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THE RECORD OF SEISMICALLY INDUCED LIQUEFACTION ON LATE QUATERNARY TERRACES IN NORTHWESTERN TENNESSEE

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INTRODUCTION

Between December 1811 and February 1812, the four largest historical earthquakes ($m_b \geqq 7.0$) in eastern North America occurred in the New Madrid (Missouri) seismic zone (NMSZ). Although this area has been the focus of considerable seismological and geological research, estimates of the repeat time of large-magnitude seismic events remain poorly constrained. The available estimates are based primarily on earthquake-frequency statistics and limited paleoseismology studies.

Johnston and Nava (1985) analyzed about 180 yr of historical seismicity data and 10 yr of instrumental data and concluded that the repeat time for large-magnitude events ($m_b \geqq 7.0$) is between 550 and 1100 yr. This estimate assumes that the data set is representative of the seismicity in the NMSZ and that the slope of the line relating earthquake frequency to magnitude (b value) is constant from small- to large-magnitude earthquakes (Johnston and Nava, 1985). However, Pacheco *et al.* (1992) reported that b values may not be constant in earthquake frequency-magnitude distributions and, thus, the estimated recurrence interval of Johnston and Nava (1985) must be considered tentative.

Two geological studies suggest that the recurrence interval of large-magnitude earthquakes in the NMSZ is on the order of 450 to 600 yr. Two exploratory trenches across the Reelfoot scarp in northwestern Tennessee (Fig. 1) revealed the only unequivocal example of Holocene surface faulting in the upper Mississippi embayment (Russ *et al.*, 1978; Russ, 1979; Kelson *et al.*, 1993). Stratigraphic relations across the northern part of the scarp indicate at least two episodes of faulting had occurred after about 2250 yr B.P. and before the 1811 to 1812 seismic events (Russ, 1979). Based on these two prehistoric earthquakes, the dating error limits, and the 1811 to 1812 events, Russ (1979) estimated an average recurrence interval of 600 yr or less for large-magnitude earthquakes in the NMSZ. This estimated average recurrence interval is corroborated by a radiocarbon age estimate of A.D. 1310 to 1540 for fault-scarp colluvium along the central Reelfoot scarp (Kelson *et al.*, 1993). However, inasmuch as Russ (1979) found no evidence that offset occurred on the Reelfoot scarp during the 1811 to 1812 earthquakes, the relation between surface ruptures on the Reelfoot scarp and large paleo-earthquakes in the NMSZ is not clear.

The widespread development of liquefaction features during the 1811 to 1812 earthquake series (Obermeier, 1989; Obermeier *et al.*, 1990), and the probable development of similar features during previous large-magnitude seismic events ($m_b \geqq 6.2$, Nuttli, 1982) has been the basis for several efforts to identify paleoliquefaction features. Saucier (1991) estimated an average recurrence

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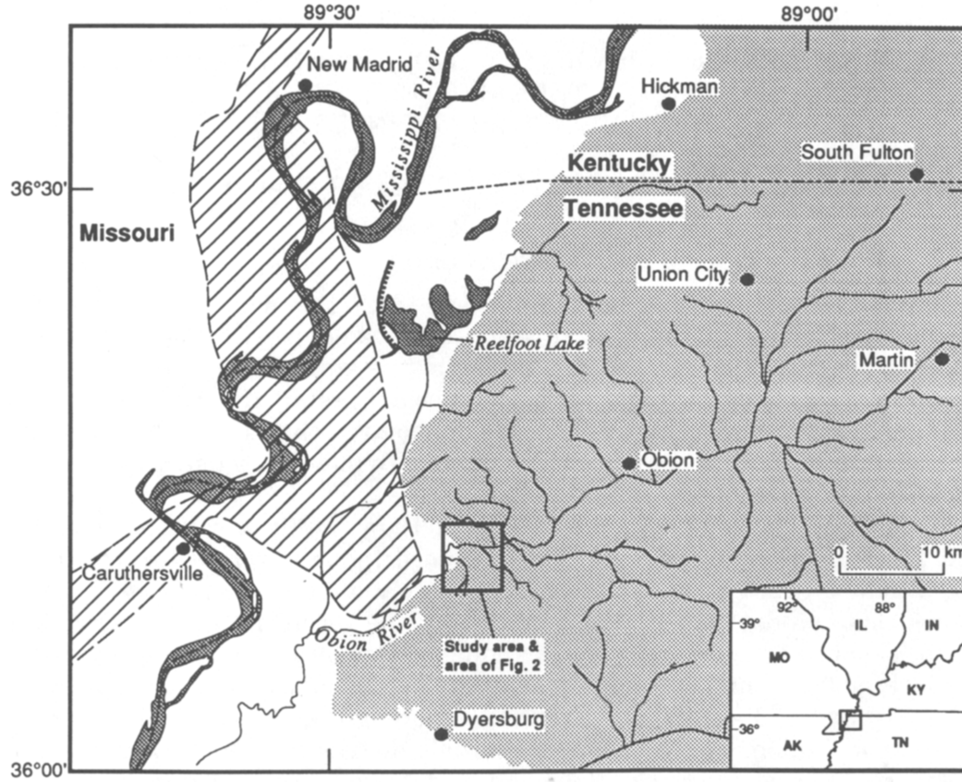

