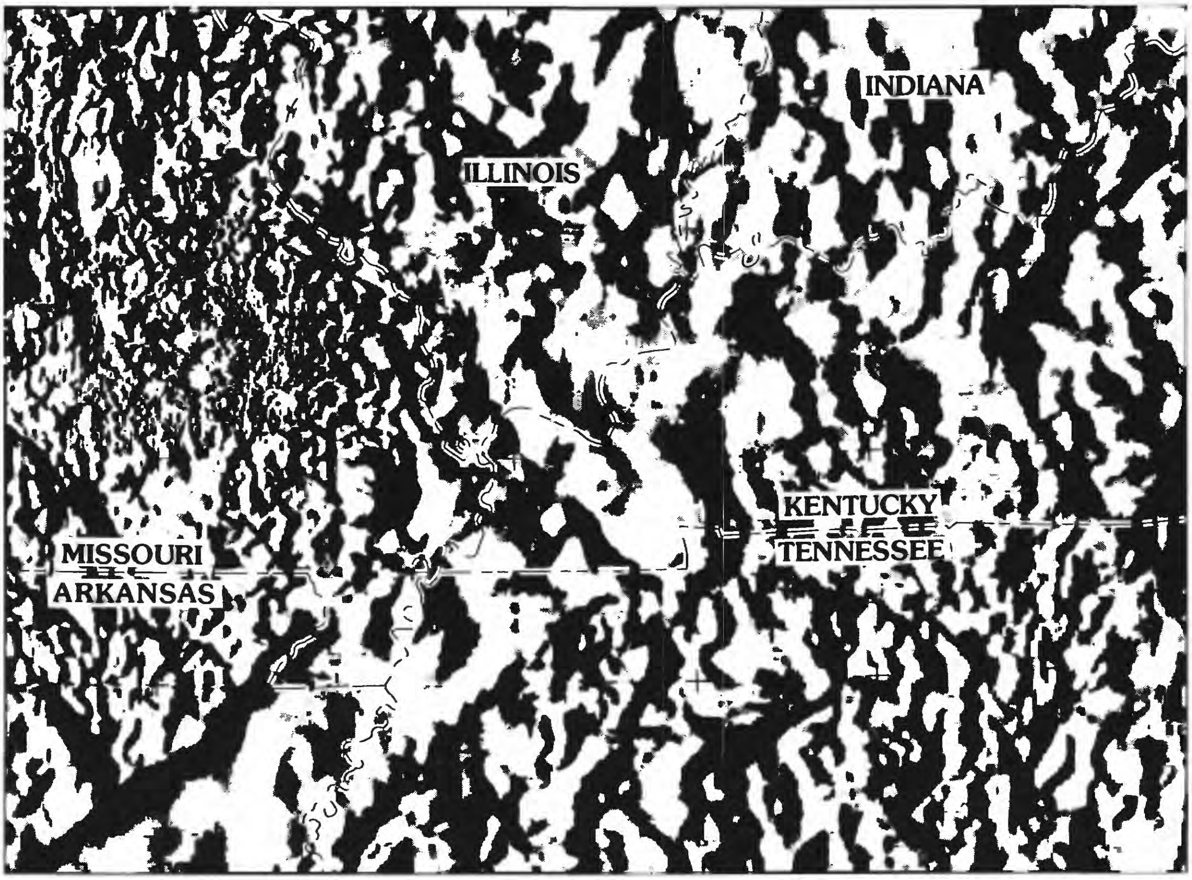
A Search for Paleoliquefaction and Evidence Bearing on the Recurrence Behavior of the Great 1811–12 New Madrid Earthquakes

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1538–H



Cover. Gray, shaded-relief map of magnetic anomaly data. Map area includes parts of Missouri, Illinois, Indiana, Kentucky, Tennessee, and Arkansas. Illumination is from the west. Figure is from *Geophysical setting of the Reelfoot rift and relations between rift structures and the New Madrid seismic zone*, by Thomas G. Hildenbrand and John D. Hendricks (chapter E in this series).

A Search for Paleoliquefaction and Evidence Bearing on the Recurrence Behavior of the Great 1811–12 New Madrid Earthquakes

By Steven G. Wesnousky *and* Lisa M. Leffler

INVESTIGATIONS OF THE NEW MADRID SEISMIC ZONE
Edited by Kaye M. Shedlock *and* Arch C. Johnston

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A SEARCH FOR PALEOLIQUEFACTION AND EVIDENCE BEARING ON THE RECURRENCE BEHAVIOR OF THE GREAT 1811–12 NEW MADRID EARTHQUAKES

By Steven G. Wesnousky[1] *and* Lisa M. Leffler[2]

ABSTRACT

The New Madrid earthquake sequence consisted of four principal events, each of estimated surface-wave magnitude ≥ 8, occurring on three separate days between December 1811 and February 1812. Although arguably the largest historical earthquakes within the conterminous United States, data on the expected repeat time of such events are few and generally equivocal.

The U.S. Army Corps of Engineers maintains a large network of major drainage ditches within the St. Francis drainage basin for flood control and land reclamation. The Corps recently reexcavated tens of kilometers of these ditches in the area of the southern limb of the New Madrid seismic zone, where pervasive liquefaction occurred during the 1811–12 earthquake sequence. We have examined the freshly excavated ditches for geologic evidence of liquefaction features that predate the 1811–12 earthquakes. Radiocarbon dates indicate the resulting vegetation-free exposures afford examination of the last 5,000 to 10,000 yr of geologic record. Historical earthquake statistics have previously been the basis to estimate the repeat time of New Madrid earthquakes at between about 550 and 1,100 yr. In contrast, any evidence of paleoliquefaction seen during our search was equivocal, and no evidence of a widespread, prehistoric liquefaction event as occurred in 1811–12 was observed. Hence, although negative evidence is a less-than-desirable basis for interpretation, an implication of our search is that the recurrence of 1811–12-type earthquake disturbances is on the order of 5,000 to 10,000 yr or more.

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INTRODUCTION

The New Madrid sequence of earthquakes consisted of four principal events, each of estimated surface-wave magnitude ≥ 8, and occurred on the days of December 11, 1811, and January 23 and February 7, 1812 (table 1). The distribution of isoseismals (Nuttli, 1973), the recognition of a distinct zone of seismicity within the region of largest isoseismals (Stauder and others, 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) lend strong credence to the argument that the source of the 1811–12 earthquake sequence was the now well-known New Madrid seismic zone (figs. 1 and 2). Although arguably the largest historical earthquakes within the conterminous United States, data bearing on the expected repeat time for earthquakes such as the 1811–12 events remain few and are generally equivocal.

The New Madrid seismic zone has no clear and unambiguously expressed fault trace at the surface (Schweig and Marple, 1991) and, hence, it is not known if the 1811–12 earthquakes produced a single through-going zone of surface faulting, as is commonly observed for large earthquakes in the Western United States. However, the 1811–12 earthquakes were associated with pervasive liquefaction phenomena that was concentrated in a zone approximately 20–50 km wide and that trends southwestward for a distance of about 150 km through portions of Missouri, Arkansas, and Tennessee (fig. 2). Extruded sand covers as much as 25 percent of the land surface in much of this area. Expressed as light-colored, commonly irregular shapes on the dark-brown soils of the Mississippi Embayment, liquefied sand that was extruded during the 1811–12 earthquakes is still readily visible today both in the field (fig. 3) and on recent aerial photographs (fig. 4). It seems certain that the occurrence today of similar-sized earthquakes in the New Madrid region would cause equally pervasive liquefaction.

Analogously, if similar events occurred in the past, we can reasonably expect similar deformations to be preserved in the geologic record. A systematic search for such geological evidence of pre-1811–12-type earthquakes is the basis of this paper.

OPPORTUNITY

Much of the New Madrid seismic zone lies within the St. Francis drainage basin of the Mississippi Embayment (fig. 2). The geology, geomorphology, and Quaternary history of the Mississippi Embayment have been described previously by Saucier (1974) and, more locally, by Guccione (1987). The St. Francis drainage basin has little topography (e.g., fig. 3), a high water table, and poor drainage. The surface deposits consist primarily of late Wisconsin glacial outwash deposited by braided streams. The transition of the Mississippi River drainage from a braided-stream system to the current meandering mode of deposition has been estimated to have taken place between about 10 to 6 ka ago at about the latitude of Memphis (Saucier, 1974). Hence, the majority of evidence for liquefaction rests upon abandoned late Wisconsin braided-stream terraces (fig. 5), which have been stable surfaces with only minor localized sedimentation since the formation of the Holocene Mississippi River meander belt.

Table 1. The New Madrid earthquake sequence.

[Surface wave (M_s) and body wave (m_b) magnitude estimates taken from Street and Nuttli (1984) as reported by Hopper (1985). Leaders (--) indicate no data]

Date	Local time	M_s	m_b
Dec. 16, 1811	2:15 a.m.	8.6	7.2
Dec. 16, 1811	8:15 a.m.	--	7.0
Jan. 23, 1812	9:00 a.m.	8.4	7.1
Feb. 7, 1812	3:45 a.m.	8.7	7.3

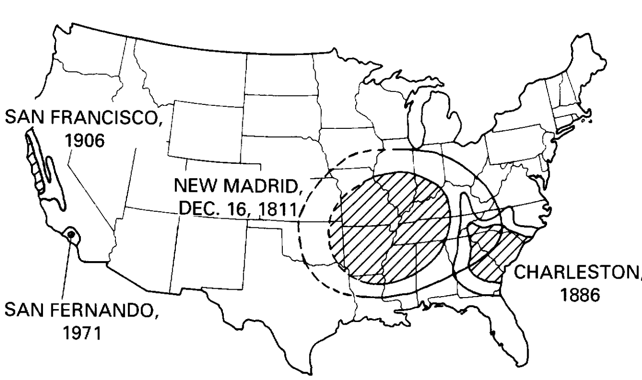

Figure 1. The large size of the 1811–12 earthquakes compared to other major historical U.S. earthquakes is shown by the relative extent of Modified Mercalli (MM) VI and VII (hachured) isoseismals for the respective earthquakes (Modified from Hamilton and Johnston, 1990).

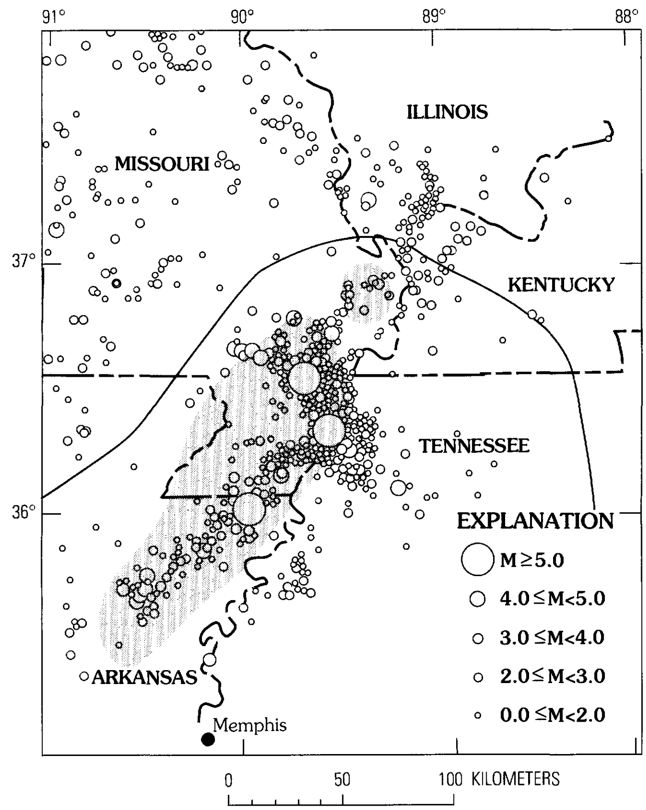

Figure 2. The New Madrid seismic zone is defined by an alignment of earthquake epicenters (circles scaled according to magnitude) that extends southwestward from near Illinois to northwest of Memphis, Tenn. Analysis of aerial photographs by Heyl and McKeown (1978) and Obermeier (1989) show that the shaded area was characterized by extensive liquefaction during the 1811–12 New Madrid earthquakes. The curved solid line marks the northern extent of the Mississippi Embayment.

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. 6). Two factors provided us a unique 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 1980's, with the record lowest stage of the Mississippi River being recorded during the summer of 1988. Simultaneously, the U.S. Army Corps of Engineers embarked on a program to reexcavate and widen several of the existing ditches. The combination of drought and excavation provided tens of kilometers of relatively vegetation-free exposures along the ditches that were used to characterize liquefaction features preserved in the geologic record (fig. 6).

