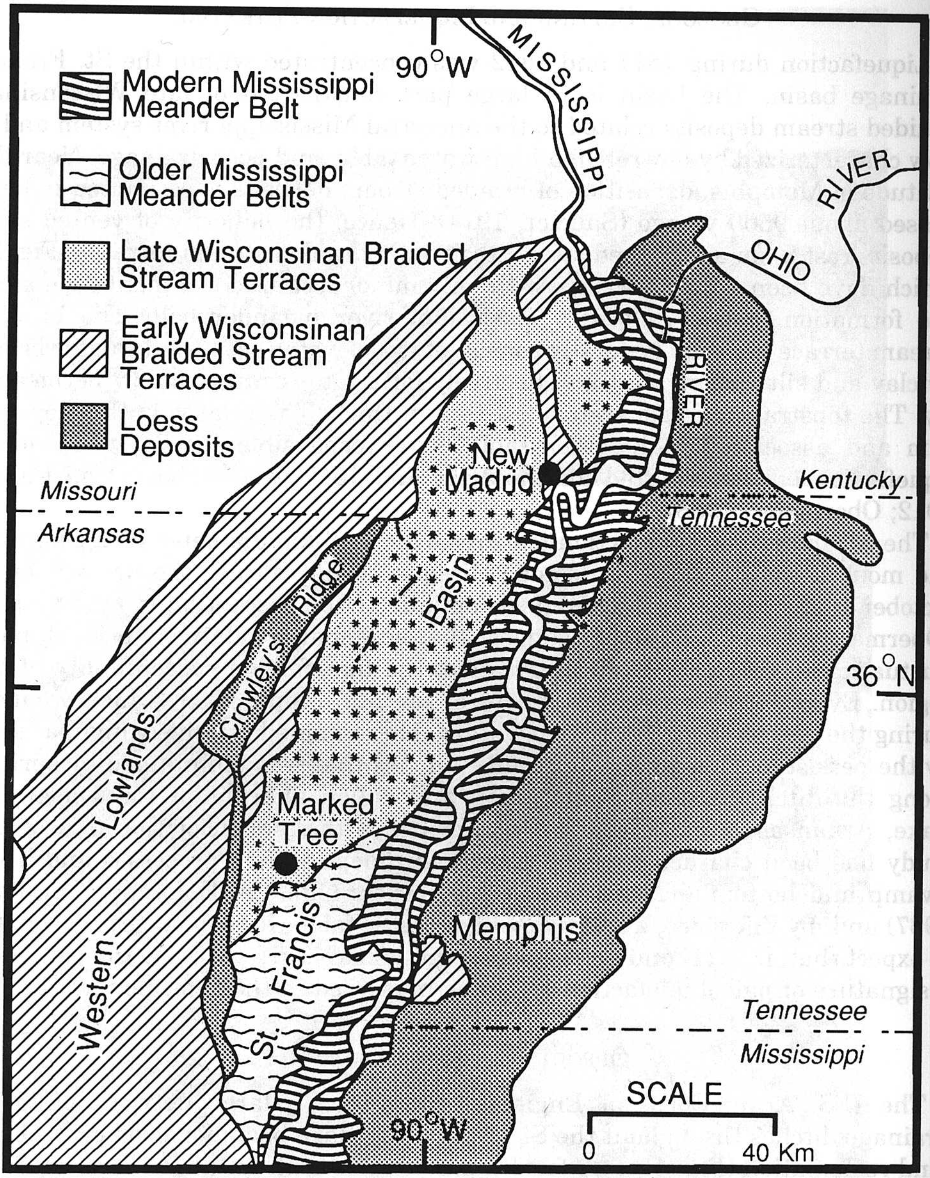



FIG. 3. Generalized Quaternary geologic map of upper Mississippi embayment (Adapted from Saucier, 1974). Sand ejected during the 1811 and 1812 earthquakes comprises greater than 1 to 25% of the areal extent of the surface in a region (overlain by asterisk pattern) that extends from north of New Madrid southwestward to Marked Tree (Obermeier, 1989).

## THE OBSERVATIONS

### *A Synopsis*

Along the ditches we examined within the meisoseismal zone, vented sand-blow deposits and sand-filled vents and fissures are frequent and share a number of common characteristics. For example, many of the exposures provided evidence of multiple episodes of liquefaction. In these instances, vented

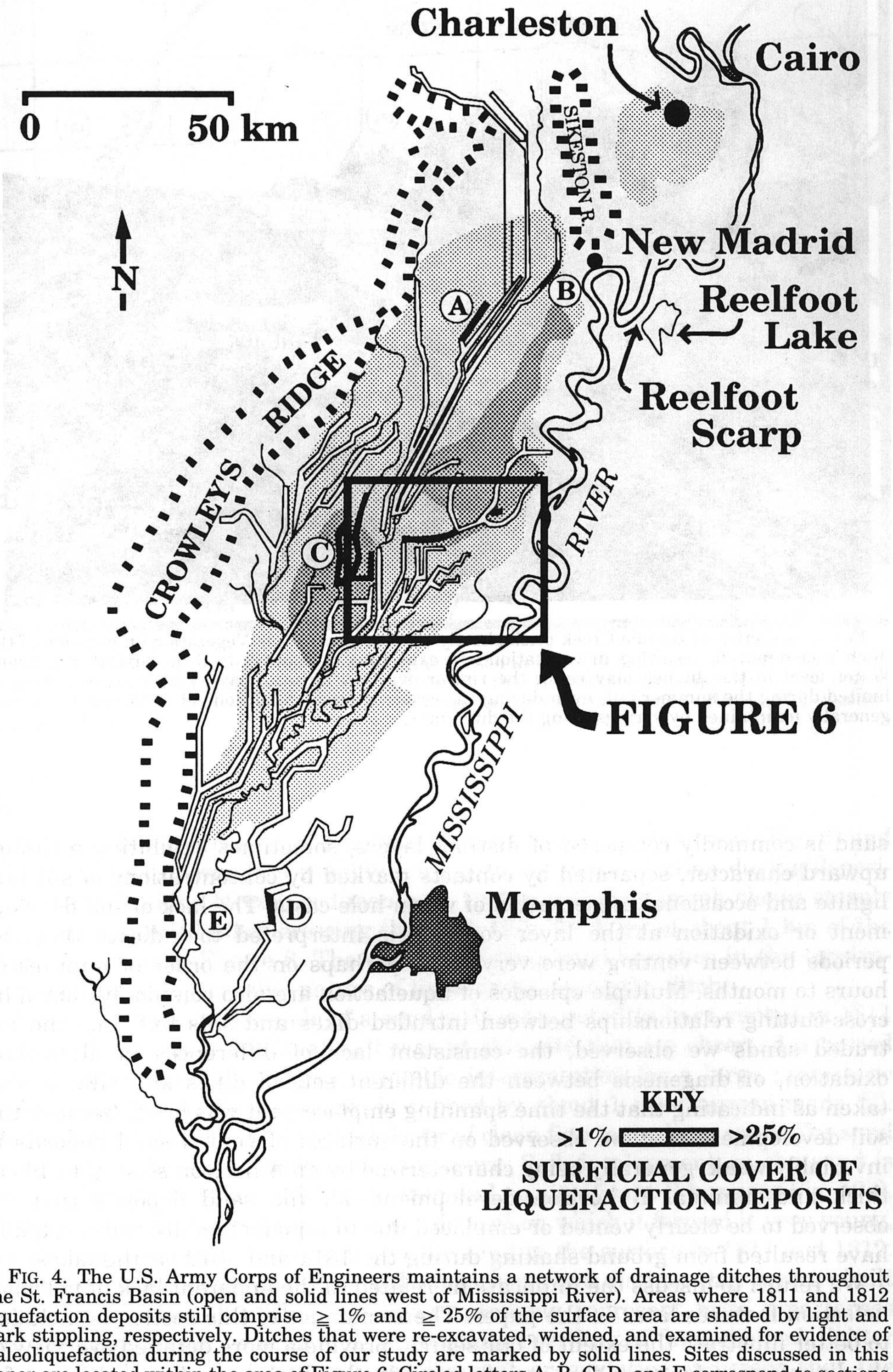



FIG. 4. The U.S. Army Corps of Engineers maintains a network of drainage ditches throughout the St. Francis Basin (open and solid lines west of Mississippi River). Areas where 1811 and 1812 liquefaction deposits still comprise ≧ 1% and ≧ 25% of the surface area are shaded by light and dark stippling, respectively. Ditches that were re-excavated, widened, and examined for evidence of paleoliquefaction during the course of our study are marked by solid lines. Sites discussed in this paper are located within the area of Figure 6. Circled letters A, B, C, D, and E correspond to sections of ditch 9, Little River, Honey Cypress ditch, Blackfish Bayou, and St. Francis River, respectively. Big Lake is located in region of Figure 6.

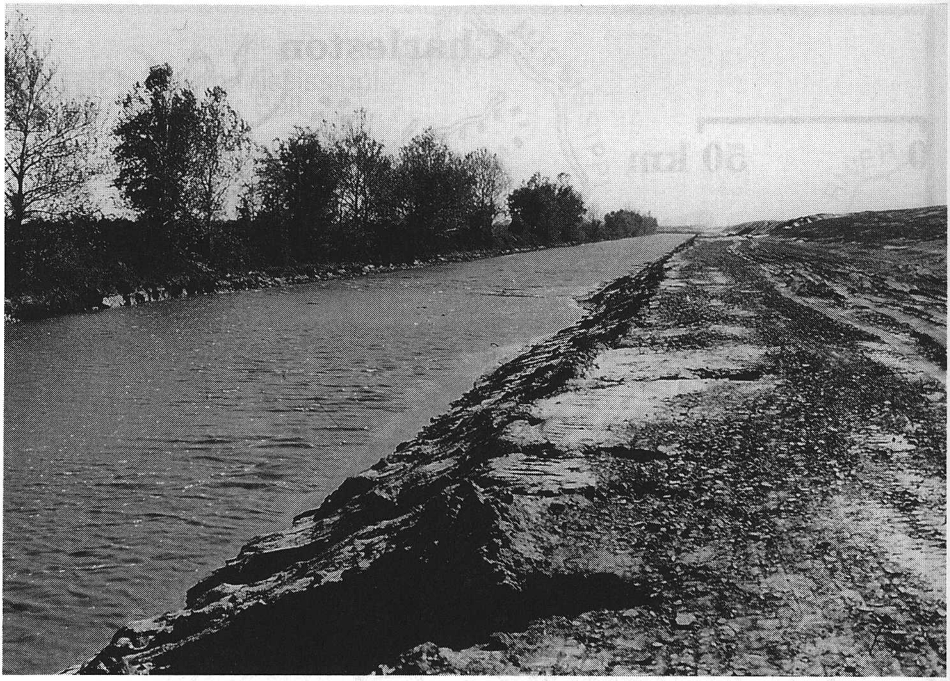


FIG. 5. A section of Buffalo Creek ditch shortly after re-excavation. Vegetation on one side of the ditch was removed, resulting in vegetation-free exposures of about 2 to 3 m vertical dimension. Water level in the ditches may reach the rim or overflow during heavy winter storms. Flow is limited during the summer but, even during the severe drought conditions of 1988, some flow was generally maintained by springs along the ditch margins.

sand is commonly composed of distinct layers, sometimes exhibiting a fining-upward character, separated by contacts marked by concentrations of silt and lignite and occasional preservation of worm-hole casts. The lack of soil development or oxidation at the layer contacts is interpreted to indicate that the periods between venting were very brief, perhaps on the order of minutes or hours to months. Multiple episodes of liquefaction are also commonly shown by cross-cutting relationships between intruded dikes and sills but, like the extruded sands we observed, the consistent lack of differences in alteration, oxidation, or diagenesis between the different sets of dikes and sills is also taken as indicating that the time spanning emplacement was brief. Because the soil development that we observed on the surfaces of vented sand deposits is invariably weak, generally being characterized by an A horizon several to 10 cm thick and minimal B horizon development, all the sand deposits that we observed to be clearly vented or emplaced due to liquefaction are interpreted to have resulted from ground shaking during the 1811 and 1812 earthquakes.