FIG. 1. Generalized map of study area in northwestern Tennessee. Lightly shaded area is covered by late Quaternary loess; area with diagonal lines is approximate area of modern seismicity; hachured line west of Reelfoot Lake is approximate location of Reelfoot scarp (Russ, 1979).

interval of about 470 yr based on historic earthquake-induced liquefaction and the age of two prehistoric sand blows about 30 km northeast of New Madrid, Missouri (Fig. 1).

In contrast to the limited seismological and geological data that suggest recurrence intervals of 450 to 600 yr, other geological investigations have found no evidence of prehistoric large-magnitude earthquakes in late Pleistocene deposits in the NMSZ. Haller and Crone (1986) found evidence of only one episode of sand blow development in an exploratory trench in Pleistocene alluvium in northeastern Arkansas, and they concluded that this liquefaction was probably associated with the 1811 to 1812 earthquakes. Saucier (1989) reported evidence of only recent, probable 1811 to 1812, liquefaction since approximately A.D. 1000 in an exploratory trench in northeastern Arkansas. Similarly, Schweig and Marple (1991) and Schweig *et al.* (1993) found evidence of only probable 1811 to 1812 liquefaction in five exploratory trenches on late Wisconsin braided-stream deposits in southeastern Missouri. Leffler and Wesnousky (1991) and Wesnousky and Leffler (1993) examined tens of kilometers of recently re-excavated drainage ditches on late Wisconsin braided-stream deposits in northeastern Arkansas and found no unequivocal evidence for prehistoric liquefaction since deposition of the alluvium at least 10,000 yr B.P. Kelson *et al.* (1993) also concluded that all of the liquefaction-related features in a trench across the central part of the Reelfoot scarp are likely related to the 1811 to 1812 earthquake sequence, although they noted equivocal evidence for a liquefaction event prior to A.D. 900.

The apparent absence of paleoliquefaction features in late Wisconsin fluvial deposits in the area where liquefaction was pervasive in 1811 to 1812 suggests that the repeat time of large seismic events in the NMSZ might be 10,000 yr or more (Saucier, 1991; Wesnousky and Leffler, 1993). To further test this hypothesis, this study was undertaken to examine the record of liquefaction in late Wisconsin fluvial deposits along the Obion River in northwestern Tennessee. These deposits are more than 20 ka and are in a geomorphic setting that is favorable for liquefaction. Thus, these deposits have the potential for recording liquefaction events as old as latest Pleistocene.

Study Area and Methods

The study area is in the Obion River drainage basin near the town of Lane, Tennessee (Figs. 1 and 2), at the eastern edge of the zone of abundant sand blows associated with the 1811 to 1812 New Madrid earthquakes (Obermeier, 1989). Two late Quaternary fluvial terraces and a deeply incised upland complex of loess overlying Tertiary gravels are present in the study area. The distribution of fluvial terraces along the Obion River is discussed by Saucier (1987). He named the lowest terrace the Finley terrace, which is about 5 m above the modern flood plain. The next higher terrace, the Hatchie terrace (Saucier, 1987), is about 10 m above the modern flood plain. Saucier (1987) correlated deposits that underlie the Finley terrace with early Wisconsin braided-stream deposits along the Mississippi River, but inasmuch as there is little numerical age control for the fluvial terraces in northwestern Tennessee this age assignment is considered tenuous.