Figure 7 is a photograph of one of the reexcavated ditches. Both sides of the ditch were heavily vegetated prior to reexcavation, as seen on the far side of the ditch. During reexcavation, the vegetation on one side of the ditch is

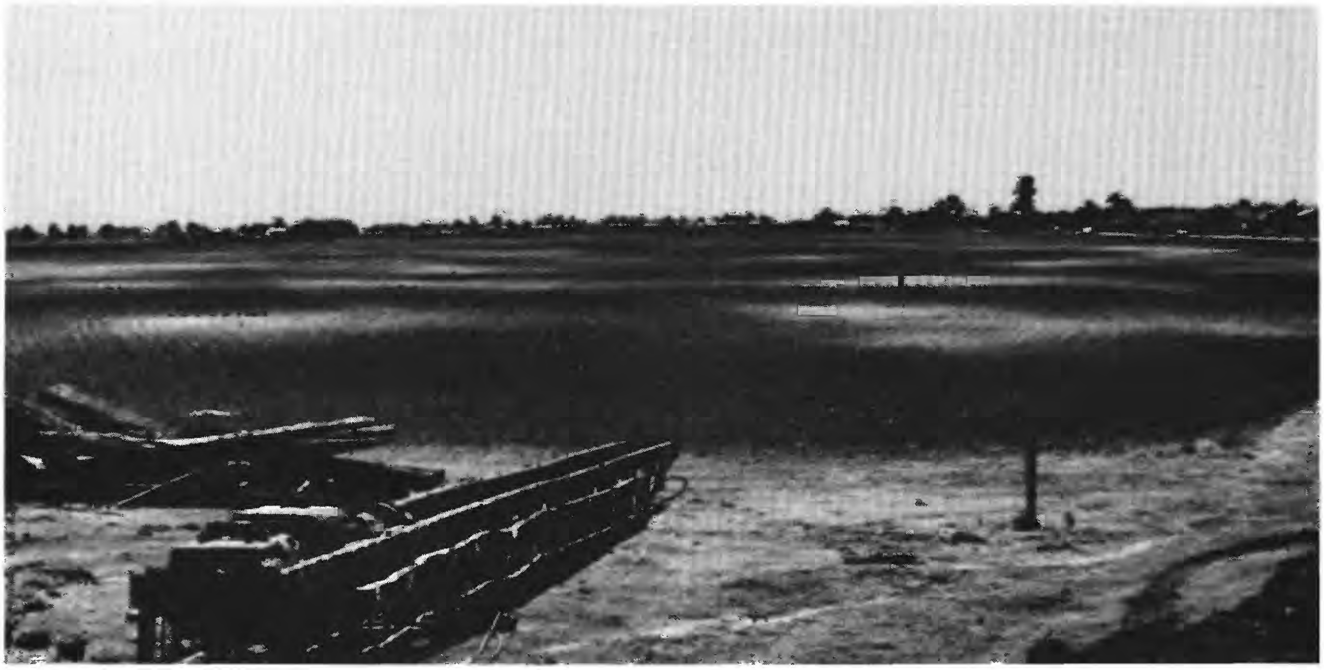

Figure 3. Liquefied sands that were extruded onto the surface during 1811–12 are still clearly visible as light-colored, circular patches on the dark-brown soil of this farm field at the intersection of Stateline (Main) ditch and State Highway 151 in northeastern Arkansas. The lack of significant relief shown here is characteristic of the entire study region.

removed, resulting in fresh exposures about 2–3 m high. Unless freshly excavated, the dense vegetation along the ditches completely obscures virtually all exposures. The purpose of this paper is to describe the character of liquefaction that we observed in these exposures and the implications of our observations on the expected recurrence time of great 1811–12-type earthquakes. We focused our efforts on the region and ditches shown in figure 8. Within this region, we concentrated on documenting the location and detailed character of liquefaction features along the ditches.

METHODOLOGY

In the ditches we examined, the upper 2 to 3 m of braided-stream-terrace stratigraphy observed is quite simple and consists of fine to coarse sand overlain by a clay and silt-rich top stratum of low permeability. However, the top stratum is not homogeneous but tends toward either of two distinct compositions.

One composition is a distinct cap of clay overlying the fine to coarse sand. Top stratum of this nature is illustrated by the photograph and accompanying schematic diagram in figure 9. Where the base of the clay top stratum is visible, it is invariably in sharp contact with the underlying sand. The tabular cross-bedding and thin interbeds of clay observed beneath the clay cap in figure 9 are consistent with deposition in a braided-stream environment. Top stratum of this character is interpreted to reflect deposition of overbank or slackwater clay and silt during flood stages of the Mississippi River and its tributaries following abandonment of the braided-stream terrace (e.g., Saucier, 1974; Obermeier, 1989).

The second kind of top stratum is a generally distinct, well-developed soil profile (fig. 10). The typical profile is capped by a 15- to 25-cm-thick A horizon that grades downward into a distinct B horizon. The B horizon is generally ≥ 1 m thick and, where sufficiently exposed, is observed to grade into unaltered silty sand or sand (C horizon). The characteristic profile is generally developed on a silty to sandy parent material, and pedogenesis appears to be dominated by the alteration of the parent silt and sand and translocation of clays through the soil column. Top stratum of this character appears associated with interfluves or bars of the original braided-stream surface.

Regardless of its origin or character, the top stratum observed forms a clay-rich, liquefaction-resistant layer generally more than 1 m thick that overlies water-saturated fine to coarse sand. Indeed, this stratigraphy provided ideal conditions for the tremendous liquefaction effects reported for the 1811–12 earthquakes (Fuller, 1912; Saucier, 1977; Obermeier, 1989). Thus, our search for evidence of paleoliquefaction initially entailed walking the entire length of the ditches shown in figure 8, looking for breaches or breaks in the top and bottom of the top stratum to systematically identify sites of sandblows, dikes, and rifts. Places

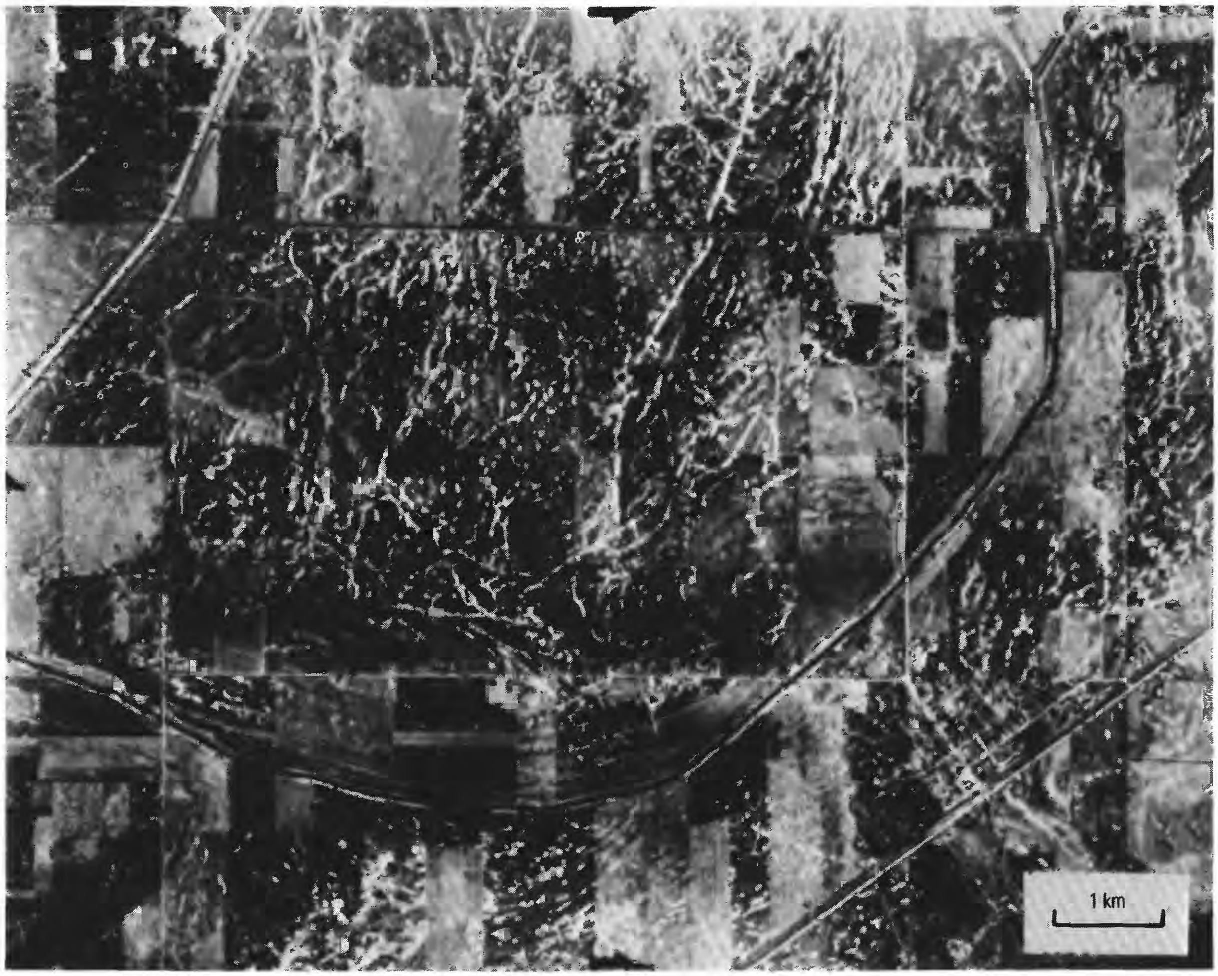

Figure 4. The pervasive nature of 1811–12 liquefaction is clearly shown by the abundant sandblows and sand rifts seen in this 1940 aerial photograph. The town of Dell, Ark., is within the New Madrid seismic zone and is located in the lower right quarter of the photograph. North is up on photograph.

where liquefaction phenomena were concentrated were later logged in detail to document the general character of liquefaction features and permanently record their location for later study. At our detailed study sites, we cleared the exposure by hand shovel or backhoe, logged it in greater detail, and examined it for evidence of prehistoric liquefaction. Because our emphasis was on identifying pre-1811–12 liquefaction, we limited analysis of individual geologic units to brief field descriptions. The results are described in following sections of this paper.

OBSERVATIONS

DITCH NO. 12

Ditch No. 12 is located west of Big Lake Wildlife Refuge in Arkansas (fig. 8) and trends east-west, which is roughly normal to the general flow direction during deposition of the braided-stream terraces (fig. 11). A 1939 aerial photograph shows numerous sand rifts or dikes crossing the ditch (fig. 12). A schematic diagram of about 1 km of the ditch is shown in figure 13. The numerous breaches in the top stratum further attest to the pervasive nature of liquefaction near the ditch.

The exposure shown in figure 14 is site 1 in figure 13. Initial examination of this exposure showed the clay top stratum overlying and in sharp contact with tabular cross-bedded, fine to medium sand (unit A). However, further examination revealed clear evidence of liquefaction beneath the top stratum. The sand of unit C flowed upward through the section to the base of the overlying clay, but it was unable to propagate through the impermeable top stratum and flowed horizontally, forming thin sills in the basal part of the clay. Thus, the top stratum behaved as an impenetrable cap in this instance. In addition, the thin anastomosing character of bedding within the sand unit B is likely due to the liquefaction of sand to the point of incipient mass flow. The gradual degradation of cross-bedding laminations from east to

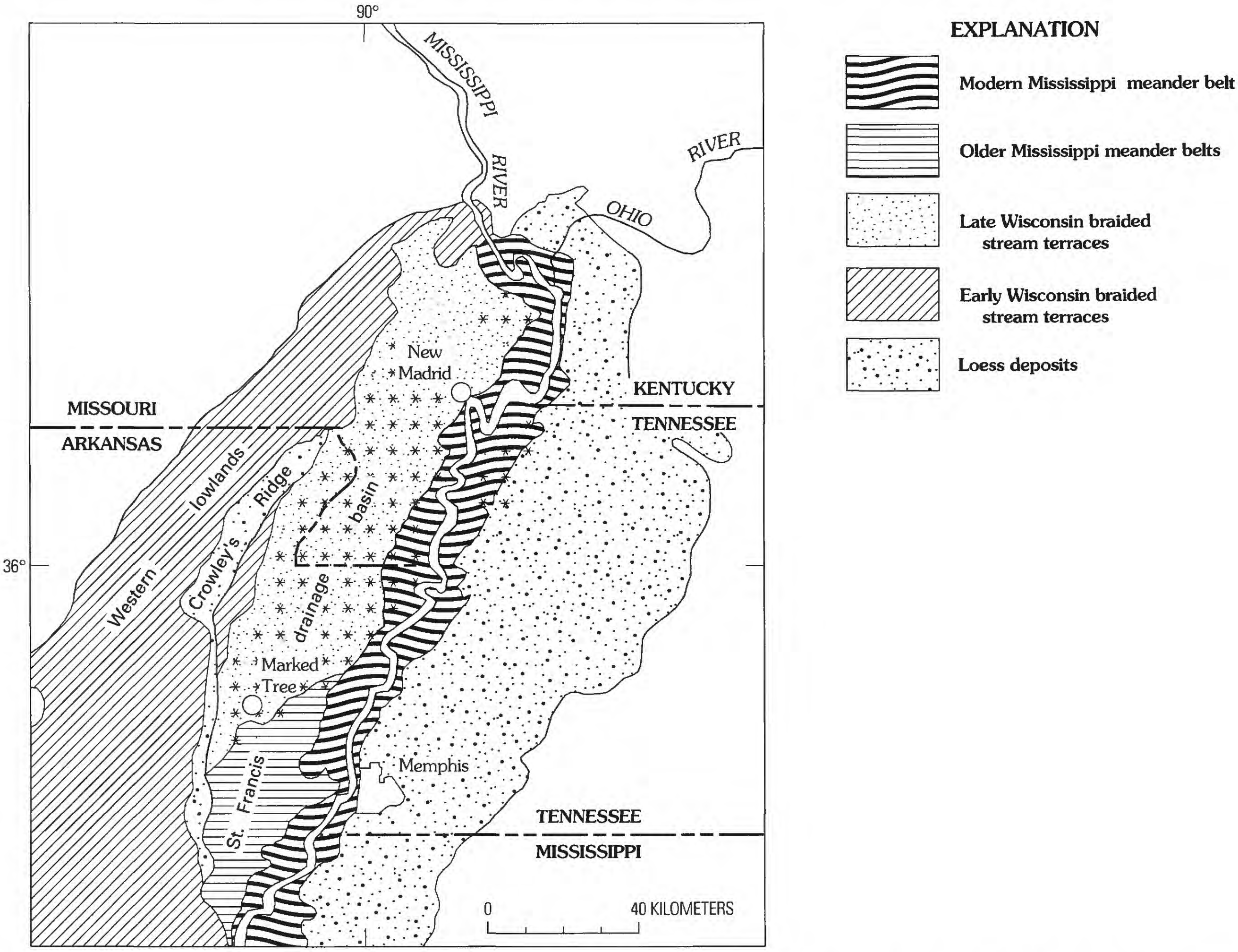

Figure 5. Generalized Quaternary geologic map of the upper Mississippi Embayment (adapted from Saucier, 1974). Sand ejected during the 1811–12 earthquakes comprise from greater than 1 to 25 percent of the surficial deposits in a region (shown by asterisk pattern) that extends from north of New Madrid, Mo., southwestward to Marked Tree, Ark. (Obermeier, 1989).

west across unit A may also be evidence of incipient liquefaction. Indeed, we seldom found evidence of original and undisturbed bedding within the sand immediately underlying the top stratum. More commonly, the sand beneath the top stratum commonly contained disturbed bedding or flow structures that we attributed to liquefaction. Site 1b (fig. 13) is another example that illustrates the disturbed character of bedding in the sand (fig. 15).