We return to discuss the implications related to the apparent lack of paleoliquefaction features later in the paper. The remainder of this section is included to better illustrate the extent of our search, provide a more detailed overview of the liquefaction features that we observed in the ditches, and provide a useful point of reference for any future efforts toward unraveling the paleoearthquake history of the region.

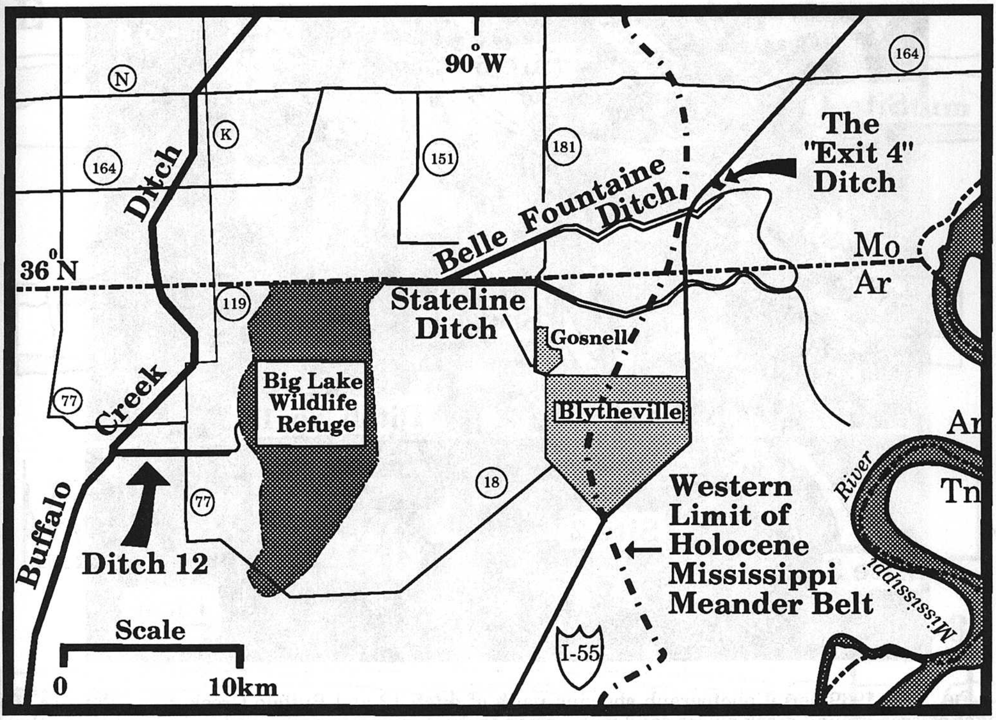



FIG. 6. Location of ditches (thick solid lines) discussed in text. Circled numbers and letters mark State highways and County roads. Region west of the Holocene Mississippi meander belt is constructed principally of Late Wisconsinan braided stream deposits (Saucier, 1974). Map location shown in Figure 4.

*Ditch 12*

Ditch 12 is located west of Big lake Wildlife Refuge in Arkansas (Fig. 6) and trends east-west, which is roughly normal to the flow direction during deposition of the braided stream sediments. A 1939 aerial photograph shows steeply dipping sand-filled dikes crossing the ditch (Fig. 7). A log of about 1 km of the ditch is shown in Figure 8. The numerous sand-filled breaches in the topstratum confirm the pervasive nature of liquefaction along the ditch.

Site 2 provides an example of a sand unit interpreted to have vented in 1811 and 1812 (Fig. 9). Additionally, it was at this site that we observed a buried sand deposit that left open an arguable interpretation for a large prehistoric liquefaction event. The exposure is capped by about 1 m of human-made fill. Beneath the fill is a 1- to 2-m-thick layer of clean fine to medium sand. The sand is fed by a dike at the base of the exposure. Soil development on the sand is marked by a 5- to 10-cm-thick A horizon and no significant B horizon (Fig. 10a). The weak soil profile suggests that the deposit on which it formed is very young, most likely a result of the ejection of the sand to the surface in 1811 and 1812. The internal structure of the ejected sand shows two distinct thin layers of silt and lignite (Fig. 10b). The thin layers probably represent brief time lapses between episodes of venting and the attendant settling of finer grained, lighter materials. The lack of any soil development or oxidation indicates that the layers were exposed for a very brief time. Saucier (1989) interpreted similar features at a liquefaction site in northeastern Arkansas to suggest that such

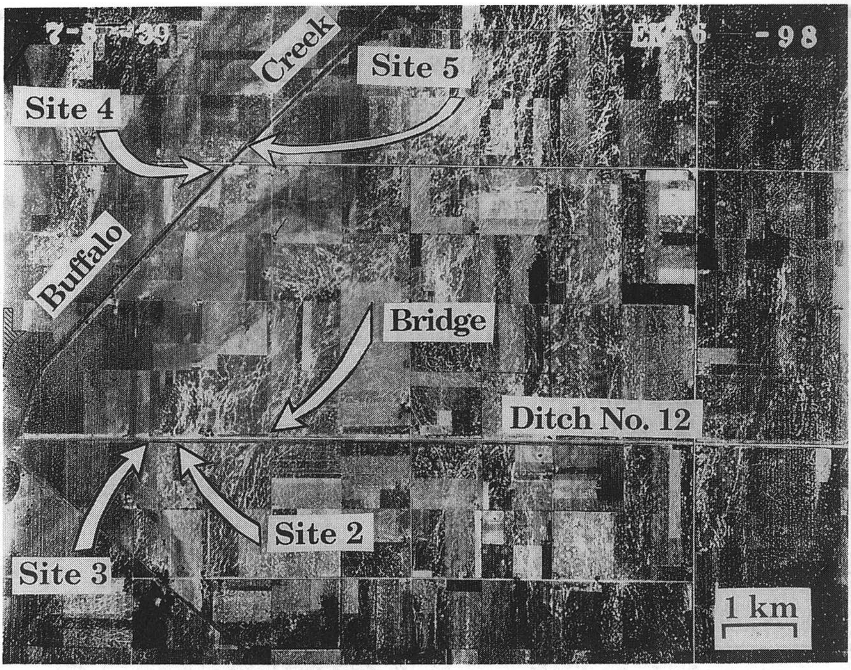



FIG. 7. A 1939 aerial photograph showing parts of ditch 12 and Buffalo Creek ditch. Patches of light-colored ground mark where sand was ejected through numerous rifts and isolated blows in the vicinity of the ditches. Buffalo Creek ditch occupies an abandoned relict south-flowing channel on the braided-stream terrace whereas ditch 12 cuts across an interfluve. Arrows locate sites 2 through 5. Up is North on the photo.

distinct layers of ejected sand represent individual events of the 1811 to 1812 New Madrid earthquake sequence.

In contrast to the weakly developed soil on the ejected sand at site 2, the buried surface on which the ejected sand rests is characterized by a well-developed soil profile, consisting of a 10- to 15-cm-thick A horizon (2Ab) and a B horizon (2Bb) that is about 1 m thick (Fig. 11). The strong development of the 2Ab-2Bb soil profile suggests that the surface on which the sand ejected was stable for a long period of time prior to being breached by liquefied sand in 1811 and 1812. The buried 2Ab-2Bb profile grades downward into a clean sand, which, in turn, rests in sharp contact with another buried surface on which the 3Ab-3Bb soil-profile is developed (Figs. 9 and 11). A speculative interpretation is that the 2Ab-2Bb profile is developed on sands ejected at the time of a prehistoric earthquake. A sand fissure feeding the buried sand and breaking the 3Ab horizon would be conclusive evidence of a liquefaction origin for the sand. However, such was not observed along the Sand-3Ab contact, which we exposed for a distance of about 15 m west of the vent. The measured magnetic directions of paleomagnetic samples from 2Bb also show it to maintain a continuous geomagnetic secular variation curve, suggesting that it was emplaced gradually over a period of time (Stephen Salyards, Department of Earth Science, University of California, Los Angeles, 90024, personal comm.). Hence, a fluvial origin for the buried sand is consistent with the observations, and interpretation of the buried sand as a result of prehistoric liquefaction is equivocal.

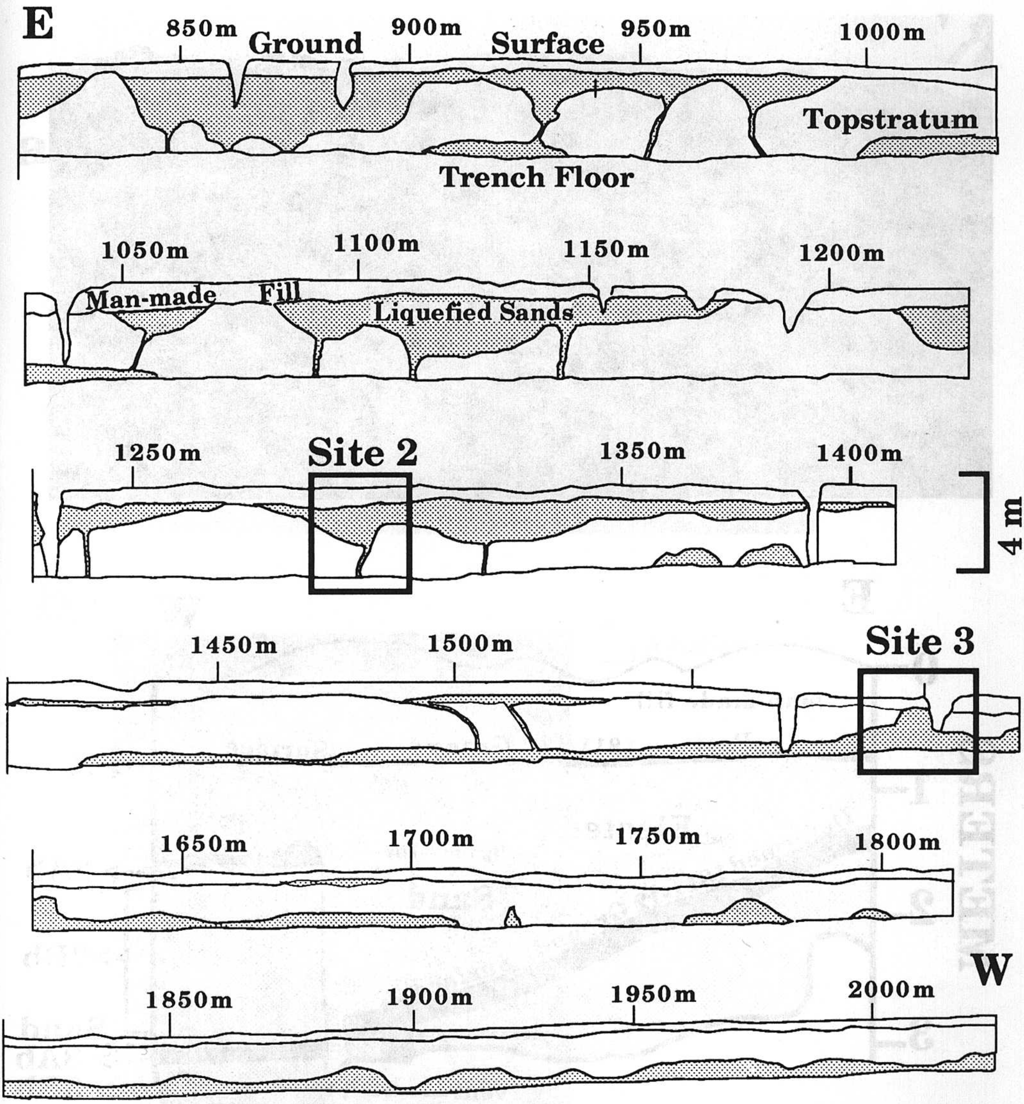



FIG. 8. Log of the south side of a section of ditch 12 near Manila, Arkansas. The upper 0.5 to 1.0 m of the section is human-made fill. The topstratum is defined by its clay-rich and generally nonliquefiable character. The shaded unit is fine and coarse sand that shows evidence of liquefaction. Evidence of fluvial bedding within sand is evident locally but generally not common. Solid boxes show sites along the trench that are documented in detail. Horizontal distances are measured with respect to west edge of bridge crossing shown in Figure 7. Note vertical exaggeration.