Three trenches were excavated on the Finley terraces on both sides of the Obion River. These terraces are mapped as having 1 to 15% of their surfaces covered by liquefied sand (Obermeier, 1989). On aerial photographs and in the field, liquefied sand on the surface contrasts markedly with the dark, fine-grained (silt and clay) sediment that underlies the remainder of the terraces. This site was chosen because the terrace morphology is well expressed, numerous sand blows are present on the Finley terraces, and the site is within a few kilometers of the zone of dense modern seismicity (Fig. 1).

To determine the age of the Finley terrace, we used a hydraulically powered drill rig to obtain two cores of the deposits underlying the terrace (OP-3 and OP-21, Fig. 2). Core OP-21 was analyzed for particle-size distribution in order to determine whether there is a deposit of loess mantling the fluvial deposits. To select specific trenching localities, an auger was used to determine the variability of sand thickness and to locate the center of suspected sand blows. Sand isopach maps were made at scales of 1:100 to 1:550. Finally, three backhoe trenches were excavated through the center of suspected sand blows, and the trench walls were mapped at scales of 1:14 to 1:20.

Results

Core Stratigraphy

Both of the cores were 5- to 6-m-long and contain an upper loess unit and a lower fluvial and/or lacustrine unit. The basal 2.8 m of core OP-21 contains very thin ($\leq$ 1 mm) laminations of fines (silt and clay) interlayered with clean