Site 1b is about 10 m west of site 1a (fig. 13), and details of the exposure are shown in figure 15. Here, the top stratum is unbroken and consists of a generally impermeable clay and clay loam. The underlying sand shows more evidence of liquefaction as compared to site 1a. No evidence of undisturbed original bedding is observed. The disrupted and generally anastomosing character of bedding within the underlying sand (unit AS, fig. 15) is interpreted to represent incipient flow due to liquefaction. In turn, the sill of white sand (unit WS) is apparently the result of impeded upward flow of sand due to the impermeable and unbroken nature of the overlying clay top stratum (unit TS). A similar interpretation may explain the sill of lignite sand (unit LG). Pressures were sufficient nearby to breach the top stratum and result in the expulsion of sand (e.g., unit WS) and lignite (e.g., unit LG) in the vicinity of this site—this is evidenced by the presence of extruded sand of similar composition on the surface (unit SC). Site 2, located about 400 m east of this site, shows the character of such a break in the top stratum.

The exposure at site 2 is capped by about 1 m of artificial levee fill (fig. 16). Beneath the levee fill is about 1 to 2 m of clean fine to medium sand. The sand is fed by a dike at the base of the exposure. Soil on the sand is immature, consisting of a 5- to 10-cm-thick A horizon and no significant B horizon. The immaturity of the soil profile on the ejected sand (fig. 17*A*) suggests that the deposit on which it formed is very young, most likely a result of the ejection of sand to the surface in 1811–12. The internal structure of the ejected

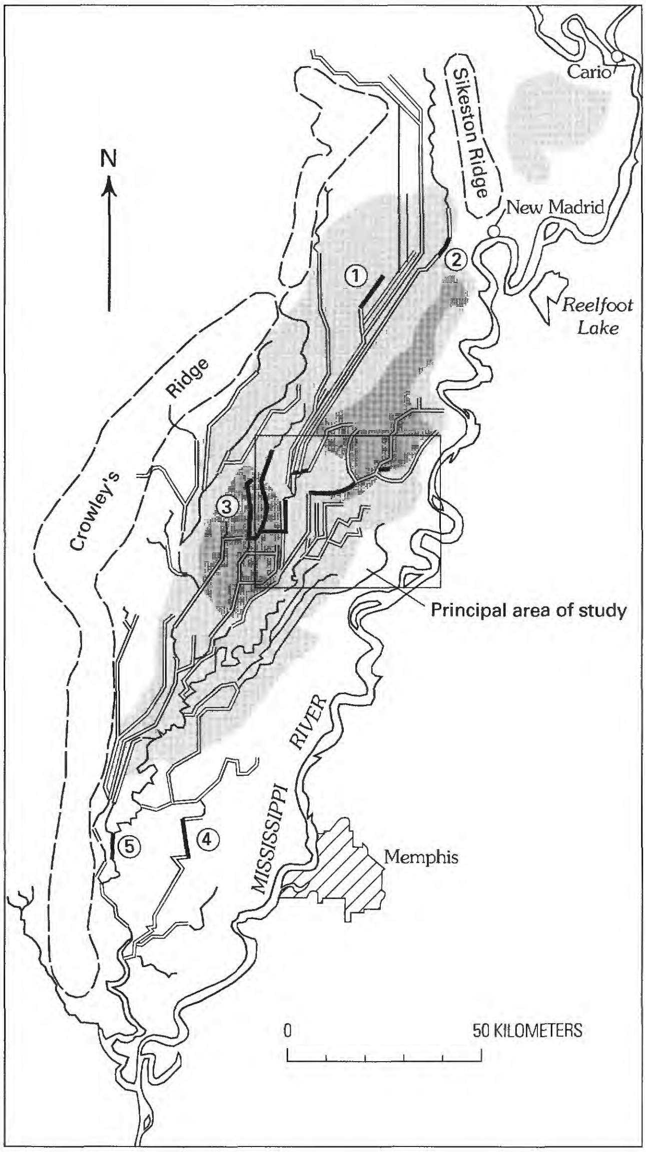

Figure 6. The U.S. Army Corps of Engineers maintains a network of drainage ditches (open lines) throughout the St. Francis drainage basin. Ditches that were reexcavated and widened during the course of our study and examined for evidence of paleoliquefaction are shown by solid lines. Areas where 1811–12 liquefaction deposits still comprise ≥ 1 percent and ≥ 25 percent of the surface area are shaded by light and dark stippling, respectively. The principal area that is discussed in this paper is outlined by the box. Circled numbers 1 through 5 correspond to sections of Ditch No. 9, Little River, Honey Cypress ditch, Blackfish Bayou, and the St. Francis River, respectively. See figure 8 for detailed map of study area.

Figure 7. Photograph of a section of Buffalo Creek ditch taken during the spring of 1987, shortly after reexcavation by the U.S. Army Corps of Engineers. The vegetation on one side of the ditch was removed during reexcavation, resulting in clean exposures about 2 to 3 m high. The water level in these ditches may reach the rim or overflow it during the heaviest winter storms. Flow is limited during the summer but, even during the severe drought conditions of 1988, spring flow from the sides of ditches is generally maintained.

sand shows two, distinct, thin layers of silt and lignite (fig. 17*A*). The thin layers probably represent brief hiatuses of the sand-blow eruption 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 relatively brief time. Saucier (1989) interpreted similar features at a liquefaction site in northeastern Arkansas in a similar manner and suggested that the distinct packages of sand may represent individual events of the 1811–12 New Madrid earthquake sequence.

In contrast to the immature soil developed on the ejected sand at site 2, the buried surface on which the ejected sand rests is characterized by a much more 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. 17*C*). The maturity of the 2Ab–2Bb soil profile suggests that the surface on which the sand was ejected was stable for a relatively long period of time prior to being breached by liquefied sand in 1811–12. The buried 2Ab–2Bb profile grades further downward into clean sand. Unique to this site, however, we observed that the buried sand rests in sharp contact with another buried surface on which the 3Ab–3Bb soil profile is developed (figs. 16 and 17*C*). A possible 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 exposed sand-3Ab contact, and we followed this contact for about 15 m to

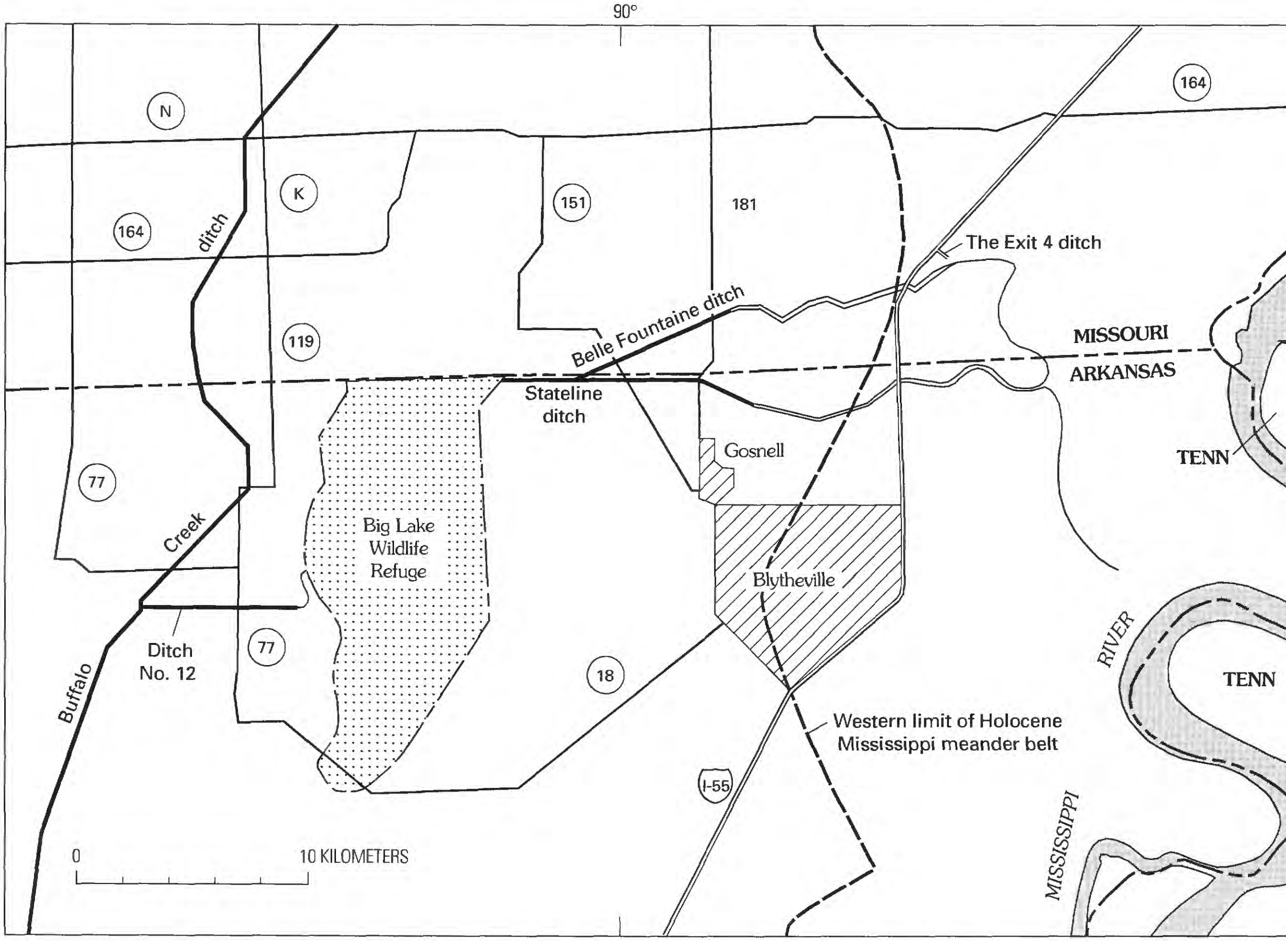

Figure 8. Map of reexcavated ditches (thick solid lines) where we concentrated on documenting the location and character of liquefaction features. Detailed studies were conducted in parts of Ditch No. 12, Buffalo Creek ditch, Stateline ditch, and the Belle Fountaine ditch. The western limit of the Holocene Mississippi meander belt is shown by dashed line. Area of this figure is shown in figure 6 as the "principal area of study." Circled numbers and letters are State and County Highway numbers.

the west of the vent until it dipped beneath the water table. Also, paleomagnetic sampling of unit 2Bb shows it to maintain a continuous secular variation curve, suggesting that it was emplaced gradually over a period of time (Stephen Salyards, Southern California Earthquake Center, University of California at Los Angeles, oral. commun., 1993). Hence, although an interpretation for the buried sand unit invoking liquefaction is tempting, an alluvial origin for the buried sand cannot be ruled out.

Another break in the top stratum along Ditch No. 12 is labeled site 3 in figures 12 and 13 and is shown in figure 18. The top stratum at this location is very dark clay and is sharply interrupted by the intrusion and ejection of very light gray, locally oxidized, very fine to fine-grained sand. Again, the soil profile developed on the extruded sand is immature, composed of a thin A horizon and virtually no B horizon. Its weak development indicates that it most likely formed since 1811–12. Again, a very well developed soil is present on the surface broken by the liquefied sand, suggesting considerable antiquity and stability to the surface on which it is developed. The composite photographs of the site in figure 19 further illustrates both the character of soil development on the top stratum and the ubiquitous and pervasive flow structures that characterize the liquefied sand.