Nearby at site 3 (Figs. 7 and 8), we obtained radiocarbon dates from wood samples to place direct limits on the age of the topstratum through which the sand vented (Fig. 12). The topstratum at this location is very dark clay and sharply interrupted by the intrusion and ejection of very light gray, locally oxidized, very fine to fine grained sand. Again, the weak soil profile developed on the extruded sand, composed of a thin A horizon and virtually no B horizon, indicates that it most likely formed since 1811 and 1812. A very well-developed soil is present on the surface through which the sand vented, suggesting considerable antiquity and stability to the surface on which it is developed.

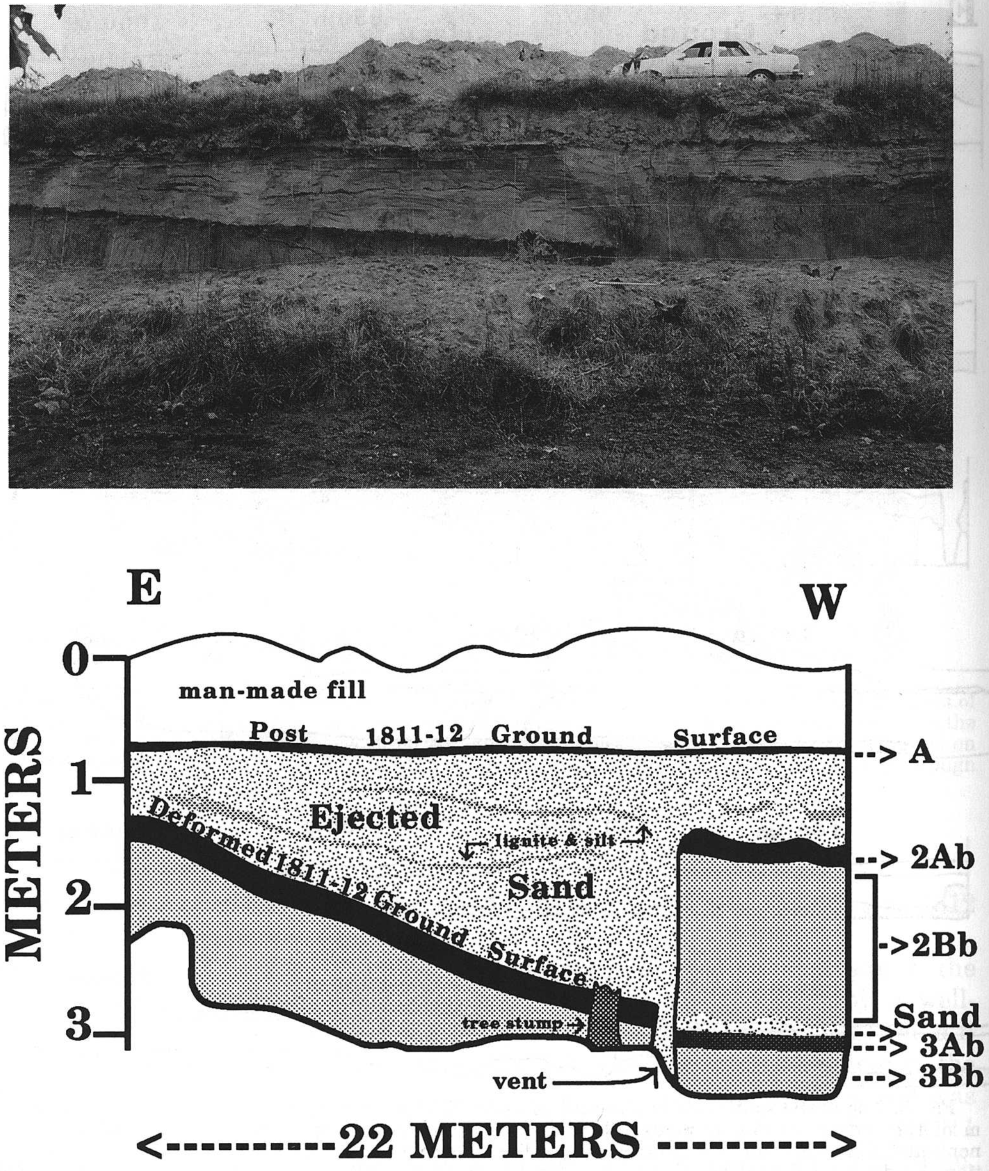
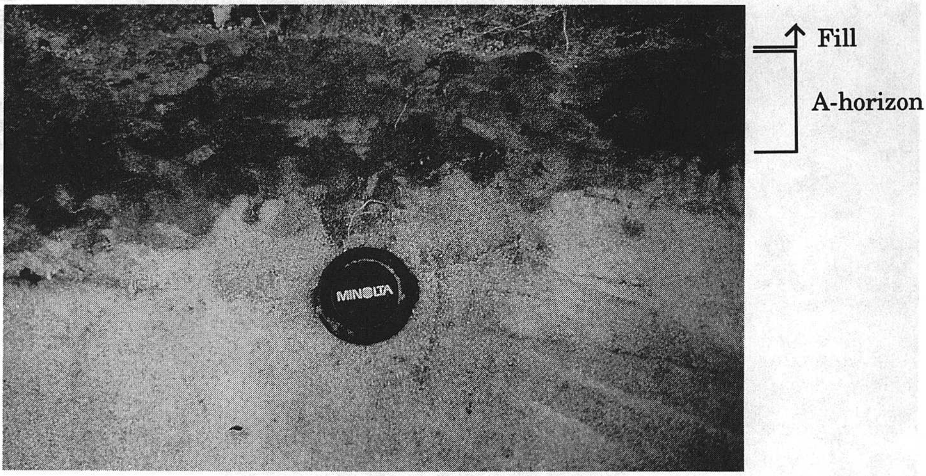



FIG. 9. Sketch (vertically exaggerated) and photo of site 2 along ditch 12 near Manila, Arkansas. String grid on photo exposure at 1-m intervals. Pedological interpretation shown on right side of sketch.

Unit 2Ab at site 3 (Fig. 12) is a loamy sand that rests in abrupt and irregular contact with the underlying silty loam (2Eb) and loam (2Bb). It may be speculated that the loamy sand (2Ab) was originally vented to the surface during a paleoliquefaction event but, like at site 2, no evidence for a feeder dike was observed. Large pieces of bark-covered wood were recovered from two locations within the lowermost meter of topstratum and tentatively identified as bald cypress (Donna Christensen, Center for Wood Anatomy Research, U.S. Forest Products Laboratory, Madison, WI 53706, personal comm.). The two a




b

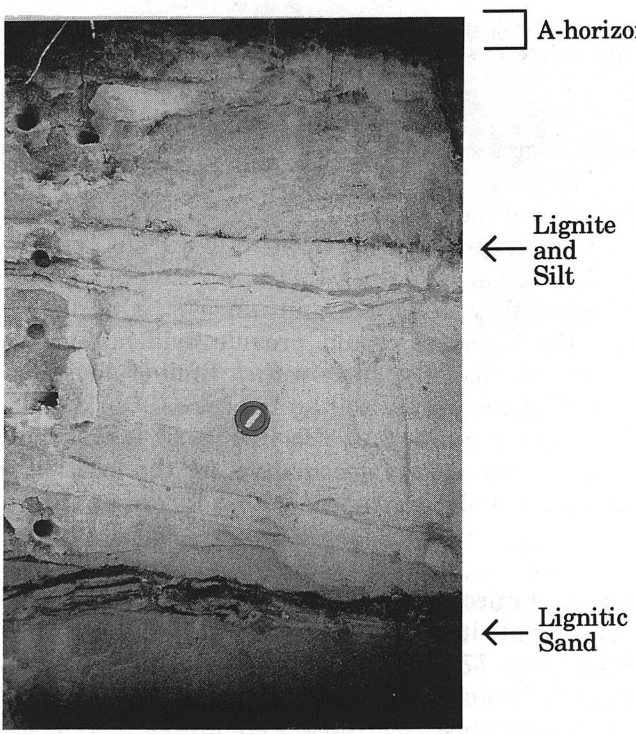



FIG. 10. (a) The soil profile developed on the ejected sand at site 2 along ditch 12 (Fig. 9) is characterized by a thin, black A horizon. Pedogenesis of sand is limited to slight oxidation of sand in few centimeters directly beneath A horizon. Although overlain by recent ditch spoils, the abundant worm-hole casts within the A horizon show soil development on the ejected sand to be undisturbed by humans. (b) The internal structure of the ejected sand is characterized by thin layers of silt and lignite that separate thicker units of sand. The A horizon in (a) is located at the top of (b). Camera lens caps provide scale. (Sampling of the ejected sand for paleomagnetic signature caused small holes observed in exposure of lower photo).

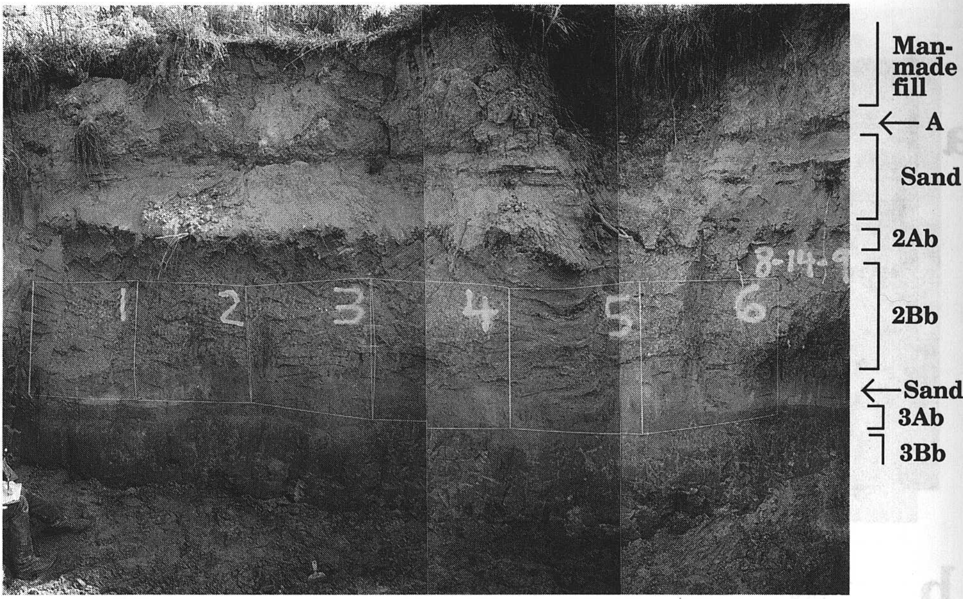



FIG. 11. Composite photo of site 2 (Fig. 9) including the sand vent and exposure to the west of the vent. String grid is placed at 1-m intervals. Pedological interpretation shown to *right* of photo.

samples have radiocarbon dates of 5090 ± 60 and 11,100 ± 100 C-14 yr B.P., respectively (Beta Analytic Inc.; Lab sample numbers Beta-38311 and Beta-41984). The wood at the base of the topstratum has an age of 11,100 ± 100 C-14 yr B.P. Thus, the topstratum represents about 5000 to 10,000 yr of accumulation since deposition of braided stream deposits ceased. Accepting the speculative assumption that unit 2Ab was vented onto an earlier surface during a paleoliquefaction event, the exposure would provide evidence for two large earthquakes in about the last 10,000 yr, or a return time of about 5000 yr. It might also be speculated that the buried soil profile here (2Bb) correlates with the buried soil profile at site 2 (units 3Ab-3Bb in Fig. 9). Yet, a liquefaction origin for unit 2Ab must remain as very speculative, for the location, composition, and texture of the unit are also consistent with a fluvial origin.