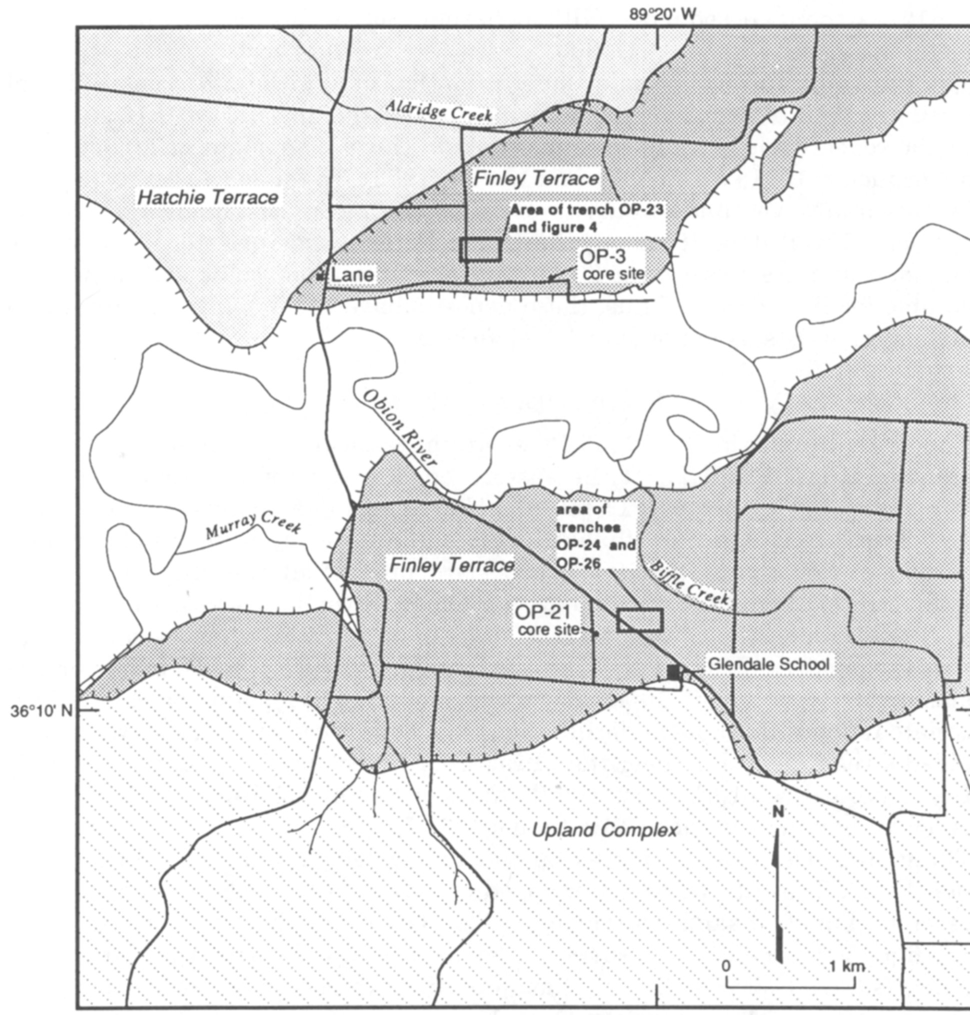

FIG. 2. Schematic map showing general geomorphology of the lower part of the Obion River near Lane, Tennessee and location of trenching and coring localities. Hachures represent scarps at edge of fluvial terraces. Terrace names from Saucier (1987); location of terrace scarps from Rodbell (unpublished mapping).

sand and silty sand (Fig. 3; Rodbell and Bradley, 1993). In contrast, the overlying 2.8 m of sediment is massive and contains less sand (Fig. 3). The ground-water table was about 4 m below the surface.

Core OP-3 has a similar stratigraphy, except that fine to coarse, light grey to grayish brown (10YR 5-7/2-3, Munsell Color Chart) quartzose sand is present below a depth of about 6 m. The sediment above about 2.8 m is massive, whereas the sediment below this level contains very thin laminations of fines (silt and clay) and sand. The ground-water table was about 5 m below the surface.

The upper 2.8 m of sediment in both cores is interpreted as loess because it lacks laminations and is texturally very similar to the ubiquitous loess that mantles the uplands in western Tennessee (Buntley *et al.*, 1977; D. Rodbell,

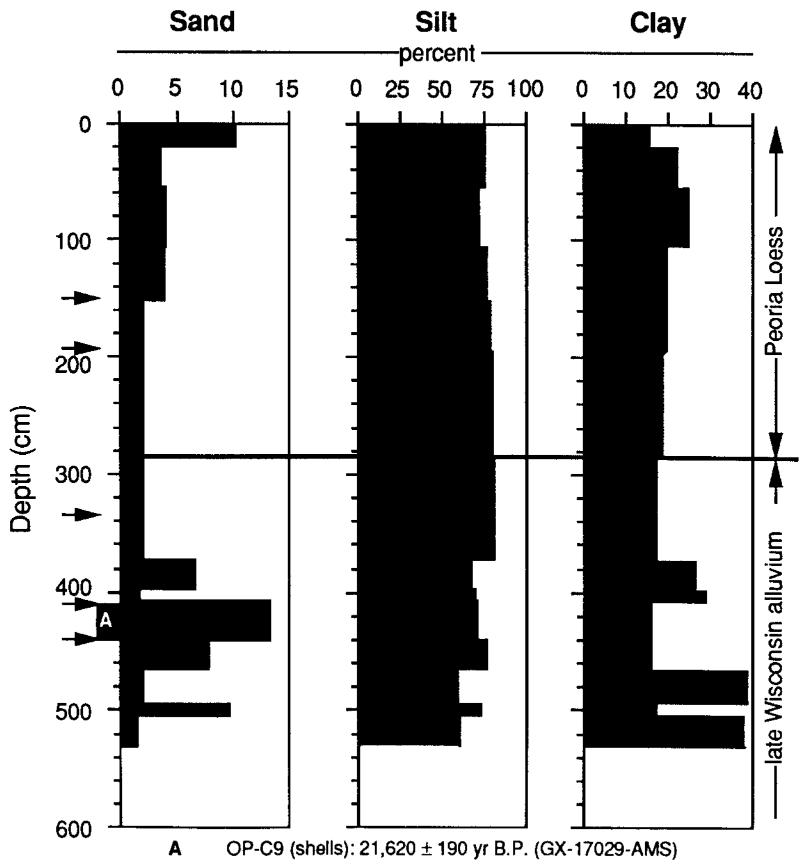

FIG. 3. Particle-size distribution and stratigraphic position of radiocarbon-dated shells for core OP-21; see Figure 2 for location. Peoria Loess is distinguished from alluvium because it is massive and generally contains less sand, whereas alluvium contains very thin ($\leq$ 1 mm) laminations of silt and clay interlayered with sand. Arrows in depth scale are core section boundaries and black rectangle is the radiocarbon sampling interval. Shells from 4.07 to 4.40 m yielded a radiocarbon age of 21,620 $\pm$ 190 yr B.P. (GX-17029-AMS).