Brown clay loam forms the lower meter of the top stratum to the east of the extruded sand at site 3 (fig. 18). The light-gray silty clay at the top of the loam may be a buried E horizon associated with an older surface. Large pieces of bark-covered wood were recovered from two sites within the clay loam (fig. 18) and were tentatively identified as bald cypress (Donna Christensen, U.S. Forest Products, written commun., 1990). The two samples have conventional radiocarbon dates of 5,090±60 and 11,100±100 radiocarbon yr B.P., respectively (Beta Analytic Inc.; lab sample numbers Beta-38311 and Beta-41984). The wood immediately overlying the liquefied

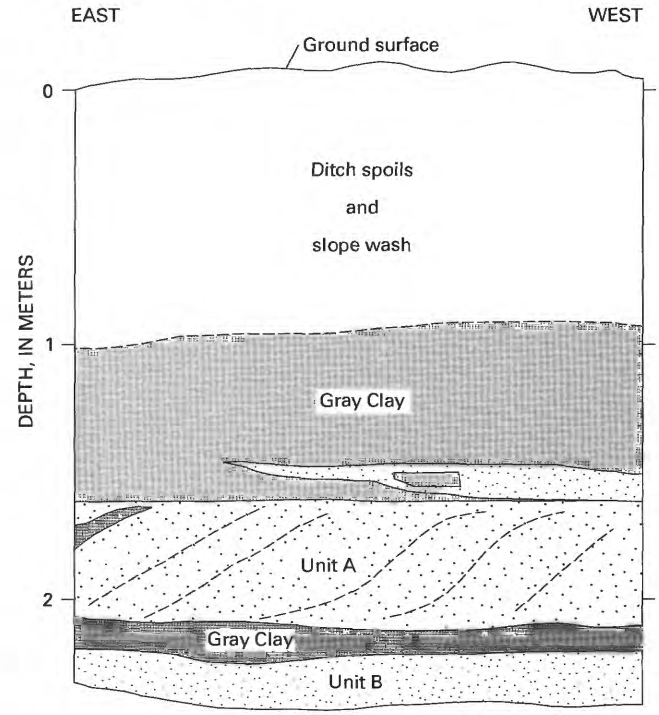

Figure 9 (facing column and above). Photograph and schematic diagram of an exposure along Ditch No. 12, Arkansas, illustrating the nature of the top stratum or "clay cap" along many of the drainage ditches. String grid in photograph indicates 1-m intervals. In this exposure, a thick clay cap overlies a sequence of tabular cross-bedded sand and thin interbeds of clay. The tabular cross-beds are consistent with deposition in a braided-stream environment. The sand of unit A is fine to medium grained, stained reddish yellow, and contains distinct topset, foreset, and bottomset beds. The light-gray, fine- to medium-grained sand of unit B contains faint, undulatory laminations. See text for further discussion.

sand has an age of 11,100±100 radiocarbon yr B.P. Thus, the overlying soil profiles represent some 5,000 to 10,000 yr of development, and our observations here show no evidence of prehistoric liquefaction during that same period of time.

BUFFALO CREEK DITCH

The Buffalo Creek ditch, which trends northerly through the area of study (fig. 8), occupies an abandoned, relict channel on the braided-stream terrace surface (fig. 11). We excavated and logged several sites along the ditch.

Site 4 is located about 150 m south of the ditch crossing with State Highway 77 between Manila and Leachville, Ark. (fig. 11). The location of the site with respect to the local geomorphology is illustrated by the aerial photograph in figure 12. The stratigraphy at the site (fig. 20) consists of a dark-brown A horizon resting on a light-gray 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 S1, S2, and S3) intrude and disrupt the host stratigraphy (fig. 20).

Site 4 provides insight into both the mechanics of the liquefaction process as well as the past history of liquefaction events at the site (fig. 20). Impermeable clay layers play a controlling role in the liquefaction process, limiting the upward migration of liquefied sand. This is demonstrated by the presence of sand sills (stippled) that extend horizontally from the central pipe to distances of approximately 5 m or more, each directly beneath relatively non-liquefiable clay or clay-rich layers. Cross-cutting relations further indicate several phases of sand injection whereby the injection of unit S1 was followed by units S2 and S3, respectively. The sharpness of the cross-cutting relations and the relative ages of the respective sand units are shown more clearly by the larger scale photomosaic shown in figure 21.

Although cross-cutting relations reveal evidence of three distinct episodes or phases of liquefaction, there is no evidence at site 4 to suggest that the hiatus between emplacement of units S1, S2, and S3 spanned any significant amount of time. Additionally, the sand (unit S3) that did reach the surface is characterized by the absence of significant soil development. The simplest interpretation of this is similar to the previous exposure: that is, the liquefied sand is the result of the 1811–12 earthquake sequence, and, possibly, the separate units of liquefied sand may be attributed to the separate earthquakes of that same sequence.

Site 5 is several hundred meters north of site 4 and about 150 m north of the Highway 77 bridge crossing (figs. 8, 11, and 12). The top stratum is composed of a well-developed soil profile (fig. 22) similar in color and composition to that observed at site 4. Unlike site 4, the liquefied sand forms a clear break in the top stratum and is responsible for venting more than 1 m of white, fine to medium sand onto the surface. Again, the soil on the top stratum is much more mature compared to soil on the ejected sand (fig. 22). 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 indicates the youthfulness of the ejected sand, and, hence, our interpretation is that liquefied sand vented in 1811–12.

The magnitude of the liquefaction at site 5 is further illustrated by the upper photograph of figure 23. The ejected sand forms a layer that is as much as 2 m thick and extends 30–40 m along the ditch. The lower photograph shows the condition of the ditch at site 5 about 4 months after it was excavated and logged. The vegetation has seriously degraded the exposure. This comparison illustrates the unique opportunity provided by the excavations of the Corps of Engineers.

Buffalo Creek ditch continues north of site 5 (fig. 24), as does evidence for 1811–12 liquefaction. An aerial photograph of the ditch near Highway 164 is shown in figure 25. Figure 26 is a schematic diagram of about 3/4 km of ditch where it crosses Highway 164. Breaches in the top stratum are common and, although remnant cross-beds are present, the sand beneath the unbreached top stratum more typically exhibits secondary flow structures that can most likely be attributed to liquefaction. A significant break in the top stratum is located 400 m south of the Highway 164 bridge and is labeled as site 6 in both the aerial photograph of the site (fig. 25) and the schematic diagram (fig. 26). A photograph and schematic diagram of the exposure at site 6 are shown in figure 27.

Site 6 and site 2 in Ditch No. 12 (fig. 16) share strong similarities. The photograph and schematic diagram (fig. 27) show a large breach in the top stratum. The top stratum, which is defined by a well-developed soil profile, represents a relatively long period of stability (fig. 28). In contrast, the sand that was extruded through the top stratum has only a 1-cm-thick A horizon and virtually no B-horizon development. Similar to sites 2 and 4, the weak soil on the extruded sand is consistent with the sand blow forming in 1811–12. We found no relations that suggested older episodes of liquefaction.

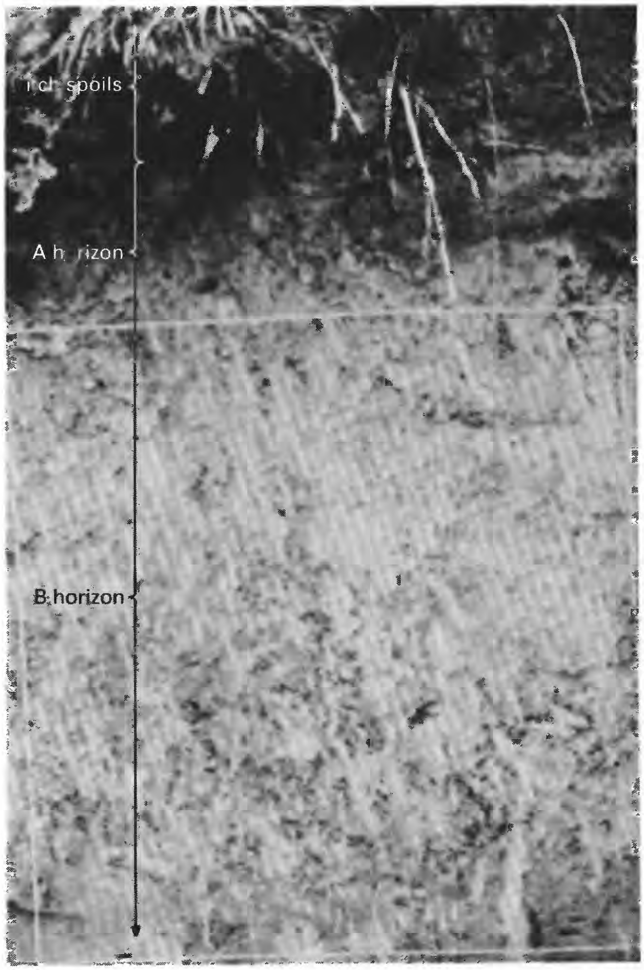

Figure 10. Photograph of an exposure along Ditch No. 12, Arkansas, illustrates the nature of the top stratum or "clay cap" along many of the ditches. The clay cap has a well-developed soil, which is formed on a silty top stratum. A typical profile is capped by a dark-brown A horizon, 15–25 cm thick, which grades downward into a thick B horizon composed of a light brownish gray, silty loam with distinct strong brown mottling due to oxidation. Local farmers refer to the material as "buckshot clay" because it contains numerous, circular iron-oxide concretions. String grid indicates 1-m intervals.

Site 7, located to the north of the Highway 164 bridge crossing (fig. 26), illustrates the character of the top stratum and the intensity of liquefaction-induced disruption beneath unbreached parts of the top stratum (fig. 29). The blocky clay of the top stratum is underlain by a very fine, sandy loam (unit B, fig. 29). The silty loam is cut by two distinct sand units, S1 and S2, respectively. The intruding sand (unit S2) has torn away part of the overlying clay top stratum. The exposure illustrates the erosion that occurs at the base of the top stratum due to the liquefaction and flow of underlying sand. Unit S1 is a very fine to medium-grained, light-gray sand. The sand of unit S2 is similar in grain size but white in color, indicating that the two units had different sources.

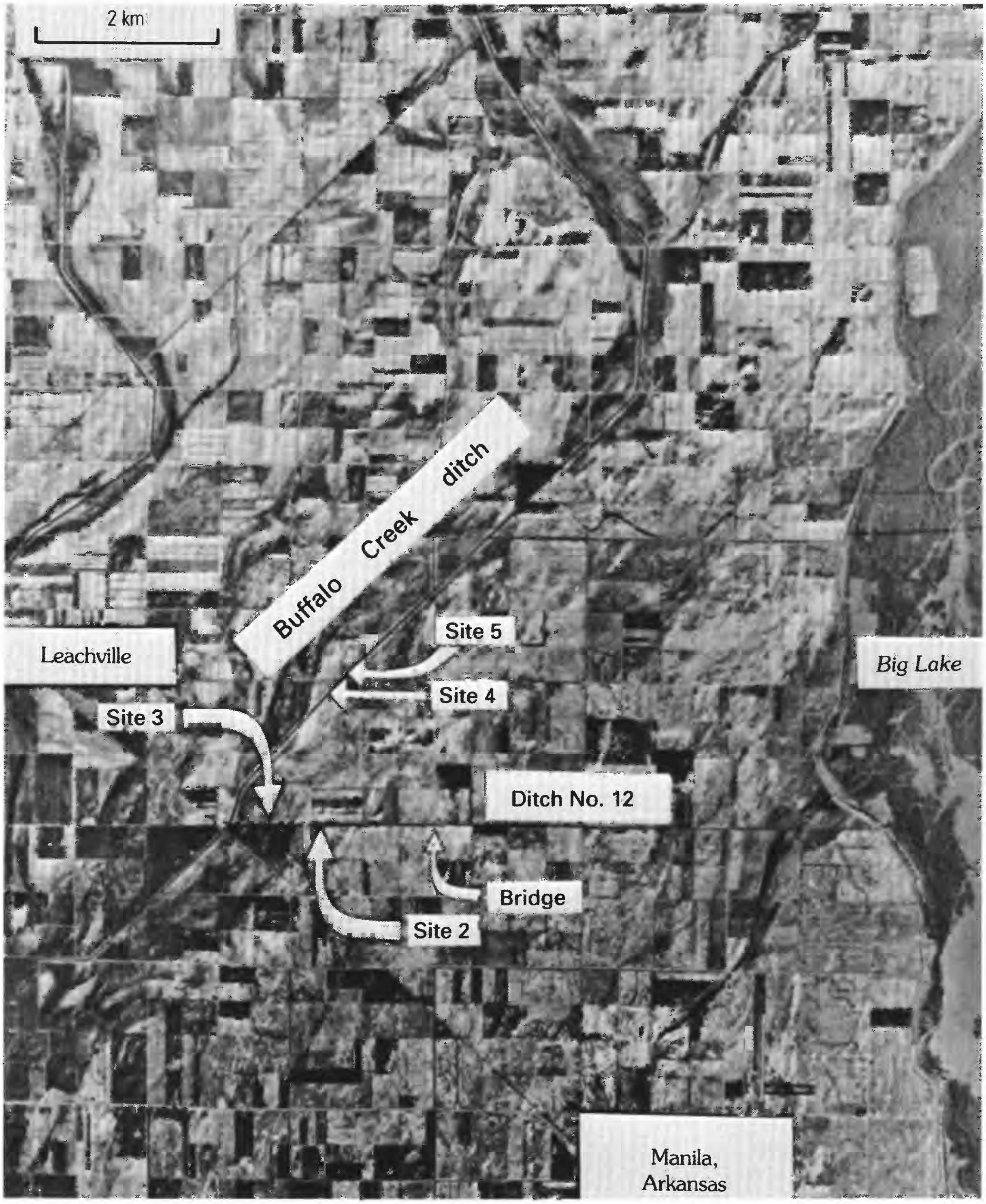

Figure 11. Manila North, Arkansas, orthophotoquad showing geomorphic character of braided-stream surface on which Buffalo Creek ditch and Ditch No. 12 are excavated. Buffalo Creek ditch is excavated along the axis of a relict channel. In contrast, Ditch No. 12 cuts across an interfluvial portion of the braided-stream terrace between Buffalo Creek ditch and Big Lake. Total elevation difference between relict channels and interfluve regions is about 1 m. Specific excavations are marked by site numbers. North is up on photograph.