*Buffalo Creek Ditch*

The cross-cutting nature of injected sills and dikes observed in the subsurface is illustrated by the exposure at site 4, which is located about 150 m south of the ditch crossing with State Hwy. 77 (Fig. 6) and shown with respect to the local geomorphology in Figure 7. The stratigraphy at the site (Fig. 13) consists of a dark brown A horizon resting on a light-gray well-developed B horizon composed of FeO-stained loam. Downward, the B horizon grades into unaltered, fine- to medium-grained alluvial sand interbedded with thin clay beds. Sand dikes and sills (units $S_1$, $S_2$, and $S_3$) intrude and disrupt the host stratigraphy (Fig. 13). Impermeable clay and loamy sand layers here inhibited the upward migration of liquefied sand, as observed by the presence of sand sills (stippled) that extend horizontally from the central pipe to distances of approximately 5 m or more directly beneath relatively nonliquefiable clay and loamy sand (unit E) layers. Cross-cutting relations further indicate three phases of sand injection,

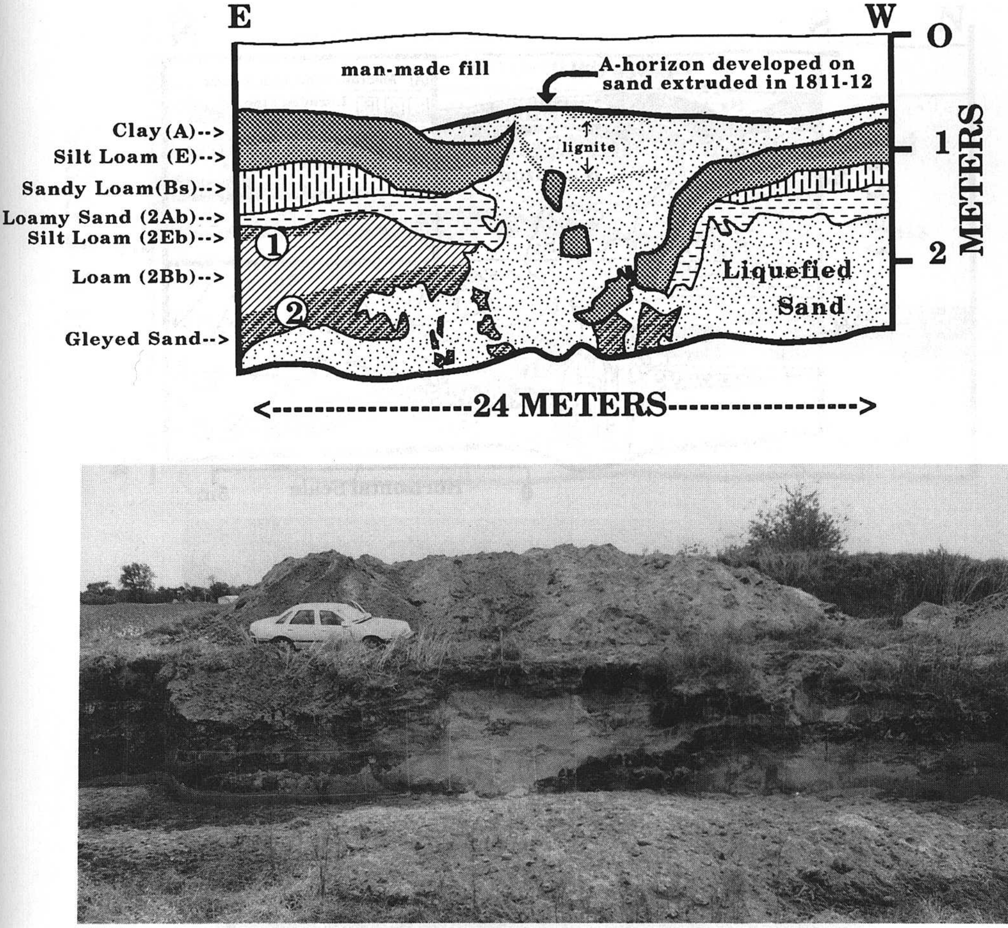



FIG. 12. Photo and sketch (vertically exaggerated) of site 3 along ditch 12 near Manila, Arkansas. Textural and pedological interpretations are at *left* of sketch. Numerals 1 and 2 indicate sites of two wood samples dated at 5090 ± 60 and 11,100 ± 100 radiocarbon years B.P., respectively. Exposure in photo is gridded by string at 1-m intervals.

with the injection of unit $S_1$ being followed by units $S_2$ and $S_3$, respectively. Although the cross-cutting relations reveal evidence of three distinct episodes or phases of liquefaction, the lack of differences in alteration, oxidation, or diagenesis characterizing the different sets of dikes and sills suggests that the time spanning emplacement of units $S_1$, $S_2$, and $S_3$ was brief. The small apparent offsets and warping of units D, E, and F are interpreted to reflect warping and readjustment of the sediments in response to flow of sand beneath, much like observed at site 2 on a larger scale. The sand (unit $S_3$) that did reach the surface is characterized by the absence of significant soil development. Hence, the three generations of sand sills and dikes may be attributed to emplacement in 1811 and 1812.

Site 5 (Fig. 7) provides another clear illustration of the characteristic weak soil development observed on vented sand deposits. The topstratum at site 5 is composed of a well-developed soil profile (Fig. 14) similar in color and composition to that observed at site 4. Unlike site 4, the liquefied sand forms a clear

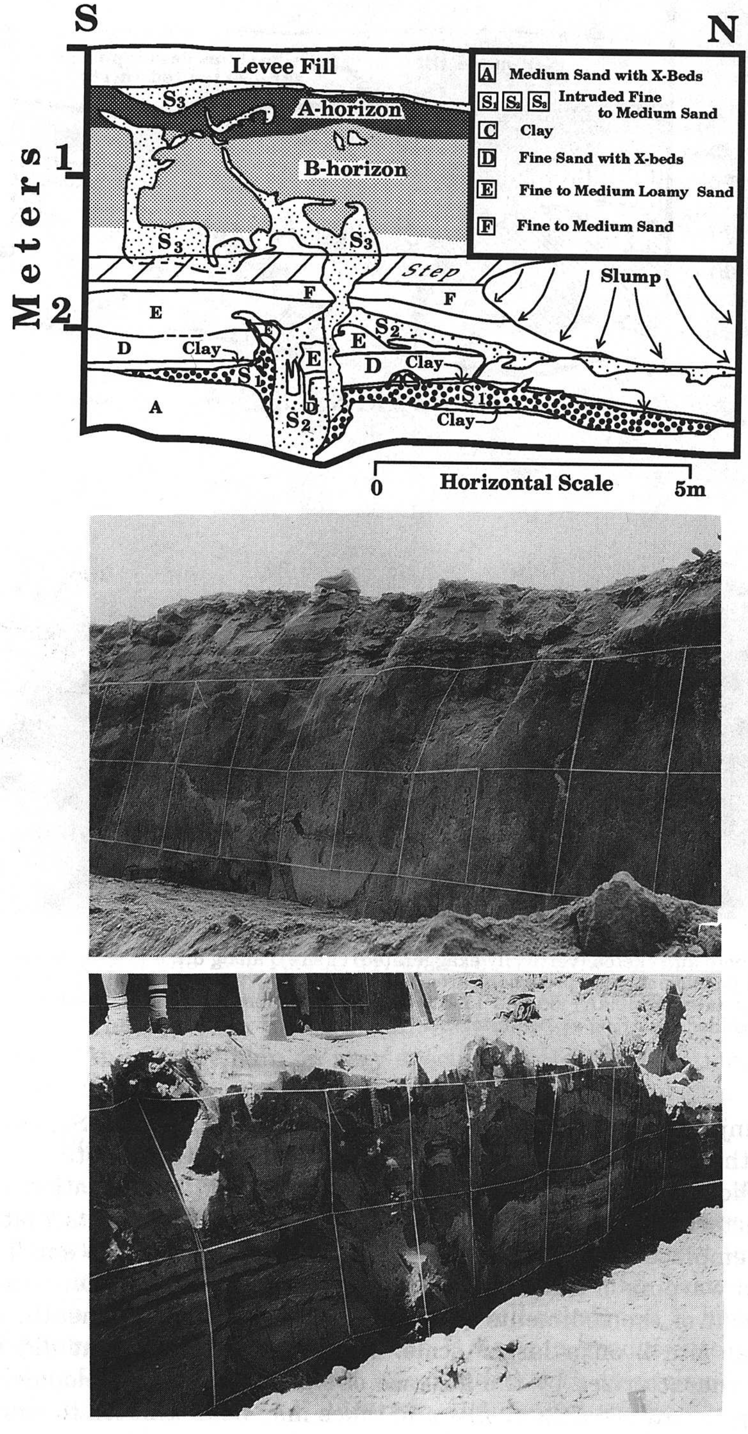



FIG. 13. Photos and sketch (vertically exaggerated) of sand dikes and sills ($S_1$, $S_2$, and $S_3$) in Buffalo Creek ditch about 150 m south of the Hwy. 77 bridge crossing between Leachville and Manila, Arkansas. Location is site 4 in Figure 7. Exposure consists of two faces separated by a step. Exposure gridded at 1-m intervals in *upper* photo and 1 × 1/2 m in *lower* photo, except adjacent to central sand dike ($S_2$) where grid is 1/2 × 1/2 m.