unpublished data). Based on its stratigraphic position and the degree of development of the surface soil (Rodbell and Bradley, 1993), this loess is probably correlative with the 10 to 20 ka Peoria Loess deposited elsewhere in the Mississippi Valley (Pye and Johnson, 1988; Forman *et al.*, 1992). This interpretation is supported by a 21.6-ka radiocarbon date from the underlying sediments.

Sediment below about 2.8 m in both cores is interpreted as alluvium. However, based on the presence of laminations of fines (silt and clay) and sand, this sediment could be partly lacustrine. Saucier (1987) cited the low to nil gradient of the Finley terrace in this area to suggest that it is underlain, in part, by lacustrine sediments. The absence of a buried soil between the loess and the underlying sediment suggests that loess deposition began during or soon after fluvial and/or lacustrine deposition. Gastropods shells from 4.07 to 4.40 m yielded an AMS radiocarbon age of of 21,620 $\pm$ 190 yr B.P. (GX-17029-AMS).

The 21.6-$\pm$ 0.2-ka radiocarbon age from the fluvial and/or lacustrine sediments indicates that the Finley terrace is late Wisconsin rather than early

Wisconsin as suggested by Saucier (1987). This date indicates that clean sand has been within about 6 m of the terrace surface for the past 20,000 yr. The apparent presence of Peoria Loess on the terrace is convincing evidence that the terrace surface has not been the site of significant fluvial deposition for at least the past 10,000 yr. The presence of clean sand near or below the ground-water table indicates that these sediments may have been in a geomorphic setting favorable for liquefaction (Obermeier, 1988) for at least the past 10,000 to 20,000 yr.

Trench Locations and Stratigraphy

The three exploratory trenches exposed the stratigraphy of numerous sand bodies and sand dikes in loess and fine-grained alluvium. We interpret the sand bodies to be sand blows (Obermeier *et al.*, 1990) because they are laterally discontinuous, contain abundant rip-up clasts of loess and fine-grained alluvium, and bury a paleo-ground surface. Trench OP-23 (Fig. 4) was oriented NW-SE in the eastern part of a broad area of sand 1.25 km ENE of Lane, Tennessee on the north side of the Obion River (Fig. 4). In the central part of the sand blow, the sand at the surface is more than 1.2-m thick, compared to 20 to 80 cm of sand at the surface elsewhere in the area (Fig. 4).