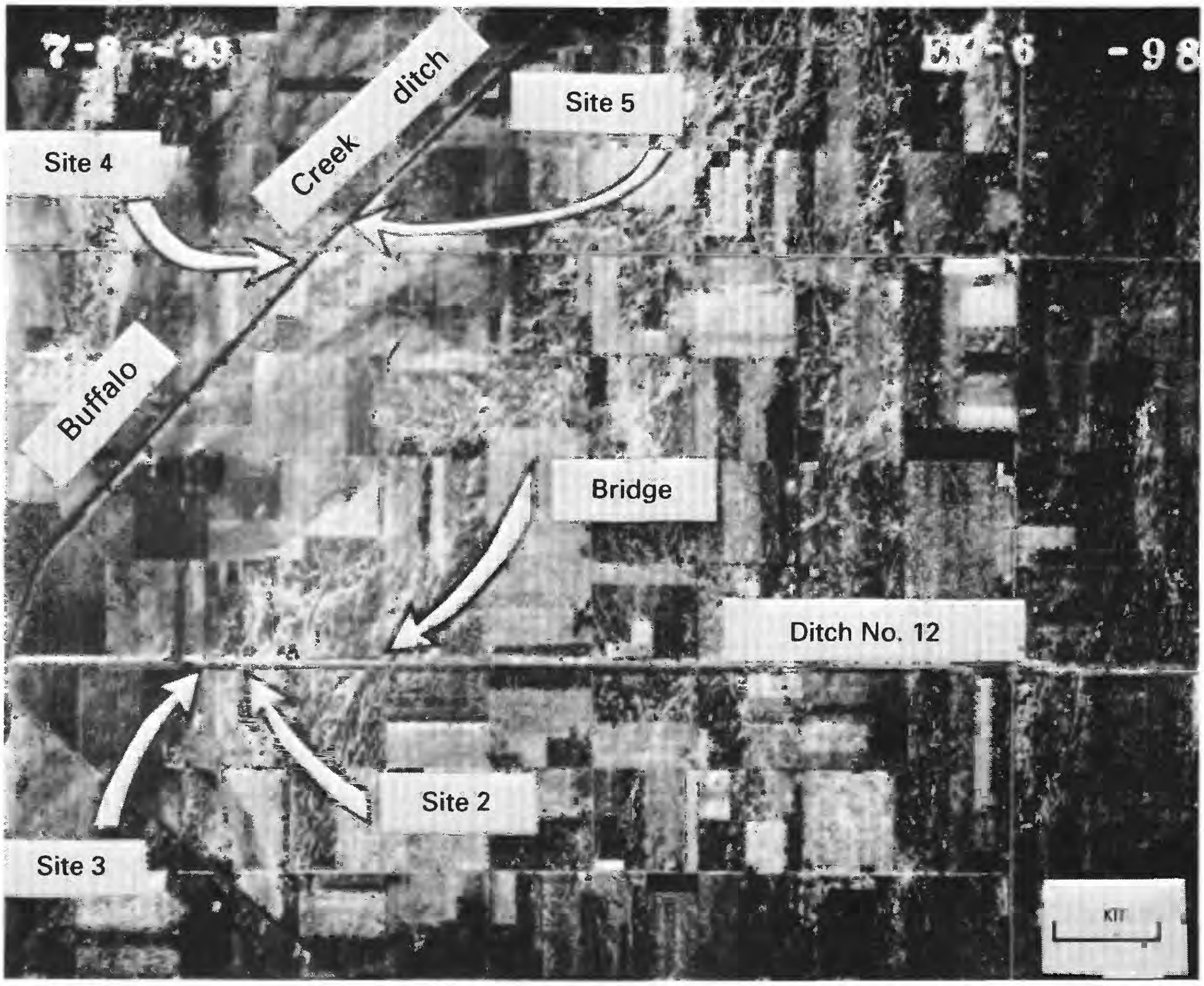

Figure 12. A 1939 aerial photograph showing part of Ditch No. 12 and Buffalo Creek ditch. Patches of light-colored ground mark numerous rifts or blows of liquefied and ejected sand in the vicinity of the ditches. Arrows locate sites 2 through 5. North is up on photograph. Note: Some white dots on this image are caused by chemical changes in the negative of the aerial photograph.

Cross-cutting relations show that unit S2 was emplaced before S1, but we saw no evidence to argue a significant period of time separating emplacement of the two units. In that regard, the simplest interpretation is that the two units resulted from the 1811–12 earthquake sequence.

Farther to the north, the articulated skeletal remains of an extinct, stout-legged llama (*Paleolama mirifica*) were exposed in the western bank of Buffalo Creek ditch, 150 m south of the County Road N bridge crossing (site 8, fig. 30) and about 5 km south of Senath, Mo. (Graham, 1990). The *Paleolama* skeleton was found near the base of the section in a massive, fine to medium sand (fig. 31). The sand is generally overlain by a top stratum of silty to clayey 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 enclosing the *Paleolama* skeleton, but the basal sand liquefied and flowed during the 1811–12 New Madrid earthquakes, breached the overlying gleyed clay, and formed a sill between the gleyed clay and overlying loam and clay deposits. This interpretation is supported by the presence of sand dikes originating from this same sand—these dikes clearly breach the entire top stratum at nearby sites, such as site 9, about 250 m to the north (fig. 32). Thus, after eliminating the effects of liquefaction, the *Paleolama* was preserved within the sand directly below the silty and clayey loam and clay units of the top stratum.

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). From our observations and prior studies (e.g., Saucier, 1974; Guccione and others, 1990), the sand underlying the top stratum and encompassing the *Paleolama* skeleton is interpreted as a braided-stream deposit, and the sequence of clay and loam are deposits that accumulated in

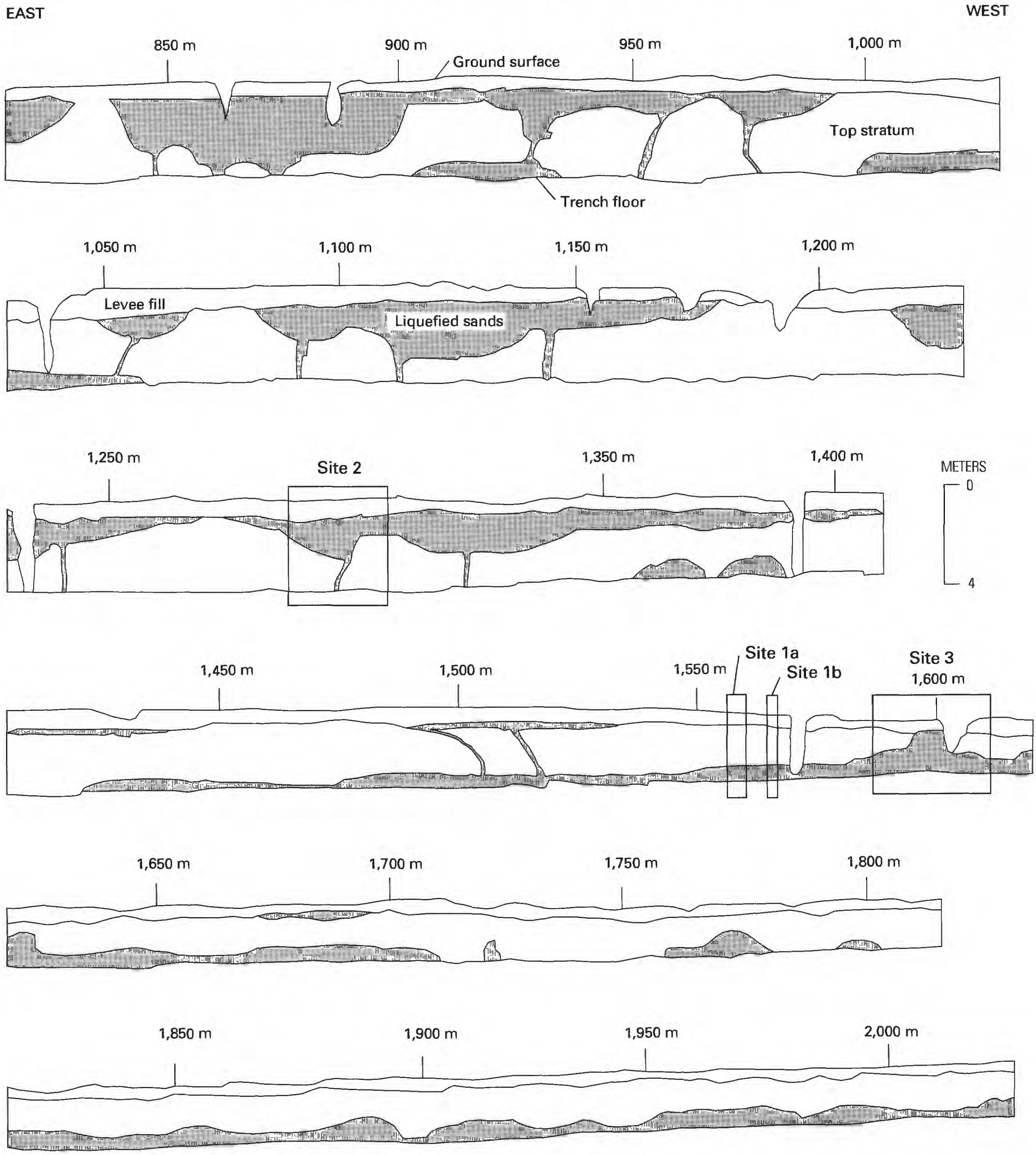

Figure 13. Schematic diagram of the south side of a section of Ditch No. 12 near Manila, Ark. The upper 0.5 to 1.0 m of the section is levee fill resulting from excavation of the ditch. The top stratum is clay rich and generally non-liquefiable in character. The shaded unit is fine to coarse sand that shows evidence of liquefaction. Evidence of original bedding is rare beneath the top stratum. Solid boxes show sites along the trench that were documented in greater detail. Horizontal distances are measured with respect to west edge of bridge crossing shown in figure 12. Note vertical exaggeration.