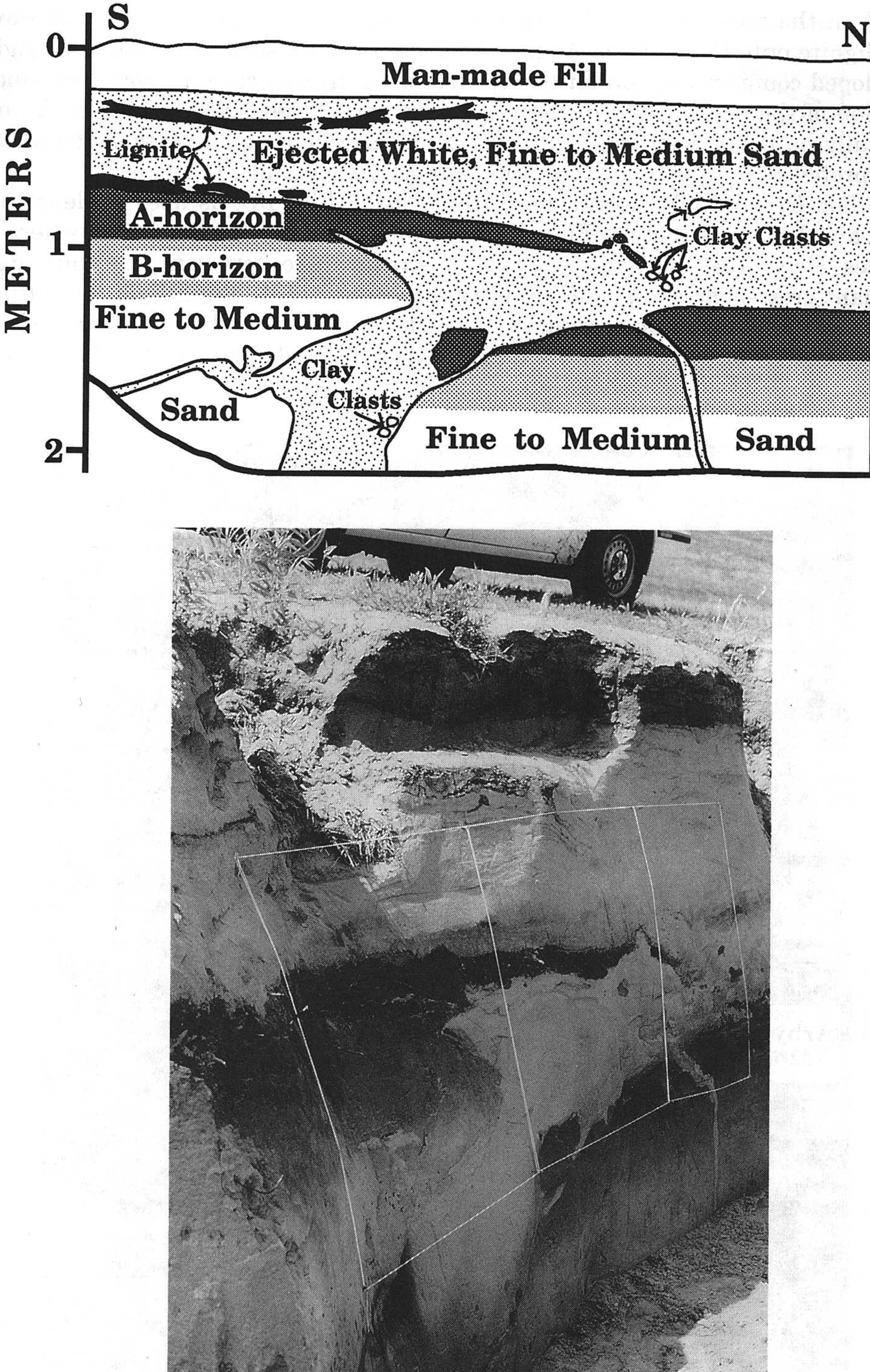



FIG. 14. Sketch and oblique photo of exposure at site 5 (see Fig. 7) along Buffalo Creek ditch. Site is about 150 m north of the intersection of the ditch with Hwy. 77 between Manila and Leachville, Arkansas. The soil profile shows about 50 cm of both apparent extension and vertical offset across a vent through which more than 1 m of sand was extruded to the surface. Soil development on the surface of the ejected sand is minimal in comparison to the thicker profile observed on the breached topstratum.

break in the topstratum and is responsible for venting more than 1 m of sand and lignite onto the surface. Again, the soil on the topstratum is more strongly developed compared to soil on the ejected sand. In this case, pedogenesis since ejection of the sand has formed an A horizon only a few centimeters thick and virtually no B horizon. The incipient soil development on the extruded sand is interpreted to indicate that the sand vented in 1811 and 1812.

Buffalo Creek ditch continues north of site 5 (Fig. 15), as does evidence for 1811 and 1812 liquefaction. Figure 16 is a log of about 3/4 km of ditch where it crosses Hwy. 164. Breaches in the topstratum are common and, although remnant cross-beds are present, the sand beneath the unbreached topstratum more typically exhibits secondary flow structures most likely attributed to liquefaction. A large break in the topstratum is located 400 m south of the Hwy.

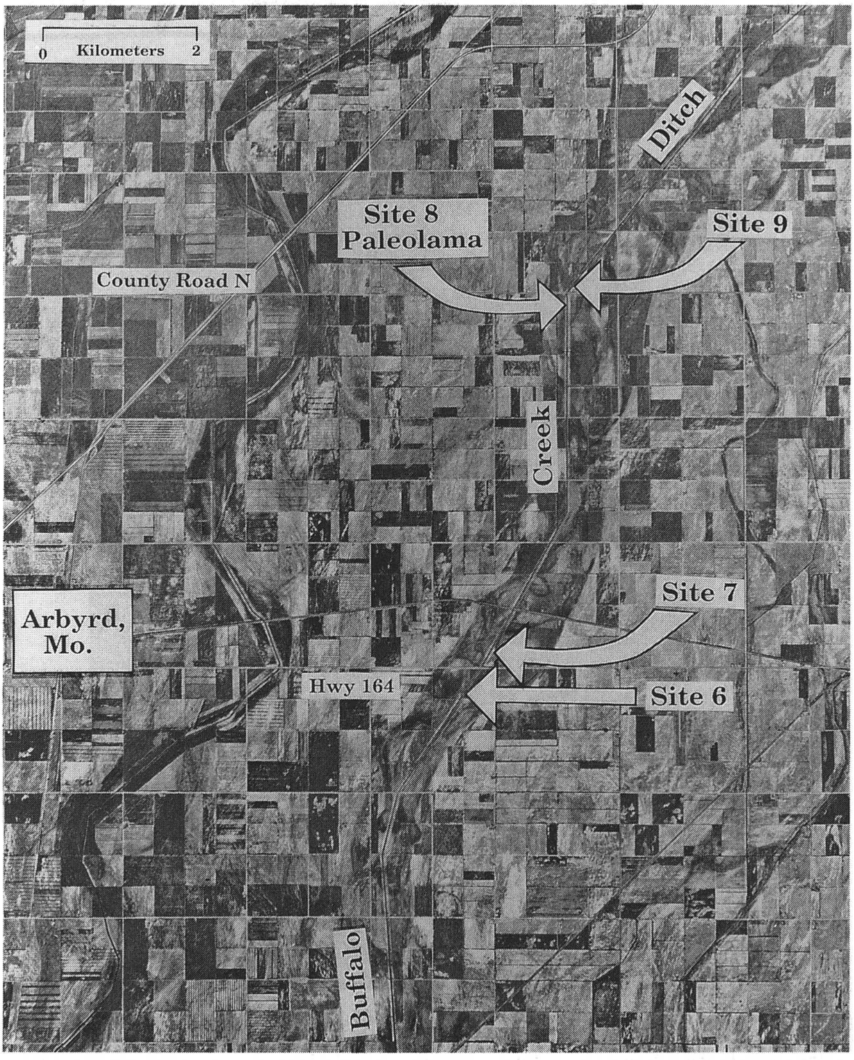



FIG. 15. Arybrd, Missouri, orthophotoquad showing Buffalo Creek ditch following the course of a relict channel on an abandoned braided-stream terrace of late Wisconsinan age. Sites 6 through 9 are discussed in the text. North is up on photo.

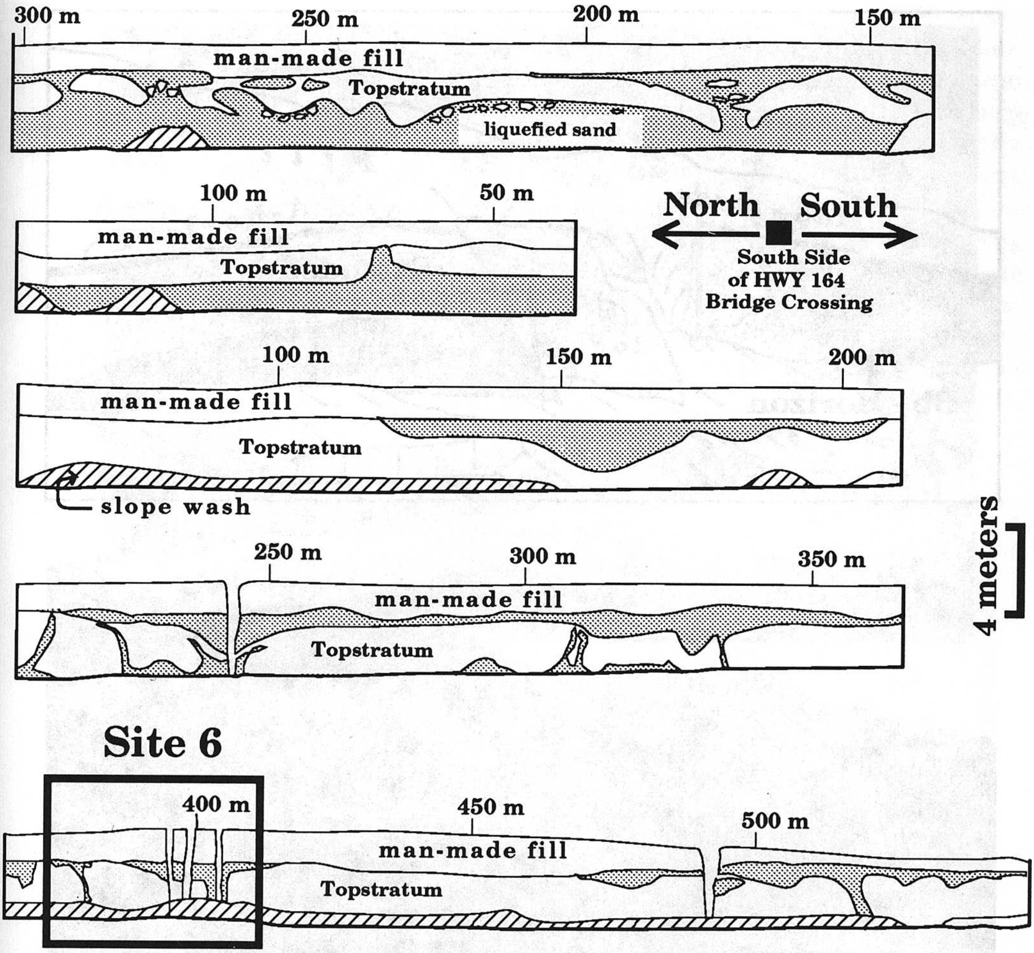



FIG. 16. Sketch (with extreme vertical exaggeration) of the east side of a section of Buffalo Creek ditch adjacent to the crossing of Hwy. 164 (Figs. 6 and 15). Human-made fill resulting from ditch excavation comprises uppermost unit. The topstratum is a clay- or silt-rich, nonliquefiable deposit. The shaded unit is fine to coarse sand that shows evidence of liquefaction. Evidence of original fluvial bedding is uncommon beneath the topstratum. Site 6 is shown in more detail in Figure 17. Horizontal distances are measured in meters to the south and north sides of the Hwy. 164 bridge crossing, respectively.

164 bridge, is labeled as site 6 in both Figures 15 and 16 and shares strong similarities with site 2 in ditch 12 (Fig. 17). The topstratum is defined by a well-developed soil profile on a sandy parent material, representing a relatively long-period of stability; in contrast, the vented sand has only a ~1-cm-thick A horizon and virtually no B horizon development. Like sites 2 and 4, the weak soil on the extruded sand is consistent with the sand blow forming in 1811 and 1812, and no relations suggesting older episodes of liquefaction were observed.