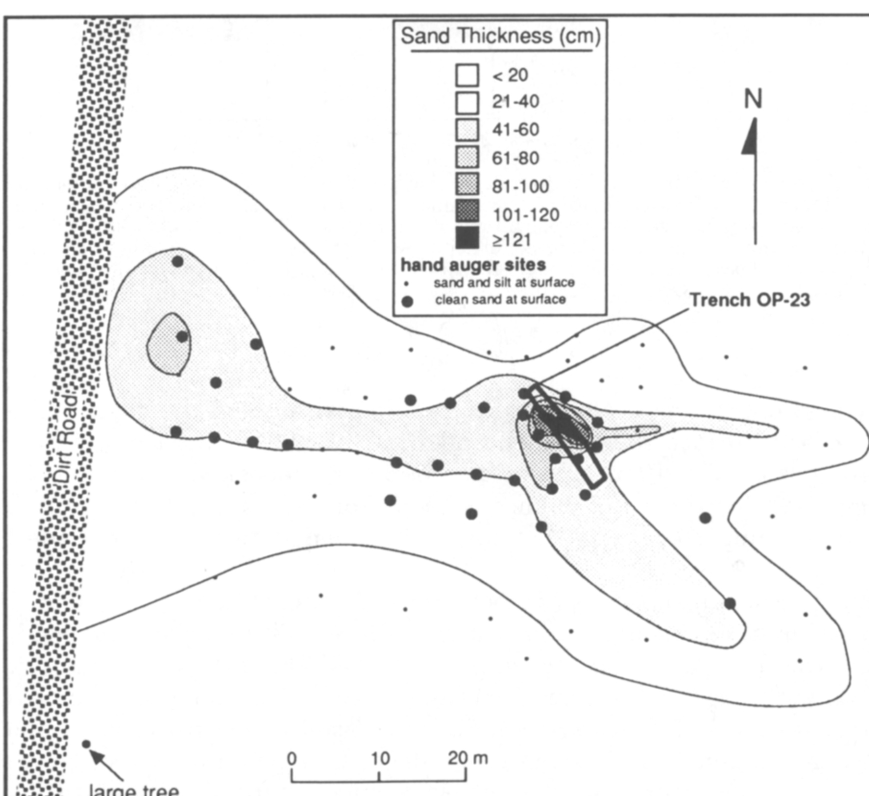

FIG. 4. Isopach map of sand at surface near the OP-23 trench site; see Figure 2 for location. In the central part of the sand blow, sand at the surface is more than 1.2 m thick, whereas elsewhere in the area sand is 20 to 80 cm thick.

Trenches OP-24 and OP-26 were located south of the Obion River, 3.5 km SE of Lane and 0.5 km northwest of Glendale School (Fig. 2). Both trenches were oriented NW–SE in the central parts of two smaller areas of sand. Maximum sand thicknesses of more than 1.2 m were observed at the OP-24 trench site, and 50 cm at the OP-26 site. The three trenches ranged in length from 15 to 60 m and were up to 2.5-m deep.

In the trenches, we identified five major stratigraphic units that generally are texturally distinct (Fig. 5; Rodbell and Bradley, 1993). Sand-blow deposits are mostly fine to coarse sand and are similar in color, texture, and composition to the sand noted in the base of core OP-3. The other four stratigraphic units consist primarily of silt, clayey silt, or buried organic material. All units are massive except for the sand-blow deposits, which commonly contain clasts of silt and clay.

Trench OP-23 exposed the largest liquefaction feature we found in the study area. A large sand blow and numerous sand dikes are located between 5 and 7 m on the northeast wall (Fig. 5). The central part of the vent is composed of fine to coarse, very pale brown to pale yellow (10YR 7/4 to 2.5Y 8/3, Munsell Color Chart) quartzose sand surrounded by silty sand. The boundary between the sand and silty sand is commonly gradational, over a distance of 5 to 10 cm. The gradational boundary and lack of any evidence of soil development along this