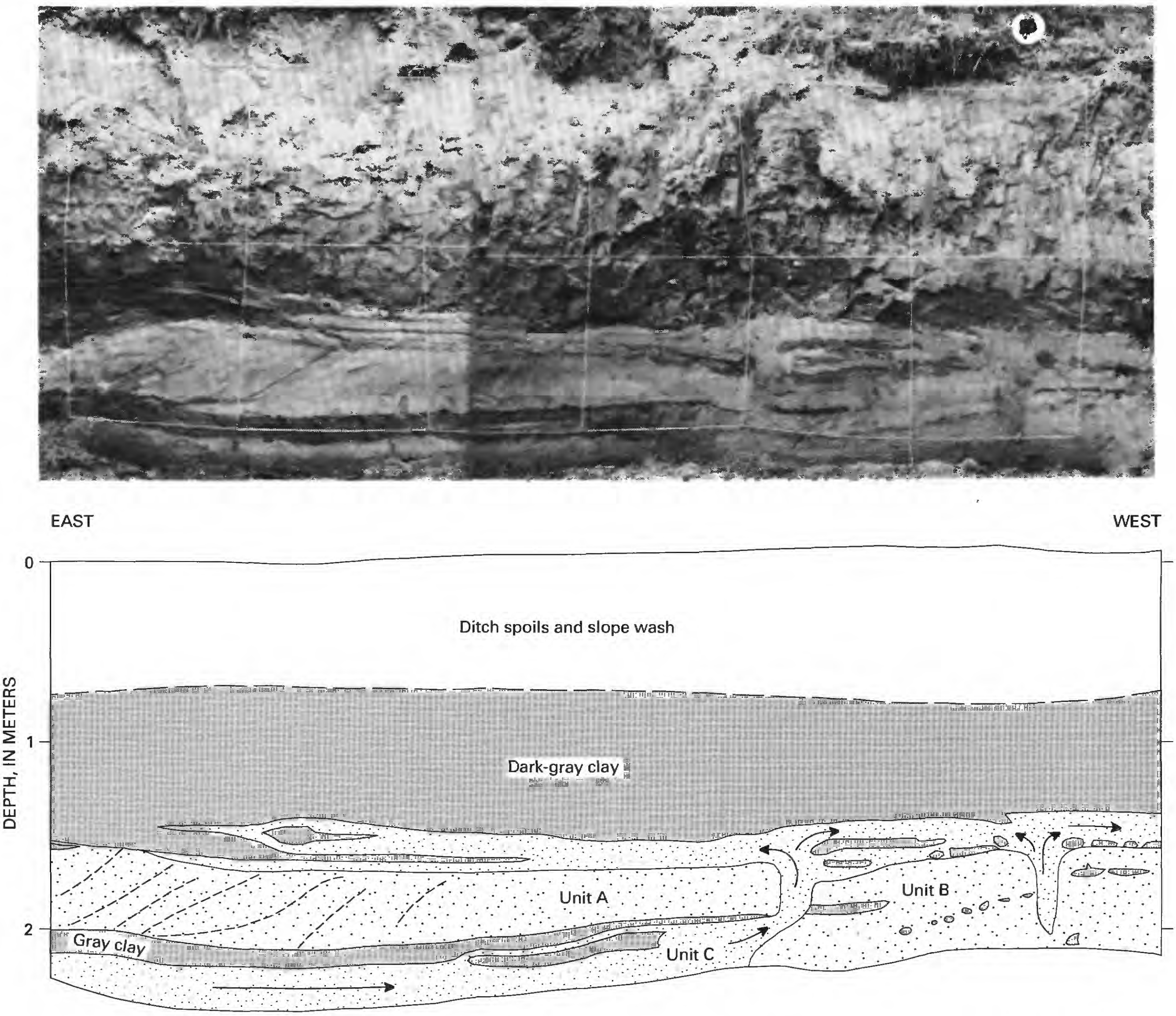

Figure 14. Photograph and schematic diagram of Ditch No. 12 at site 1a near Manila, Ark. See figure 13 for details of location. Exposure shows tabular cross-beds and the confinement of liquefaction features beneath a relatively impermeable clay top stratum. The sand of unit C flowed upward to the base of the overlying clay, at which point it was unable to propagate through the top stratum and flowed horizontally, forming thin dikes beneath the clay top stratum (arrows indicate flow direction). Unit A consists of cross-bedded, brownish-yellow and light-gray fine- to medium-grained sands. Unit B is composed of thin anastomosing lenses and beds of light-gray and gray, fine- to medium-grained sand. Unit C is light-gray, fine- to medium-grained sand—this sand is generally massive near the base of the exposure and occurs in thin horizontal beds directly beneath the overlying clay top stratum. The disturbed character of bedding in the sand labeled unit B indicates that the sand also liquefied but that mass flow was minimal. The incipient nature of liquefaction in unit A is evidenced by the gradual degradation of cross-beds from east to west across the unit. String grid in photograph indicates 1-m intervals. No vertical exaggeration.

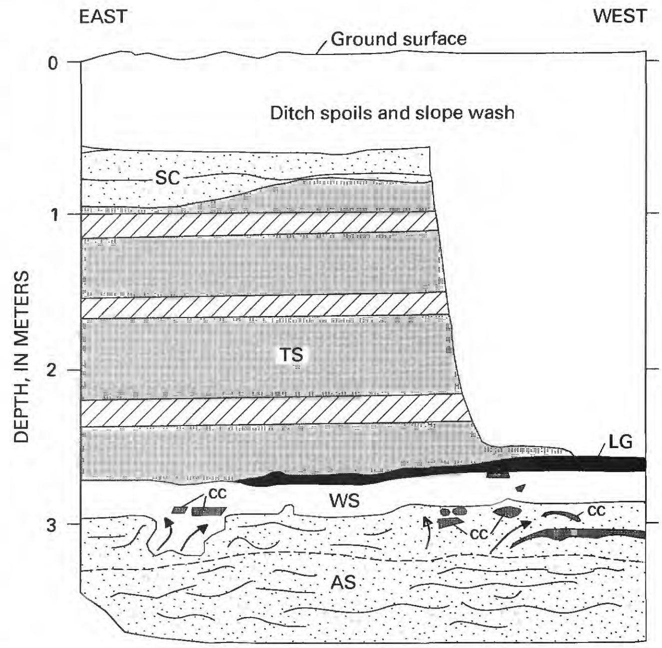

Figure 15 (above and facing column). Photograph and schematic diagram of site 1b along Ditch No. 12 near Manila, Ark. (see fig. 13). Sand underlying the clay top stratum (TS) shows disrupted bedding and laminae, which are interpreted to indicate deformation due to liquefaction subsequent to deposition. The top stratum (TS) is unbroken, and, hence, flow due to liquefaction was confined beneath the top stratum at this particular site. Note the clean white sand (WS), which appears to represent lateral flow beneath the top stratum, resulting in emplacement of a sill of sand. String grid in photograph indicates approximate 1-m intervals.

EXPLANATION

- SC Thin interbeds of light-gray fine to medium sand and brown fine to medium sand containing abundant lignite. Bioturbated(?)
- TS Top stratum of gray and grayish-brown clay and clay loam. Mottling of color and texture suggestive of Krotovina
- WS Fine to medium white sand containig abundant gray clay clasts (cc)
- LG Sand- to granule-size lignite. Lignite granules are well rounded
- AS Anastomosing lenses of pale-brown and gray, fine to medium sand containing numerous small clay clasts (cc). Interpreted direction of flow marked by arrows

low-energy backswamp and slackwater settings that collected since the terrace was abandoned approximately 11,000 yr B.P. The stratigraphy and radiocarbon dates at this site and site 3 (fig. 18) are virtually identical, lending support to the idea that the deposits exposed in the ditch represent about 5,000 to 10,000 yr of time in the vicinity of Buffalo Creek ditch and Ditch No. 12.

STATELINE AND BELLE FOUNTAINE DITCHES

The Stateline and Belle Fountaine Ditches, which trend easterly from the Big Lake Wildlife Refuge (fig. 8), were reexcavated to a significantly greater width than Ditch 12 or Buffalo Creek ditch (fig. 33), and, although the ditch walls had a shallow slope, they provided about 5 m of vertical exposure. In contrast to the deposits along Ditch No. 12 and Buffalo Creek ditch, the base of the gray, blocky top stratum, where present, was not observed at any point along the base of the ditches. The thicker top stratum characteristic of the Stateline and Belle Fountaine ditches is consistent with the interpretation of Guccione (1987) that these ditches are excavated into thick, backswamp deposits.

Numerous sand blows are present in fields adjacent to the ditches (fig. 34), but our search revealed only one major break in the top stratum near the eastern end of the studied section of Stateline ditch (fig. 8). The occurrence of relatively few large breaks in the top stratum are probably the result of the thick top stratum along these ditches as compared to Ditch No. 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 section, as shown at site 10 (fig. 35).

A 1-m-thick layer of extruded sand is connected to several dipping sand dikes at site 10 (fig. 35). The stratigraphy and structure of the vented sand layer indicates four distinct episodes of venting or sand extrusion. More specifically, there exist four approximately flat-lying layers of sand (fig. 36). These episodes are represented by four nearly flat-lying packets of sand whose contacts are characterized by concentrations of silt and lignite, some flare structures, and, along the uppermost internal contact, preserved worm-hole casts. The lower three layers are composed of distinct, fining-upward sequences. The contacts thus represent hiatuses in venting of the sand, but the absence of soil development or oxidation on these buried surfaces implies a brief period of time between deposition of the individual packages. Most

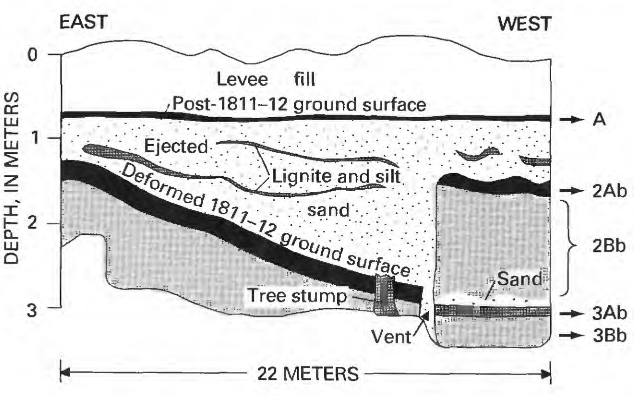

Figure 16 (above and facing column). Photograph and schematic diagram of site 2 along Ditch No. 12 near Manila, Ark. String grid in photograph indicates 1-m intervals. Note vertical exaggeration of schematic diagram. Labels along right side of schematic diagram refer to soil horizons. See text for discussion.

likely, the silt and lignite at the contacts represent a late-stage settling of the finer grained fraction of the vented material. Although the surface is disturbed, soil development on the upper surface of the extruded sand is minimal.

The weak soil development on the surface of the extruded sand is consistent with deposition during the 1811–12 earthquake sequence, and the absence of soil development or oxidation on the interval between sand layers is consistent with the interpretation that the layers are due to separate liquefaction episodes during the 1811–12 sequence. Hence, we observed no evidence in this and similar exposures along these ditches that favors a pre-1811–12 origin for the liquefaction features.

EXIT 4 DITCH

The Exit 4 ditch, which strikes in a southerly direction from its intersection with Interstate 55 about 2 km south of exit 4 (fig. 8), is a local farm-field drainage ditch (fig. 37) located within the Holocene Mississippi meander belt (fig. 38). Because it is in the Holocene meander belt, the surface has probably been stable for a shorter period of time. The large-scale aerial photograph in figure 39 shows numerous arcuate lineaments that trend across the ditch, and the intersection of one lineament with the ditch is marked as site 11.

The photograph and schematic diagram of site 11 (fig. 40) show that the arcuate trends are from sand extruded onto the surface, most likely because of seismically induced liquefaction. The extruded sand in this area forms arcuate lineaments because they follow the course of abandoned meander belt point-bar deposits. The source beds of the sand are likely shallowest above the abandoned point-bar deposits and, hence, are most likely to fail here during liquefaction.

Site 11, like many others and those documented previously, shows evidence of multiple episodes of liquefaction, but the lack of significant pedogenesis on the surface sand suggests a recent genesis for the deposits. Similarly, the contact between units S1 and S2 (fig. 40) is marked only by a concentration of silt, suggesting that the units were emplaced within a short time of each other. Here again, the evidence of liquefaction is consistent with an 1811–12 genesis.

DISCUSSION

Many of the exposures we examined show evidence of multiple episodes of liquefaction. The vented sand is commonly composed of distinct packets, each separated by a hiatus in deposition marked by concentrations of silt and lignite, occasional flare structures, or preservation of worm-hole casts (e.g., figs. 16, 17, 35, and 36). In all cases, the lack of soil development or oxidation at layer contacts indicates that the hiatuses were very brief, perhaps on the order of minutes or hours to months. Moreover, soil development on the surface of the extruded sand is invariably weak, generally characterized by a 1- to 2-cm-thick A horizon and virtually no B horizon, which indicates that the sand deposit is relatively young (e.g., figs. 17 and 28). The 1811–12 earthquake sequence consisted of four great earthquakes on three different days within a period of 3 months (table 1). The multiple episodes of liquefaction we interpret in the vented packages of sand are best explained to be the result of individual events of the 1811–12 earthquake sequence. Multiple episodes of liquefaction are commonly shown by cross-cutting relationships between intruded dikes and sills (e.g., fig. 20). The consistent lack of alteration, oxidation, or diagenesis between the different sets of dikes and sills argues for an 1811–12 genesis for all of these features. In summary, our search has revealed no evidence of liquefaction that cannot be best attributed to the 1811–12 earthquake sequence.

Our observations of liquefaction features centered principally on a late Wisconsin braided-stream terrace in the vicinity of Big Lake, Ark. Saucier (1977) estimated that the terrace was abandoned about 9,500 yr ago. Our radiocarbon dates at site 3 (fig. 8) and site 8 (fig. 31), each on samples collected adjacent to the contact between outwash sands and the overlying top stratum (which is interpreted to have developed since abandonment of the terrace), range from 10,380 to 11,100 radiocarbon yr B.P. These ages generally agree with Saucier's (1974) estimate of 9,500 yr B.P. Similarly, backswamp sedimentation in Big Lake, Ark., is estimated to have started more than 9,900 yr ago (Guccione, 1987) and more than 6,500 yr ago for a site farther east, near Belle Fountaine ditch (fig. 8). The apparent absence of older liquefaction features in the geologic record similar to those attributed to the 1811–12 earthquake supports an argument that similar liquefaction events have not occurred in approximately 10,000 yr prior to the 1811–12 sequence.

At this stage, we should place our observations in the context of prior geological and seismological efforts to estimate the expected recurrence interval of 1811–12 New Madrid-type earthquakes. The search for geological evidence bearing on the repeat time of 1811–12 earthquakes is not new. As early as 1971, Saucier (1977) examined the geological effects of the 1811–12 earthquakes and clearly recognized the potential value of geological studies of liquefaction features for predicting the recurrence interval of infrequent major earthquakes in the region. Saucier (1991) 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 1811–12 earthquakes. Moreover, based on archaeological age estimates, the inferred that the lack of evidence for liquefaction-inducing events prior to 1811–12 extended back 500 to 1,000 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.