Further limits on the period of time represented by exposures along the ditches were placed by the discovery of the articulated skeletal remains of a Paleolama at site 8 (Fig. 15). The remains were exposed in the western bank of Buffalo Creek ditch, 150 m south of the County Road N bridge crossing, and about 5 km south of Senath, Missouri (Graham, 1990). The Paleolama skeleton

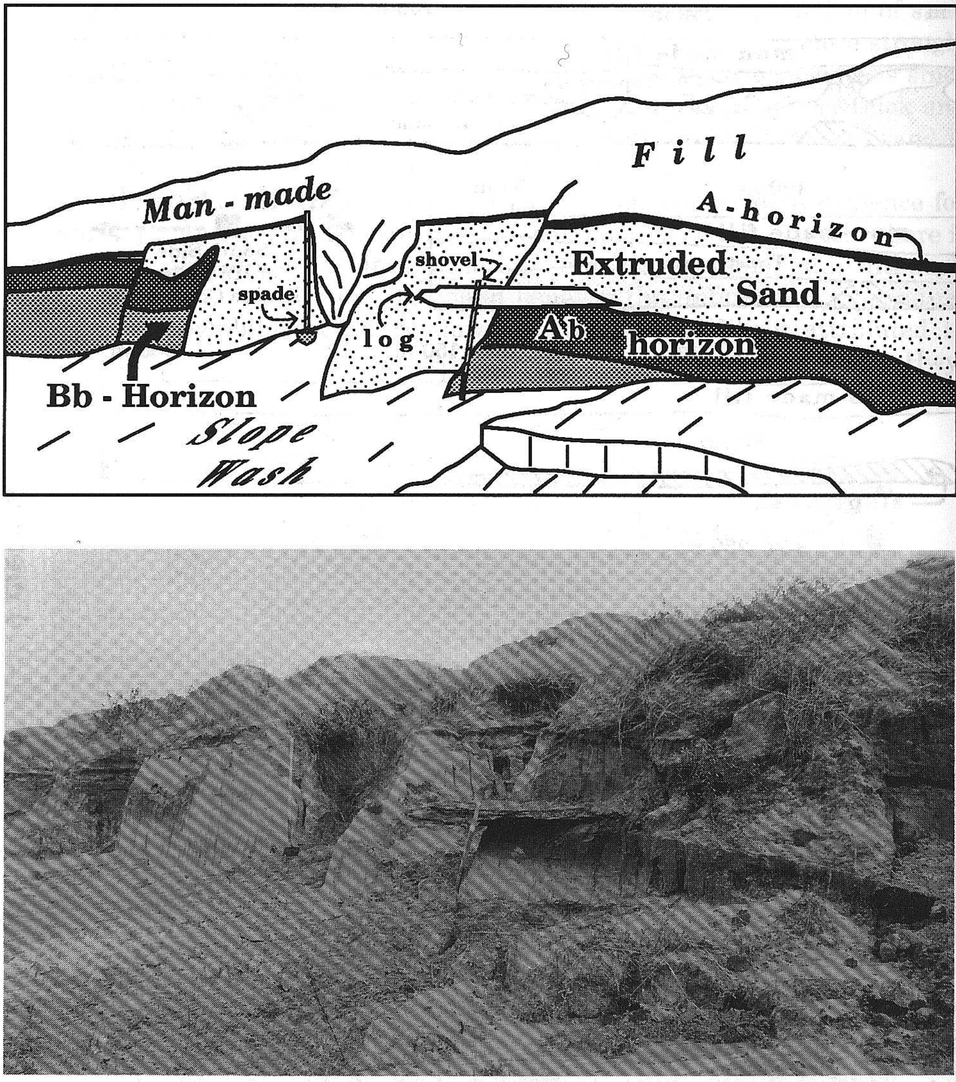



FIG. 17. Photo and sketch of major breach in topstratum at site 6 along Buffalo Creek ditch. The buried log rests on the A horizon developed on the surface at the time of the 1811 and 1812 earthquakes. The Ab soil horizon is a dark gray clay loam that averages 20 to 25 cm thick and grades downwards into the Bb horizon, which is a light yellowish brown loam that extends below the exposure. The A horizon on the extruded sand is a 1- to several-cm-thick, dark brown clay loam. The extruded sands are light gray to brownish yellow in color, medium to coarse grained, abundant in small clay clasts, generally devoid of silt or clay fraction, and locally strongly oxidized.

was found near the base of the section in a massive, fine to medium sand (Fig. 18). The sand is overlain by a topstratum of sandy clay loam, silt loam, and clay. The sand both encompasses and occurs within a gleyed, dark gray clay. The complex stratigraphic relations between the sand and the gleyed clay are interpreted to be the result of liquefaction. The gleyed clay originally rested directly on the sand that encompassed the Paleolama skeleton, but the basal sand liquefied and flowed during the 1811 and 1812 New Madrid earthquakes, breaching the overlying gleyed clay and forming a sill between the gleyed clay

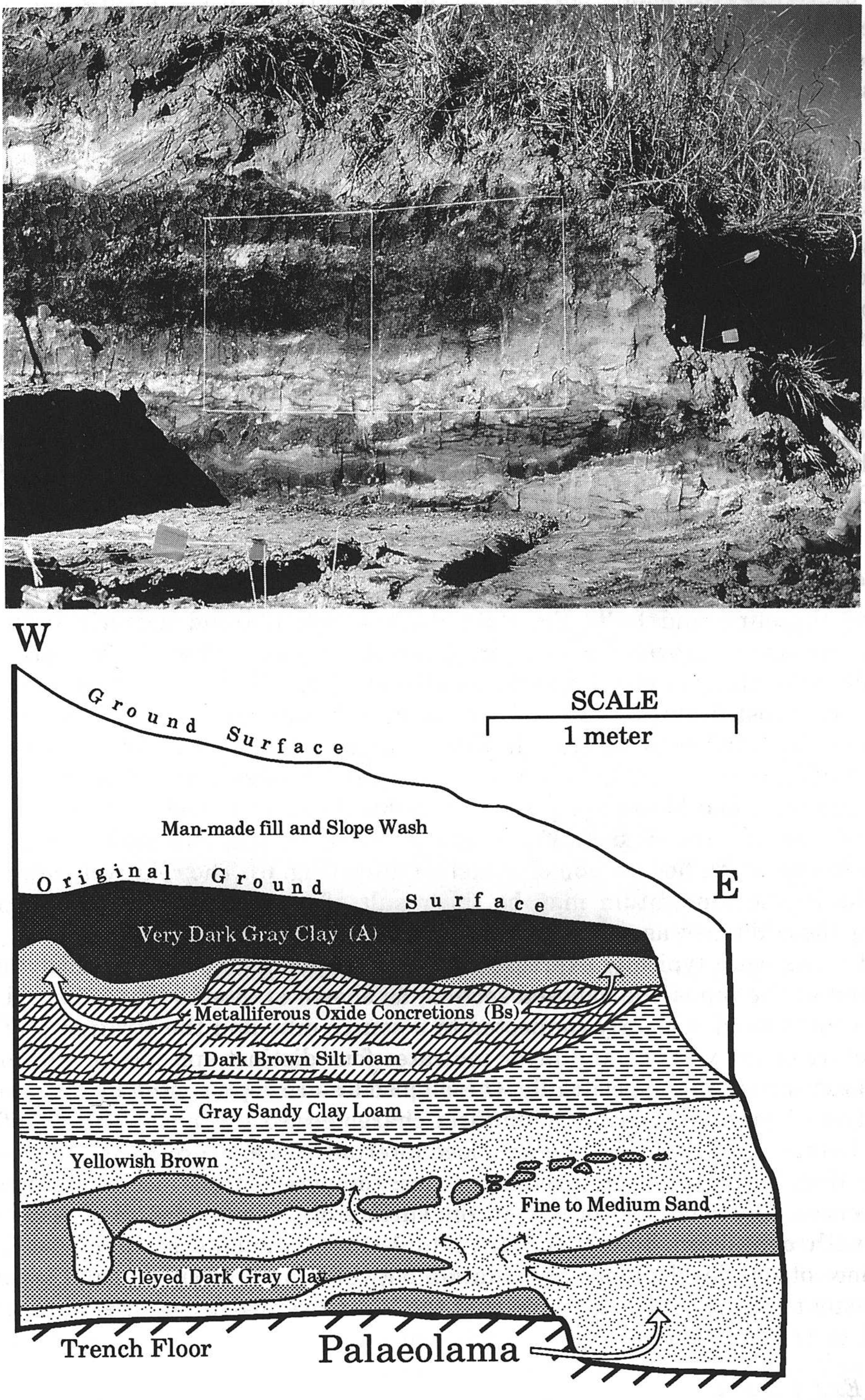



FIG. 18. Photo and sketch of site 8 (see Fig. 15 for location). A 1-m string grid provides scale on photo. Small survey flags at base of excavation mark the location of skeletal remains of a Paleolama. A radiocarbon date places the age of the skeletal remains at about 10,380 ± 380 yr B.P. The skeletal remains were located in the fine to medium sand beneath a gleyed dark gray clay. No vertical exaggeration.

and overlying gray sandy clay loam. This interpretation is supported by presence of sand dikes, which both originate from this same sand and clearly breach the entire topstratum at nearby sites along the ditch. Thus, the Paleolama was preserved within the sand directly below gleyed dark gray clay.

A radiocarbon age for the Paleolama, determined from accelerator mass spectrometry (AMS) techniques applied to Amino acids extracted from the preserved bones, is 10,890 ± 30 yr B.P. (Graham, 1990; Russell Graham, Research and Collection Center, Illinois State Museum, Springfield IL, 62703, personal comm.). From our observations and prior studies by others (e.g., Saucier, 1974, Guccione *et al.*, 1990), the sand underlying the topstratum and encompassing the Paleolama skeleton are interpreted as braided stream deposits and the sequence of clay and loam are deposits that accumulated in low-energy backswamp and slackwater settings since deposition of braided stream deposits ceased approximately 11,000 yr B.P. The stratigraphy and radiocarbon dates at this site and site 3 (Fig. 12) are virtually identical, lending further support to the idea that the ditch exposures in this region provide a 5000 to 10,000 yr geologic record in the vicinity of Buffalo Creek ditch and ditch 12.

### *Stateline and Belle Fountain Ditches*

The Stateline and Belle Fountain ditches, which trend easterly from Big Lake, Arkansas, provided about 5 m of vertical exposure (Fig. 6). In contrast to the deposits along ditch 12 and Buffalo Creek ditch, the base of the gray blocky clay-rich topstratum was not observed at any point along the base of the ditches. The thicker topstratum in these ditches is consistent with the interpretation of Guccione (1987) of the presence of thick backswamp deposits.

Numerous sand blows are present in fields adjacent to the ditches (Fig. 19), but our search revealed only one major break in the topstratum, near the eastern end of studied section of Stateline ditch (Fig. 6). The relatively few large breaks in the topstratum may be the result of greater topstratum thickness along these ditches as compared to ditch 12 and the Buffalo Creek ditch. The sand blows were typically expressed in cross section as 0.5- to 1-m-thick layers of sand at the top of the exposed section, as shown at site 10 (Figs. 19 and 20). The vented sand is clearly connected to a source dike and the stratigraphy and structure of the vented sand layer indicates four distinct episodes of venting or sand extrusion. More specifically, these episodes are represented by four nearly flat-lying layers of sand, with contacts characterized by concentrations of silt and lignite and, along the upper most internal contact, preserved worm-hole casts (Fig. 21). The lower three layers are composed of distinct fining-upward sequences. The weak soil profile on the surface of the extruded sand is consistent with deposition during the 1811 to 1812 earthquake sequence, and the absence of soil development or oxidation between the underlying sand layers is consistent with the interpretation that the layers were also emplaced during the 1811 to 1812 sequence.