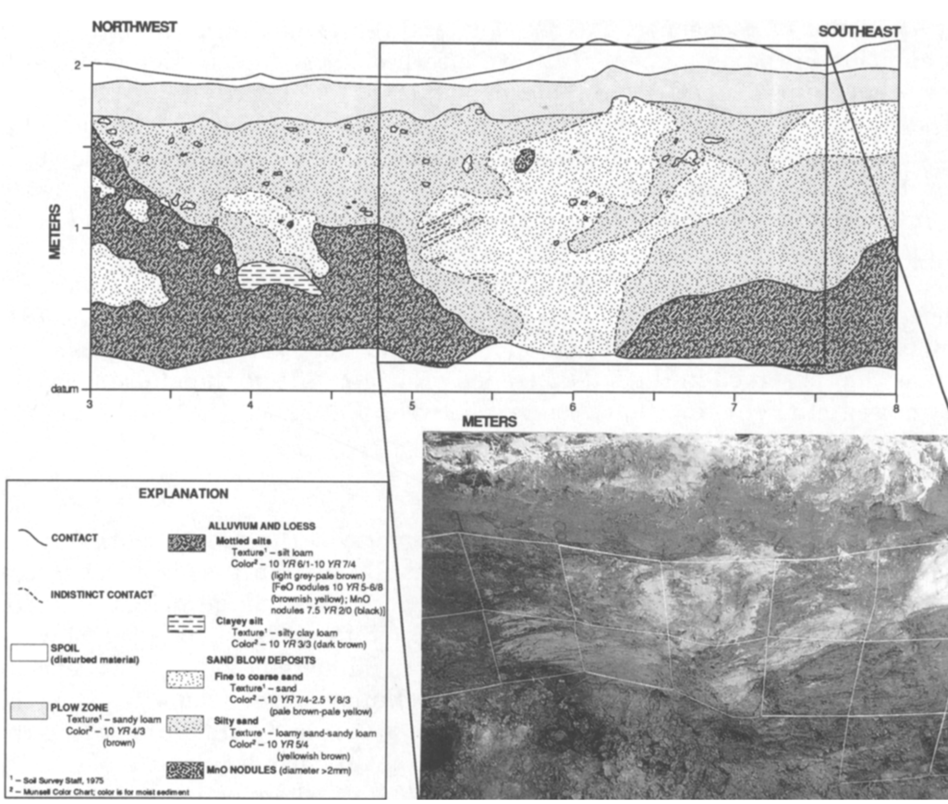

FIG. 5. Map and photograph of part of northeast wall of trench OP-23 showing probable 1811 to 1812 sand blow. Body of fine to coarse sand near 6-m mark is interpreted as core of sand blow. Vertical scale in m above an arbitrary datum; horizontal scale in m from northwest end of the trench. See Figures 2 and 4 for details of trench location.

boundary suggest that these two units were deposited during the same liquefaction event. The silty sand around the margin of the sand blow is probably a mixture of liquefied sand, which was injected from below, and of loess and fine-grained alluvium through which the sand blow penetrated. Thus, we interpret the silty sand as a transitional deposit between the main dike of intruding sand and the surrounding host of loess or fine-grained alluvium. The silty sand may have been deposited during the initial phase of liquefaction, and the fine to coarse sand may represent a later stage of the sand blow eruption. The interlayering of fine to coarse sand and silty sand at the northwest edge of the sand blow (Fig. 5) suggests that multiple episodes of liquefaction occurred at this site. The absence of any soil development other than localized oxidation in both the fine to coarse sand and the silty sand indicates that this sand blow formed recently, probably during the 1811 to 1812 earthquakes.

The southwest wall of the OP-23 trench revealed a similar stratigraphy, although this wall did not intersect the central part of the vent and exposed much less of the sand blow. Numerous pods of mottled silt are present in the sand dikes, and we interpret the pods to be clasts of alluvium that were incorporated into the liquefied sand as the sand intruded the alluvium.

Trenches OP-24 and OP-26 exposed several other relatively young liquefaction features (Rodbell and Bradley, 1993) including several large sand blows interconnected by numerous sand dikes and a partially decomposed stump breached by a small sand dike. The sand on the surface at this locality shows little evidence of pedogenesis, except for localized oxidation and mixture with silt and clay in the plow zone. Thus, we interpret these liquefaction features to have formed during the 1811 to 1812 earthquakes.

The fine to coarse quartzose sand composing the sand blows and sand dikes was probably derived from the sandy units noted in the cores. The similarity in color, texture, and composition between the liquefied sand and the sands below about 6 m in the OP-3 core suggests that the sands composing these sand blows originated at least several meters below the present ground surface.

The lack of soil development on all sand-blow deposits observed in this study indicates that liquefaction occurred recently, probably during the 1811 to 1812 New Madrid earthquake series. Evidence of multiple episodes of liquefaction such as that observed in the OP-23 trench probably reflects the multiple events of strong ground shaking that occurred between December 1811 and February 1812 (Saucier, 1989).

Conclusions

This study revealed that (1) the Finley terrace at the mouth of the Obion River in northwestern Tennessee is composed of alluvium that is at least 21.6 ka and is mantled by the 10 to 20 ka Peoria Loess; (2) sandy alluvium has been in a geomorphic setting favorable for liquefaction for at least the past 21.6 ka; (3) the lack of significant soil development on numerous sand blow deposits exposed in three exploratory trenches on the Finley terrace indicates that the sand blows probably formed from liquefaction of the sandy alluvium during the multiple episodes of strong ground shaking that occurred during the 1811 to 1812 earthquakes; and (4) no evidence of prehistoric liquefaction was found in the trenches.

These results are consistent with results from numerous studies in the NMSZ that suggest that a sequence of large-magnitude earthquakes comparable to the 1811 to 1812 series has not occurred in the past 10,000 yr or longer.

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