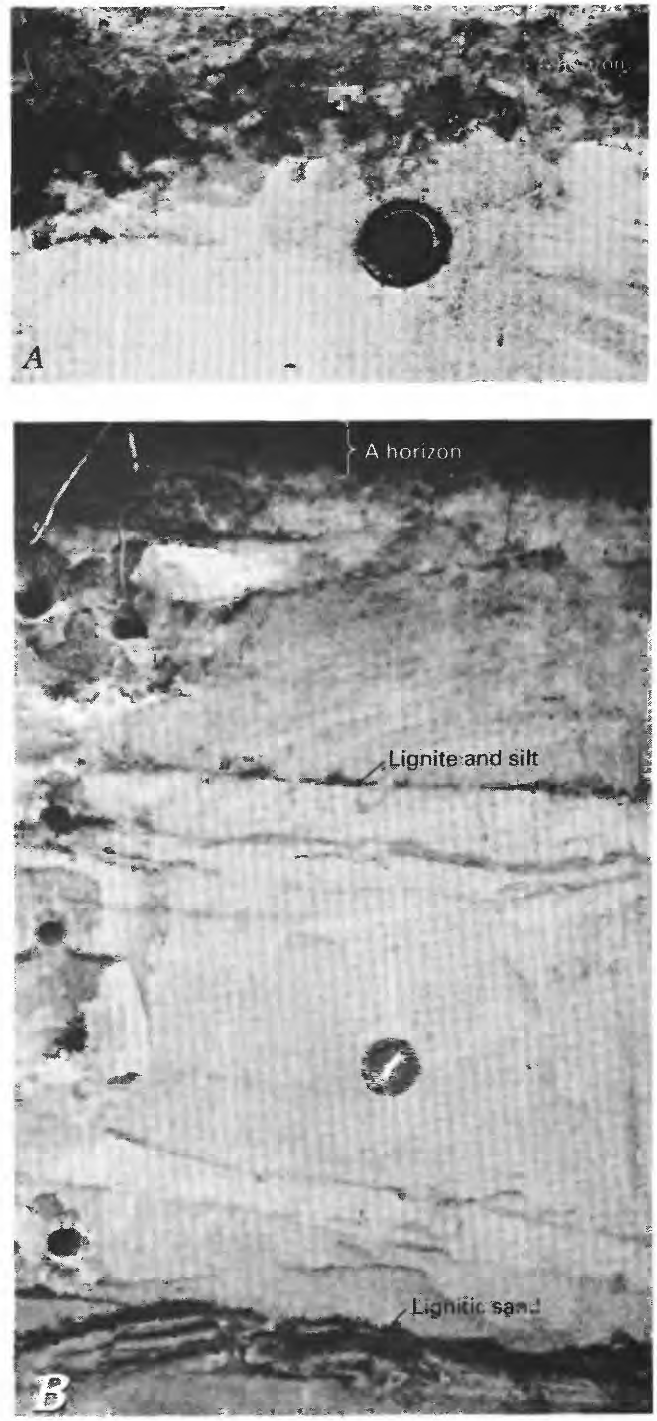

Figure 17 (facing column and above). *A*, Soil profile developed on the ejected sand at site 2 along Ditch No. 12 (see fig. 16) is characterized by a thin, black A horizon and a very weak B horizon. Although overlain by artificial levee fill, the abundant wormhole casts within the A horizon attest to the undisturbed nature of the surface of the ejected sand. *B*, The internal structure of the ejected sand (see fig. 16) is characterized by thin layers of silt and lignite that separate thicker units of sand. Sampling of the ejected sand for paleomagnetic signature caused small holes evident in this photograph. The A horizon shown in *A* is also shown at the top of *B*. See text for further discussion. *C*, Photograph of area shown in part of schematic diagram (in fig. 16) that includes sand vent and section to the west of vent. String grid in photograph indicates 1-m intervals.

The first reported geologic evidence for paleoearthquakes and, hence, an estimate of recurrence intervals for large New Madrid earthquakes is from trenching of the Reelfoot scarp (Russ and others, 1978; Russ, 1979). The fault strikes northwesterly from the southwestern end of Reelfoot Lake to the Mississippi River (fig. 6). It is perhaps the only feature in the region that shows unambiguous evidence of Holocene movement. The oldest deposits in the trench are about 2,000 yr old. Structural, stratigraphic, and geomorphic data revealed evidence of two episodes of fault movement prior to 1811–12. Combining the geologic observations with the historical record, Russ (1979) interpreted that there may have been three earthquakes of sufficient size to produce liquefaction during the last 2,000 yr and, on that basis, suggested a recurrence time of 600 yr or less for such events in the region. At first glance, Russ' (1979) observations conflict with the 10,000-yr-long absence of liquefaction events prior to 1811–12, as 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 1811–12 earthquakes. Moreover, earthquakes as small as m_b = 6.2 can produce liquefaction at distances of 15 to 20 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 1811–12-type earthquakes but, rather, the occurrence of smaller earthquakes in the northern part of the New Madrid seismic zone.

Recently, Saucier (1991) reported stratigraphic evidence of two liquefaction events during the past 1,300 yr at an archaeological site about 30 km northwest of Reelfoot Lake. Noting that liquefaction was induced by a nearby $m_b \cong 6.2$ earthquake in 1895 and also by the 1811 and 1812 earthquakes, (treating the 1811–12 sequence as a single

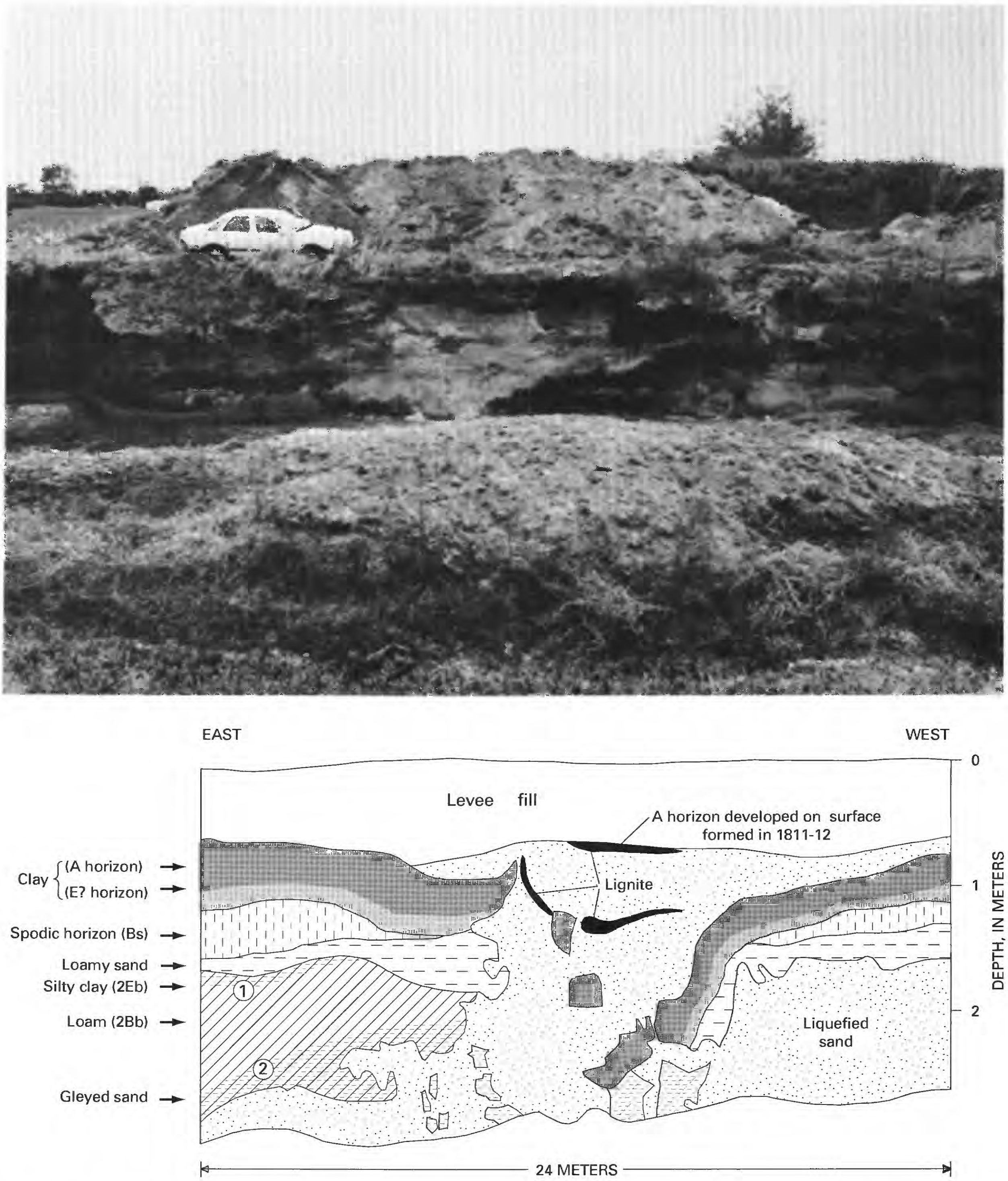

Figure 18. Photograph and schematic diagram of site 3 along Ditch No. 12 near Manila, Ark. Circled numbers 1 and 2 indicate sites of two wood samples dated at 5,090±60 and 11,100±100 radiocarbon yr B.P., respectively. String grid in photograph indicates 1-m intervals. Note vertical exaggeration of schematic diagram. See text for further discussion.

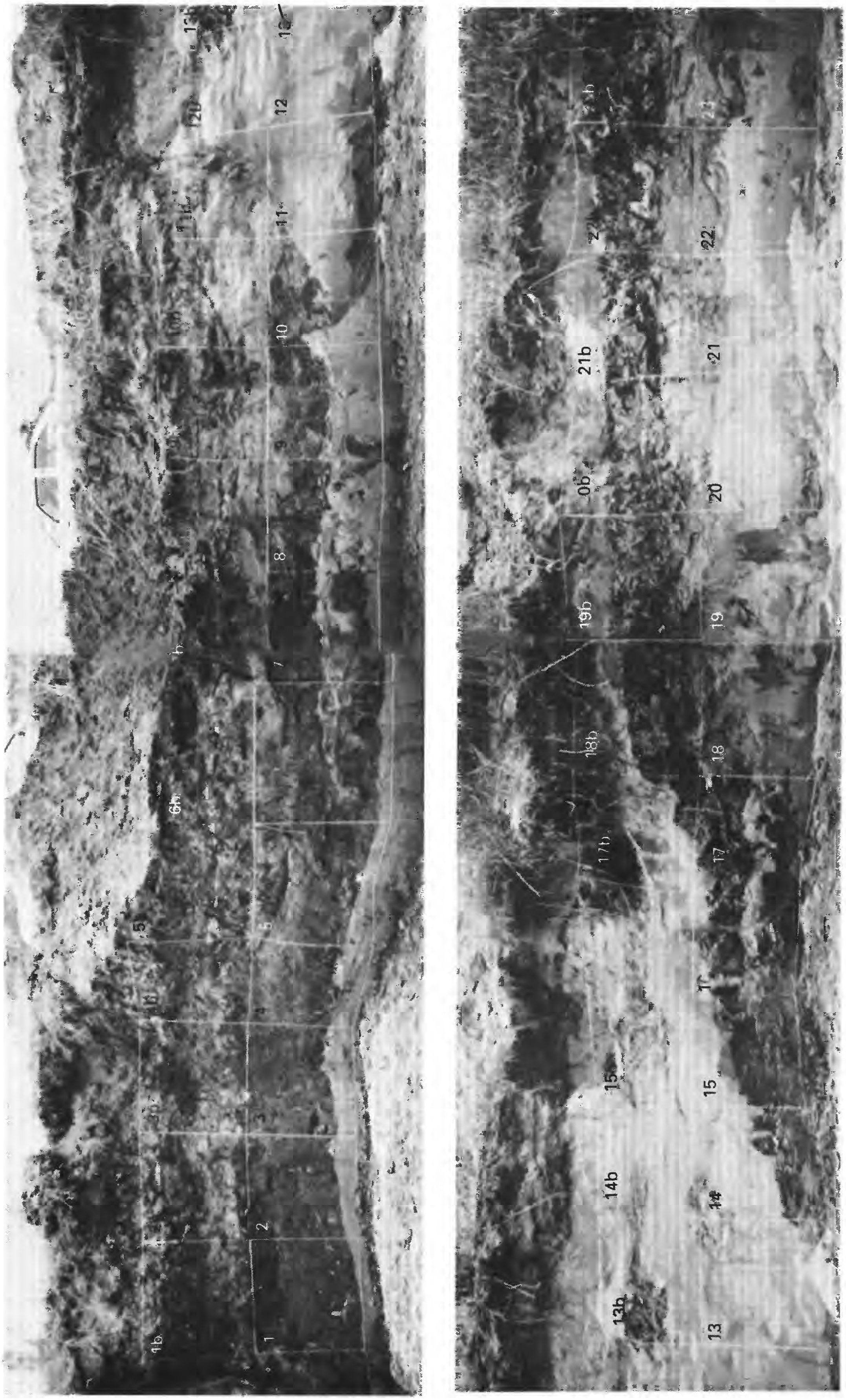

Figure 19. Large-scale photomosaic of figure 18. String grid in photograph indicates 1-m intervals; outcrop is labeled from 1 to 23 from east (left) to west (right) along the exposure. Wood recovered for radiocarbon dating was taken from panel 2. The pervasive nature of the flow accompanying liquefaction of the underlying sands is evidenced by the diapiric flow structures, the presence of numerous clasts of top stratum within the liquefied sands, and the accompanying break in the top stratum.