### *The Exit 4 Ditch*

The character of liquefaction within the Holocene meander belt of the Mississippi is exhibited in the Exit 4 ditch (Fig. 6). The local farm-field drainage ditch strikes southeast from its intersection with Interstate 55 about 2 km south of Exit 4 in Missouri. Because the ditch is located within the Holocene Mississippi

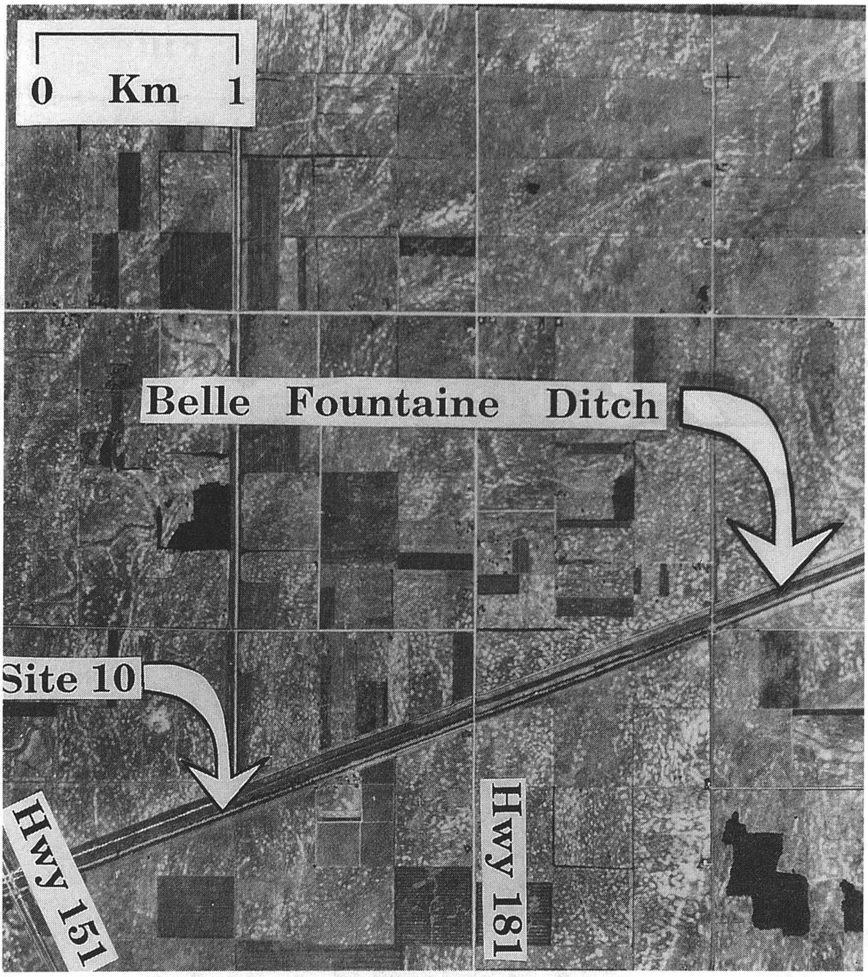



FIG. 19. Portion of the Denton, Missouri, orthophotoquad showing site 10 along Belle Fountain ditch surrounded by numerous sand blows (light-colored patches) in the adjacent fields. North is up on photo.

River meander belt, the sediments are likely younger than those composing the braided stream terrace surface cut by Buffalo Creek ditch and ditch 12. The large-scale aerial photo in Figure 22 shows numerous arcuate lineaments in the vicinity of site 11. The arcuate trends mark sand-filled fissures. The fissures form arcuate lineaments because they follow the course of abandoned meander belt point bar deposits. The source beds of the vented sand are likely shallowest and thickest within the abandoned point-bar deposits and, hence, most likely to fail here during liquefaction.

Site 11 marks the intersection of one lineament with the Exit 4 ditch and serves to illustrate the character of these liquefaction features (Fig. 23). The site shows evidence of two episodes of liquefaction. The lack of significant pedogenesis on the surface sand suggests a recent age for the deposit. Similarly, the contact between units S1 and S2 is marked only by a concentration of silt and clay, suggesting the units were emplaced within a short time of each other, probably in 1811 and 1812.

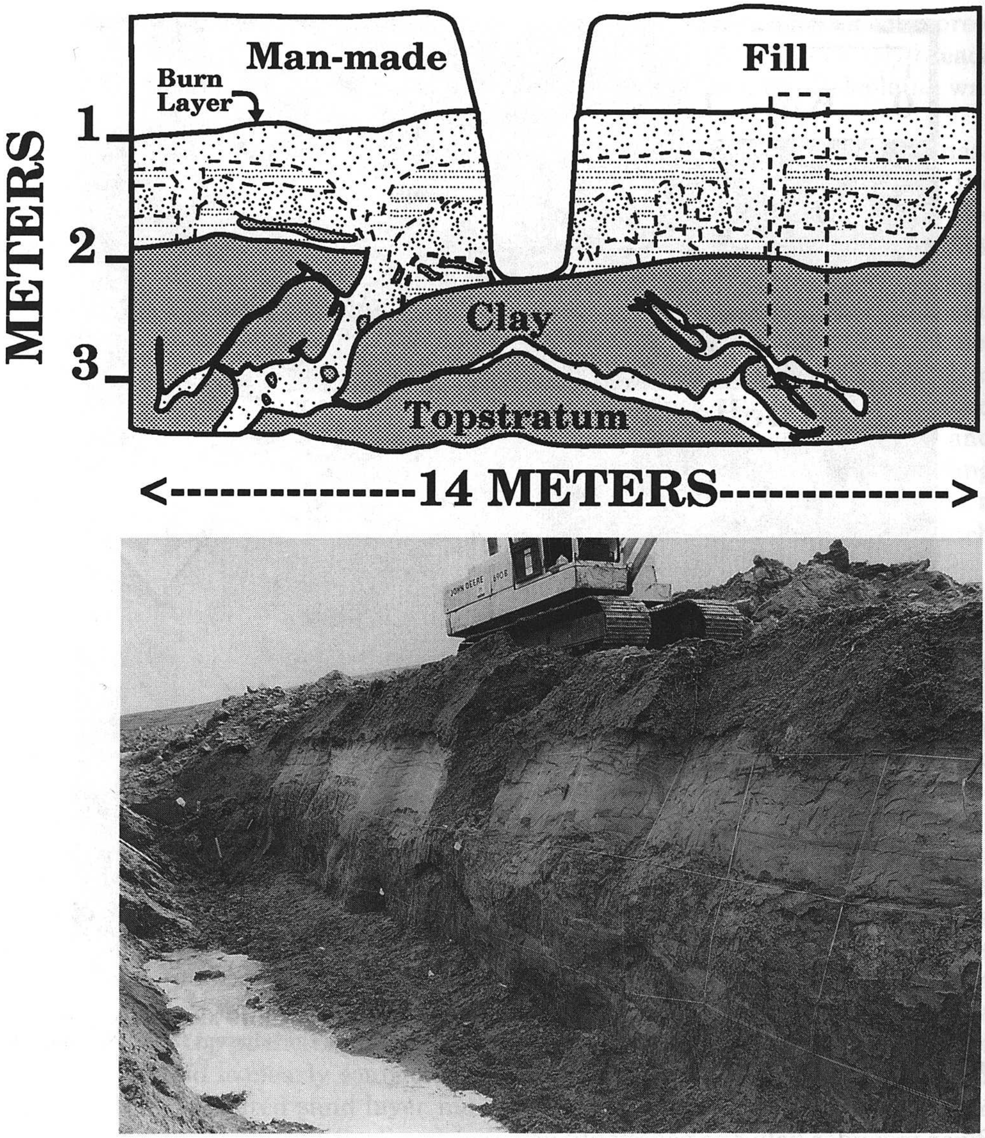



FIG. 20. Photo and sketch of exposure at site 10. Sand vented onto the surface through dikes in the clay topstratum to form a layer about 1 m thick. Internal contacts (dashed) within the ejected, very fine to fine sands (dotted and stippled) indicate four distinct episodes of venting, all of which are most likely due to the 1811 and 1812 earthquake sequence. The vertically oriented dashed box is the location of the larger-scale photo in Figure 21, which shows details of the internal stratigraphy of vented sand.

## DISCUSSION

Our observations of liquefaction features centered largely on late Wisconsinan braided stream deposits in the vicinity of Big Lake, Arkansas (Fig. 6). Saucier (1977) estimated that the surfaces formed by these deposits were abandoned about 9500 yr ago. Radiocarbon dates at sites 3 (Fig. 12) and 8 (Fig. 18), each on samples collected adjacent to the contact between the braided-stream outwash sand and the overlying topstratum, which is interpreted to have developed since


FIG. 21. Photo of part of exposure shown in Figure 20 shows four distinct layers of yellowish brown sand lying on clay topstratum. The individual sand layers are interpreted to result from separate episodes of venting during the 1811 to 1812 earthquake sequence.

deposition of braided stream deposits ceased, range from 10,380 to 11,100 radiocarbon yr B.P., in general agreement with Saucier's estimate. Similarly, backswamp sedimentation in Big Lake, Arkansas, is estimated to have started more than 9900 yr ago, and more than 6500 yr for a site farther east, near Belle Fountain ditch (Guccione, 1987). The radiocarbon age for wood taken from the middle of the topstratum at site 3 (Fig. 12), is about 5000 yr. Hence, the geologic record preserved in the ditches covers approximately the last 5000 to 10,000 years, and we did not observe clear evidence for a widespread paleoliquefaction event during that period of time.

The search for geological evidence bearing on the repeat time of 1811 and 1812 earthquakes is not new. As early as 1971, Saucier (1977) examined the geological effects of the 1811 and 1812 earthquakes and recognized the potential value of geological studies of liquefaction features for predicting the recurrence interval of infrequent major earthquakes in the region. Saucier reported observations of liquefaction features at eight archaeological sites but found no evidence of ground disturbance or liquefaction that could not be attributed to the 1811 and 1812 earthquakes. Moreover, based on archaeological age estimates, he inferred the lack of evidence for liquefaction-inducing events prior to 1811 and 1812 extended back 500 to 1000 yr or more. To our knowledge, Saucier's work was the first attempt to use liquefaction features to unravel the paleoearthquake history of a fault zone.

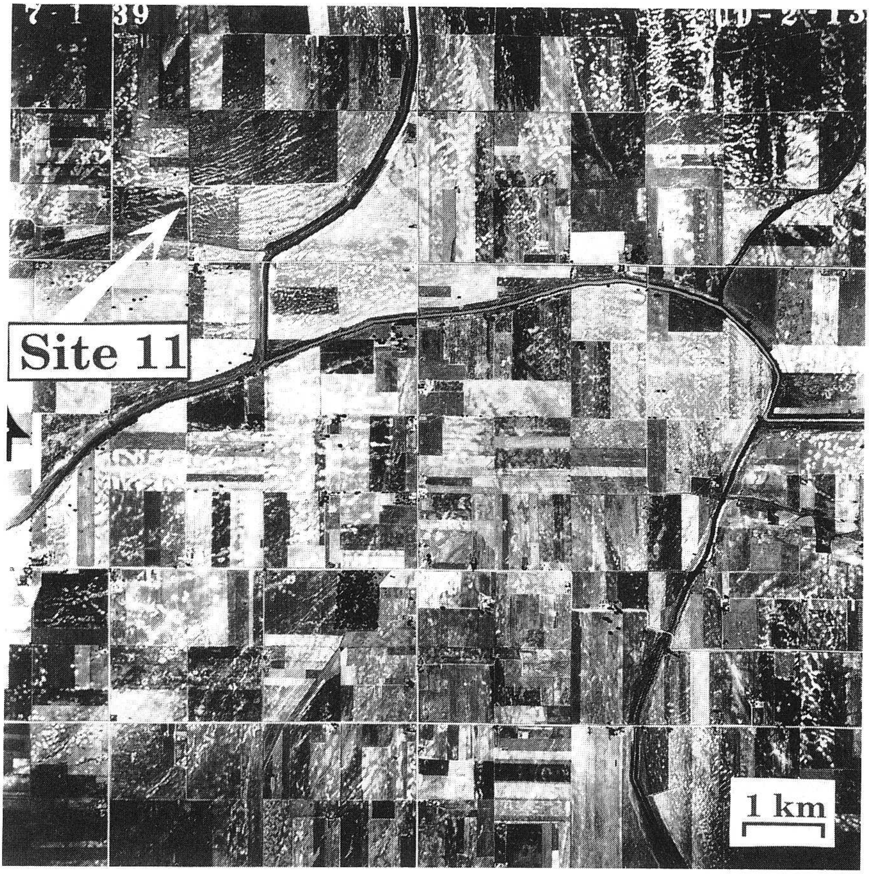



FIG. 22. A 1939 aerial photo showing location (arrow) of site 11 along Exit 4 ditch (prior to construction of Interstate 55). Sharp white lineations mark sands vented along trend of abandoned point bar deposits.

The first reported geologic evidence for paleoearthquakes and, hence, estimate of recurrence intervals for large New Madrid earthquakes is from trenching of the Reelfoot fault (Russ *et al.*, 1978; Russ, 1979). The fault strikes northwesterly from the southwestern end of Reelfoot Lake to the Mississippi River (Fig. 4). It is perhaps the only feature in the region that shows unambiguous evidence of Holocene movement. The oldest deposits in the trench were about 2000 yr old. Structural, stratigraphic, and geomorphic data revealed evidence of two episodes of fault movement prior to 1811 and 1812. Combining the geologic observations with the historical record, Russ (1979) interpreted three earthquakes of sufficient size to produce liquefaction during the last 2000 yr and, on that basis, suggested a recurrence time of 600 yr or less for such events in the region. At first glance, Russ' observations conflict with the 10,000-yr-long absence of liquefaction events prior to 1811 and 1812 implied by our observations. However, it should be noted that Russ (1979) found insufficient evidence to prove that any of the faults or liquefaction features in the trench were produced during the 1811 and 1812 earthquakes. Moreover, earthquakes as small as $m_b \approx 6.2$ can produce liquefaction at distances of 15 to 20

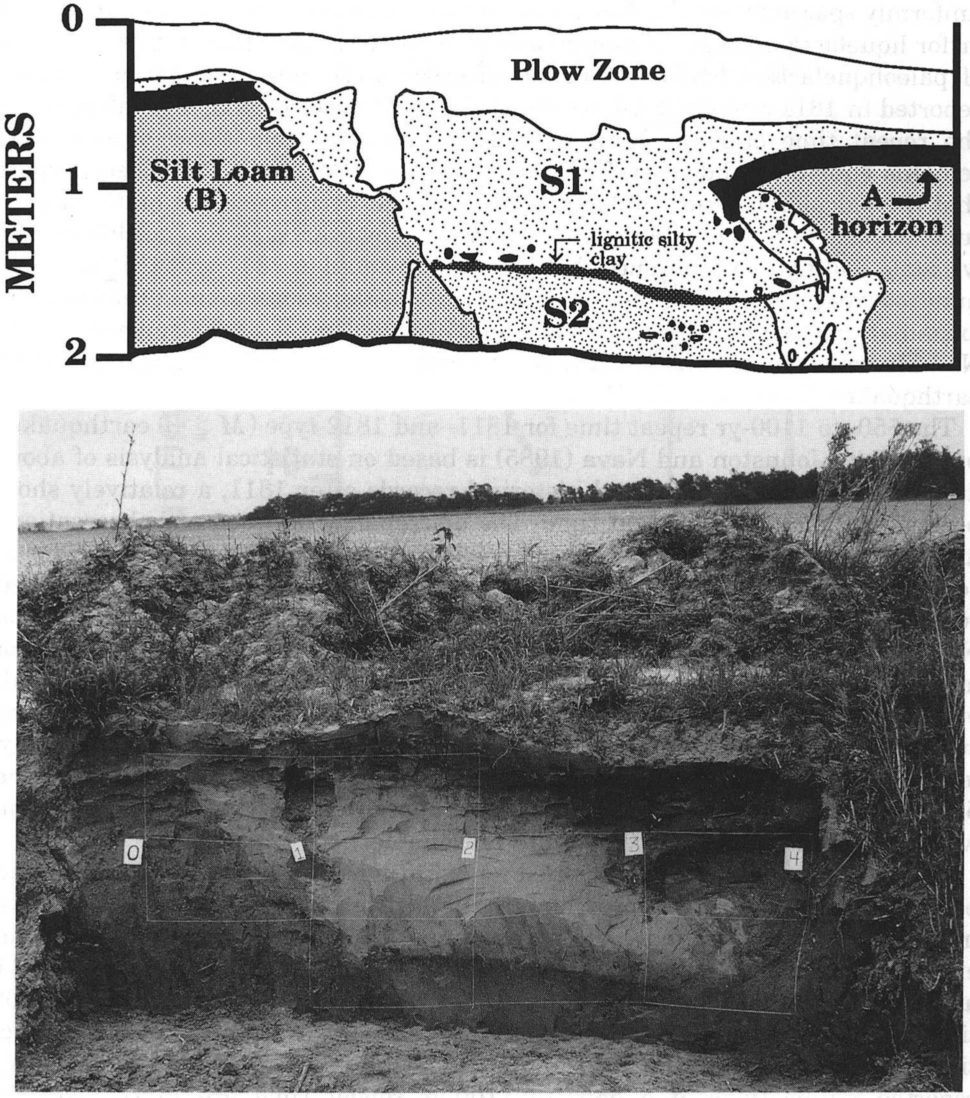



FIG. 23. Photo and sketch (no vertical exaggeration) of site 11 in southeastern Missouri. Sand units S1 and S2 were vented to surface in 1811 and 1812. Aerial photo of this location is shown in Figure 22.

km from the earthquake source (e.g., Youd and Wieczorek, 1982). We suggest that one or more of the paleoearthquakes interpreted by Russ (1979) do not represent a recurrence of 1811- and 1812-type earthquakes but, rather, the occurrence of smaller earthquakes in the northern part of the New Madrid Seismic Zone.

Saucier (1991) more recently reported stratigraphic evidence of two liquefaction events during the past 1300 yr at an archaeological site about 30 km northwest of Reelfoot Lake. Noting that liquefaction was induced by a nearby $m_b \approx 6.2$ earthquake in 1895 and also by the 1811 and 1812 earthquakes (treating the 1811 to 1812 sequence as a single earthquake), and assuming uniformly spaced intervals, Saucier estimated an average recurrence rate of 468 yr for liquefaction-inducing events near New Madrid. Like Russ (1979), the size of paleoliquefaction features Saucier observed were small compared to those reported in 1811 and 1812. Hence, as stated by Saucier (1991), any inference of the repeat time of great New Madrid earthquakes from these observations remains equivocal and, therefore, based on our field studies, we also suspect that the paleoliquefaction probably represents the recurrence of smaller magnitude events in the New Madrid Seismic Zone. However, it is also not likely that we could distinguish differences between sand vented in 1811 and 1812 or a few hundred years earlier on the basis of soil considerations alone. Additionally, examination of similar 500- to 1500-yr-old archaeological sites elsewhere in the New Madrid Seismic Zone has revealed no conclusive evidence of severe pre-1811 earthquakes (Saucier, 1977, 1989).

The 550- to 1100-yr repeat time for 1811- and 1812-type ($M \geqq 8$) earthquakes put forth by Johnston and Nava (1985) is based on statistical analysis of about 10 yr of instrumental data and historical records after 1811, a relatively short portion of the expected repeat time. The discrepancy between our observations and the repeat time estimates based on seismicity may then reflect that rates of seismicity are not stationary through time or, more pointedly, that the historical record is simply too short to accurately portray the long-term behavior of the New Madrid Seismic Zone (Fig. 24). Furthermore, estimates of repeat time of large earthquakes based on the linear extrapolation of the recurrence of small events may be inaccurate, because it is now known that earthquake frequency curves for faults are commonly not linear across the entire magnitude range (e.g., Youngs and Coppersmith, 1985). Thus, to cast doubt on the accuracy of the 550- to 1100-yr repeat time in light of the apparent absence of paleoliquefaction we observed in our study seems quite reasonable.

To summarize, our search revealed no definitive evidence for any widespread paleoliquefaction during approximately the last 5000 to 10,000 yr. Speculative interpretation that buried sand layers at sites 2 and 3 were vented in an extensive paleoliquefaction episode results in an estimated return time of 1811 and 1812 earthquakes equal to about 5000 yr or more. A yet even shorter repeat time might be argued if geologic or pedogenic processes have removed liquefaction features predating the 1811 and 1812 earthquakes. However, if previously reported implications of a 550- to 1100-yr repeat time are indeed correct, between about 5 and 20 1811- and 1812-type events should be recorded in the 5000 to 10,000 years of geologic record exposed in the ditches. When further noting the widespread occurrence and large sizes of liquefaction features induced by the 1811 to 1812 sequence, it seems that evidence of paleoliquefaction should be clear and abundant. Hence, although negative evidence must be considered with extraordinary caution, the lack of evidence indicating any widespread paleoliquefaction event suggests to us a repeat time of 5000 to 10,000 yr or more for events of a size equal to the great 1811 and 1812 earthquakes (Fig. 24).

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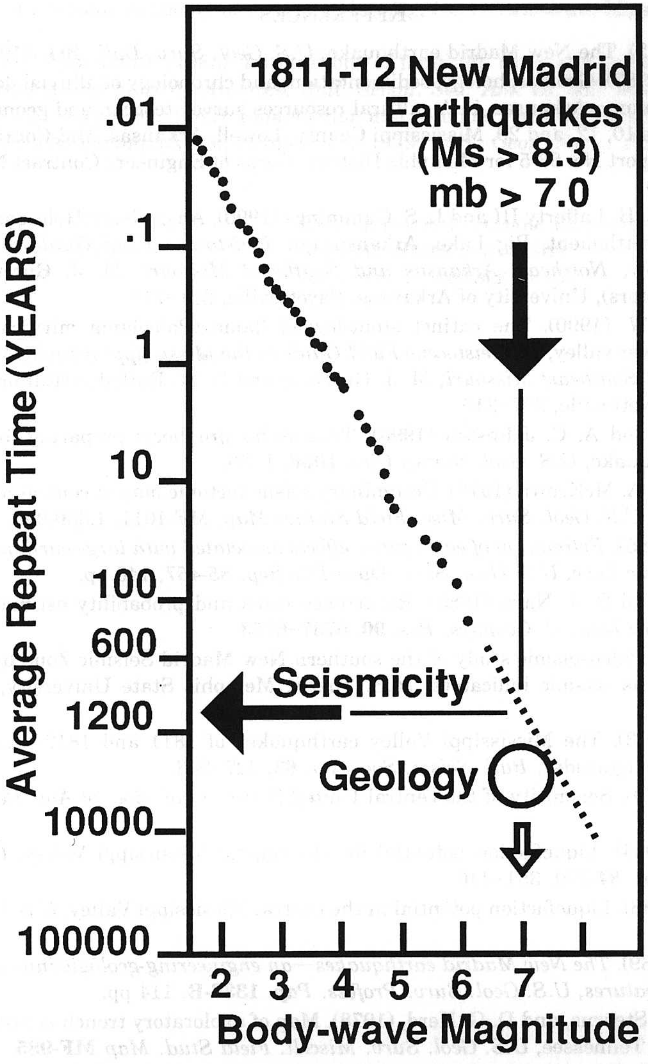


FIG. 24. Schematic diagram illustrating apparent discrepancy between estimates of repeat time for great New Madrid earthquakes based on statistical analysis of historical and instrumental records of seismicity and our search for evidence of paleoliquefaction in the meizoseismal zone, respectively. Solid dots show average repeat time of earthquakes of size greater than or equal to a given body-wave magnitude for the New Madrid Seismic Zone for the period 1816 to 1983 (adapted from Johnston and Nava, 1985). The largest earthquake reported during the period since 1811 to 1812 is $m_b = 6.2$. Extrapolation (dashed line) of magnitude-frequency statistics covering the period since 1811 to 12 (solid arrows) implies a 550- to 1100-yr repeat time for 1811- and 1812-type earthquakes ($m_b > 7$, $M_s > 8.0$). The lack of clear evidence for widespread paleoliquefaction is our basis to suggest a significantly longer repeat time for such events in the region (open circle and arrow), on the order of 5000 to 10,000 yr or more.

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