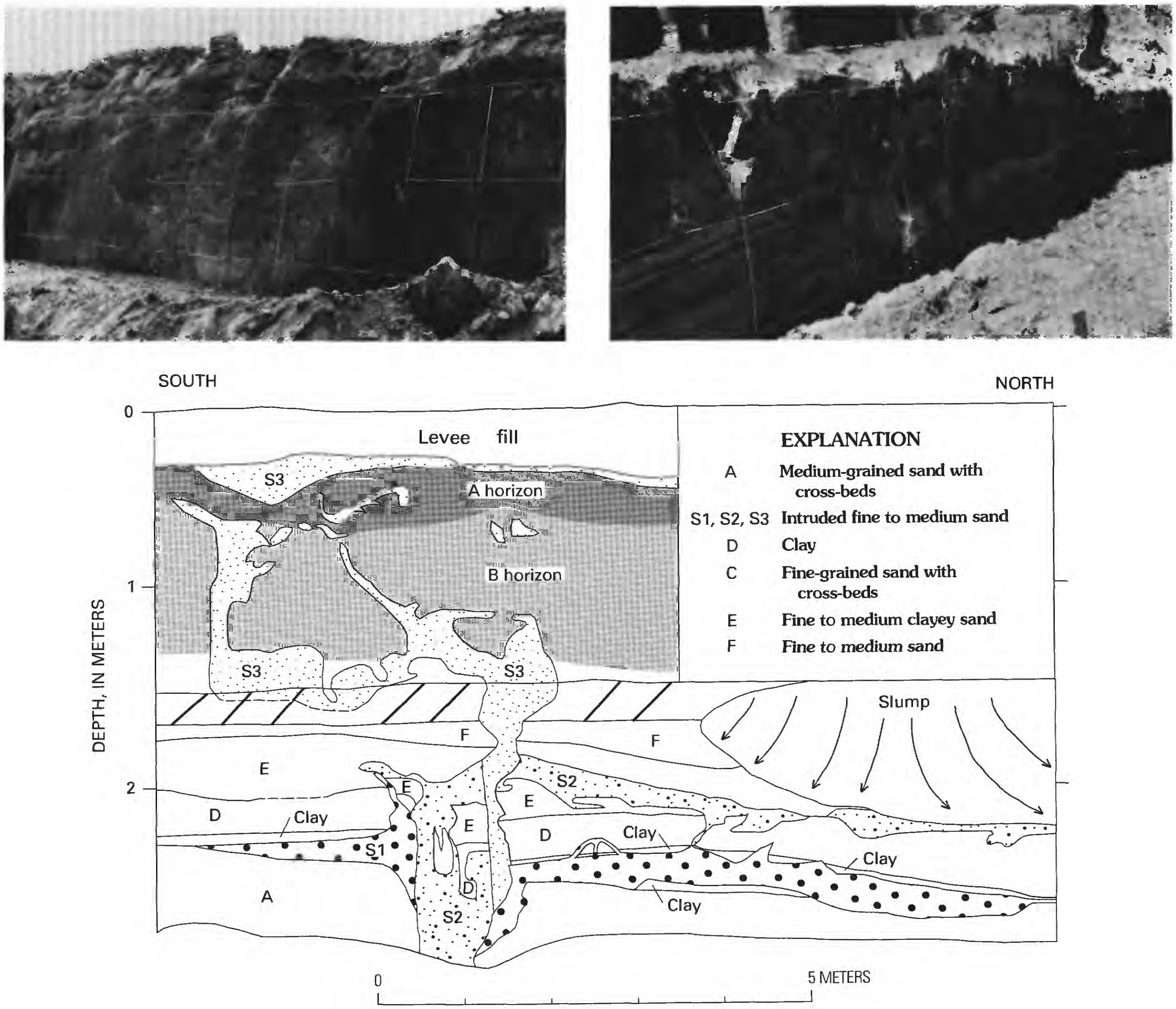

Figure 20. Photographs and schematic diagram of sand dikes and sills in Buffalo Creek Ditch, about 150 m south of the Highway 77 bridge crossing between Leachville and Manila, Ark. Location is site 4 in figure 12. Note vertical exaggeration of schematic diagram. Exposure consists of two faces separated by a step, each gridded at 1-m intervals, except adjacent to central sand dike (S2) where grid is 0.5 m.

earthquake), and assuming uniformly spaced intervals, Saucier estimated an average recurrence rate of 468 yr for liquefaction-inducing events near New Madrid, Mo. Like Russ (1979), the scale of paleoliquefaction features Saucier observed were small compared to those reported in 1811–12. Hence, as stated by Saucier (1991), any inference of the repeat time of great New Madrid earthquakes from these observations remains equivocal, and, more likely, the paleoliquefaction features represent the recurrence of smaller magnitude events in the New Madrid seismic zone.

Earthquake-frequency statistics have been the basis for estimating the average recurrence interval of 1811–12-type earthquakes. The most recent estimate using earthquake-frequency statistics yields a recurrence interval of $M \geq 8$ earthquakes of 550 to 1,100 yr (Johnston and Nava, 1985). In contrast, the apparent lack of a widespread paleoliquefaction event in the geologic record may imply a repeat time of 5,000 to 10,000 yr or more for the occurrence of 1811–12-type earthquakes (fig. 41). Johnston and Nava's (1985) estimate is based on the extrapolation of about 10 yr of instrumental data and historical records for the period after 1811. This represents a relatively small part of the expected repeat time. Furthermore, an assumption of stationarity is implicit to the extrapolation of earthquake-frequency statistics to determine the repeat time of larger, less frequent earthquakes.

Figure 21. This large-scale photomosaic of a part of the lower photograph in figure 20 shows the sharp cross-cutting relationships associated with the injection of sand dikes and sills. The location is site 4 along Buffalo Creek ditch (see fig. 12) and encompasses the lower and central part of the schematic diagram shown in figure 20. The wispy character of cross-bedding in units A and D (see fig. 20) may result from incipient liquefaction. Horizontal strings indicate 1-m intervals, and vertical strings indicate 1-m or 2-m intervals.

The discrepancy between our observations and the repeat-time estimates based on seismicity may simply show that the historical record is too short to accurately portray the behavior of faults in the region. In addition, 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 are commonly non-linear throughout the entire magnitude range for all fault zones (e.g., Youngs and Coppersmith, 1985). Our observations in the New Madrid region, if correct, would imply that the earthquake-frequency curve should truncate sharply at the largest expected magnitude (fig. 41).

The possibility exists that pre-1811–12 events may have occurred without producing liquefaction if water-table conditions were unfavorable. Of course, such a possibility would obviate the implications of our work. However, the

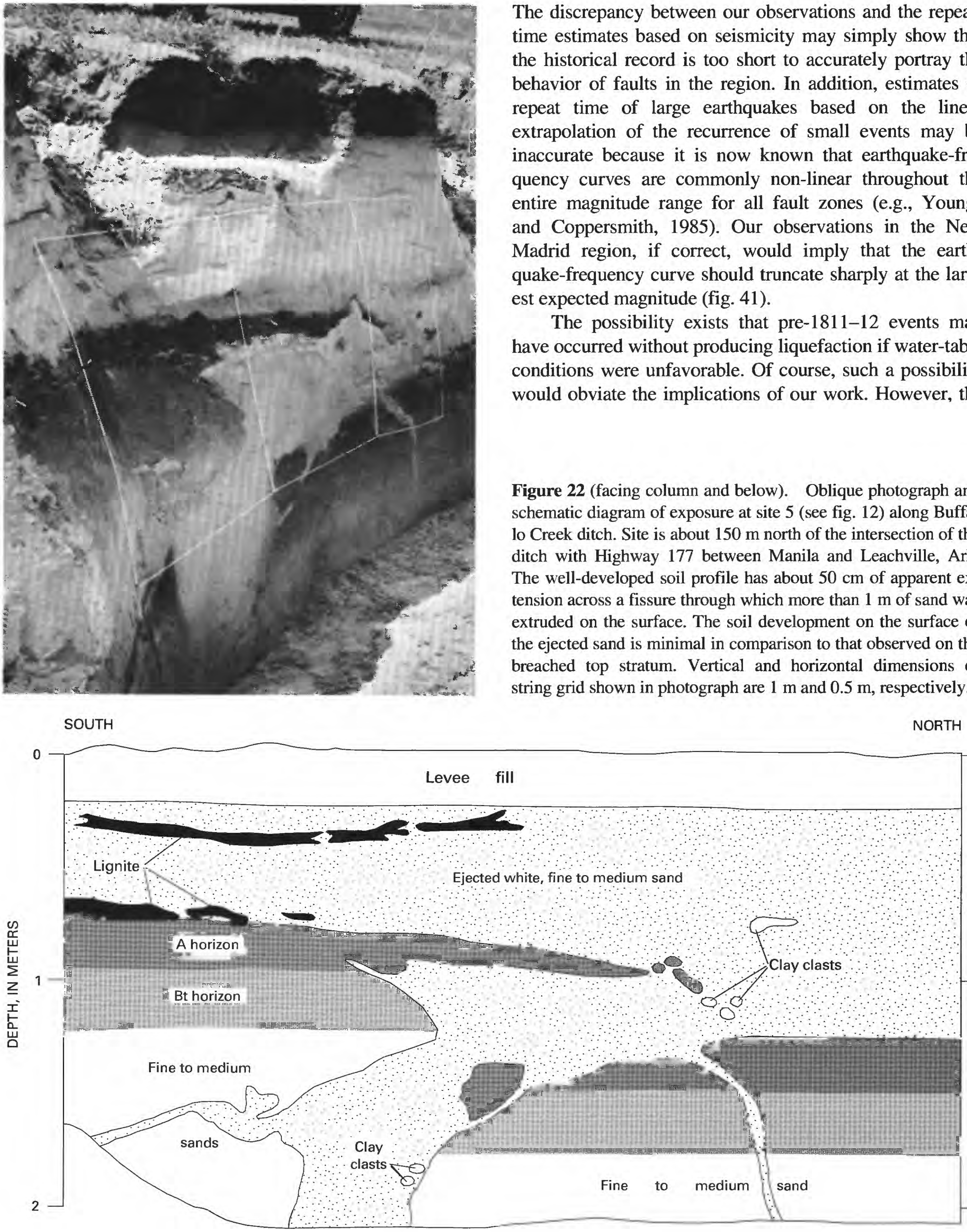

Figure 22 (facing column and below). Oblique photograph and schematic diagram of exposure at site 5 (see fig. 12) along Buffalo Creek ditch. Site is about 150 m north of the intersection of the ditch with Highway 177 between Manila and Leachville, Ark. The well-developed soil profile has about 50 cm of apparent extension across a fissure through which more than 1 m of sand was extruded on the surface. The soil development on the surface of the ejected sand is minimal in comparison to that observed on the breached top stratum. Vertical and horizontal dimensions of string grid shown in photograph are 1 m and 0.5 m, respectively.

Figure 23. The portion of ditch wall logged in figure 22 is at lower left of upper photograph. Extruded sand is white, in contrast to the dark A horizon on the top stratum. The buried soil cuts from left to right across the photograph and outcrops at the 1-m-long stake emplaced vertically along the face of the ditch. Renewed growth along the ditch wall is most rapid where the organic-rich soil crops out. The line of vegetation between the stake and the telephone pole marks the base of the extruded sand, which is as much as 2 m thick and extends about 30 to 40 m along the strike of the ditch. The lower photograph shows approximately the same view of the site, taken 4 months subsequent to logging the exposure. Rapid revegetation and erosion quickly degrades the exposures provided by the reexcavations of the Corps of Engineers.

possibility that such conditions existed in the past 10,000 yr should be tempered by pollen data of core in the Big Lake area that indicates that the region has supported backswamp vegetation throughout the Holocene (Guccione, 1987). Furthermore, even during the record low stages of the Mississippi River, which occurred during the drought period of 1988, the water table remained relatively high, as evidenced by persistent flow in ditches that was maintained by springs along ditch edges. Thus, it seems reasonable that if an 1811–12-sized earthquake occurred during the last 5,000 to 10,000 yr, it would have induced liquefaction that would be recorded in the geologic record.

CONCLUSIONS

Excavations by the U.S. Army Corps of Engineers provided an opportunity to examine the subsurface characteristics of liquefaction over a significant area of the 1811–12 meizoseismal zone. Deformation due to 1811–12 liquefaction is pervasive throughout the region. In contrast, we observed in the geologic record no evidence for prehistoric liquefaction similar in character or extent to that which occurred in 1811–12. Prior studies and radiocarbon age limits that we have placed on specific exposures indicate that the ditch exposures generally encompass about 5,000 to 10,000 yr of geologic record. Although lack of evidence provides less than a desirable basis for interpretation, we interpret from our observations, and our perception that similarly pervasive liquefaction would have accompanied similar prehistoric events, that earthquakes of similar size to the great 1811–12 New Madrid earthquakes have not occurred during 5,000 to 10,000 yr or more prior to 1811–12.

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FIGURES 24–41

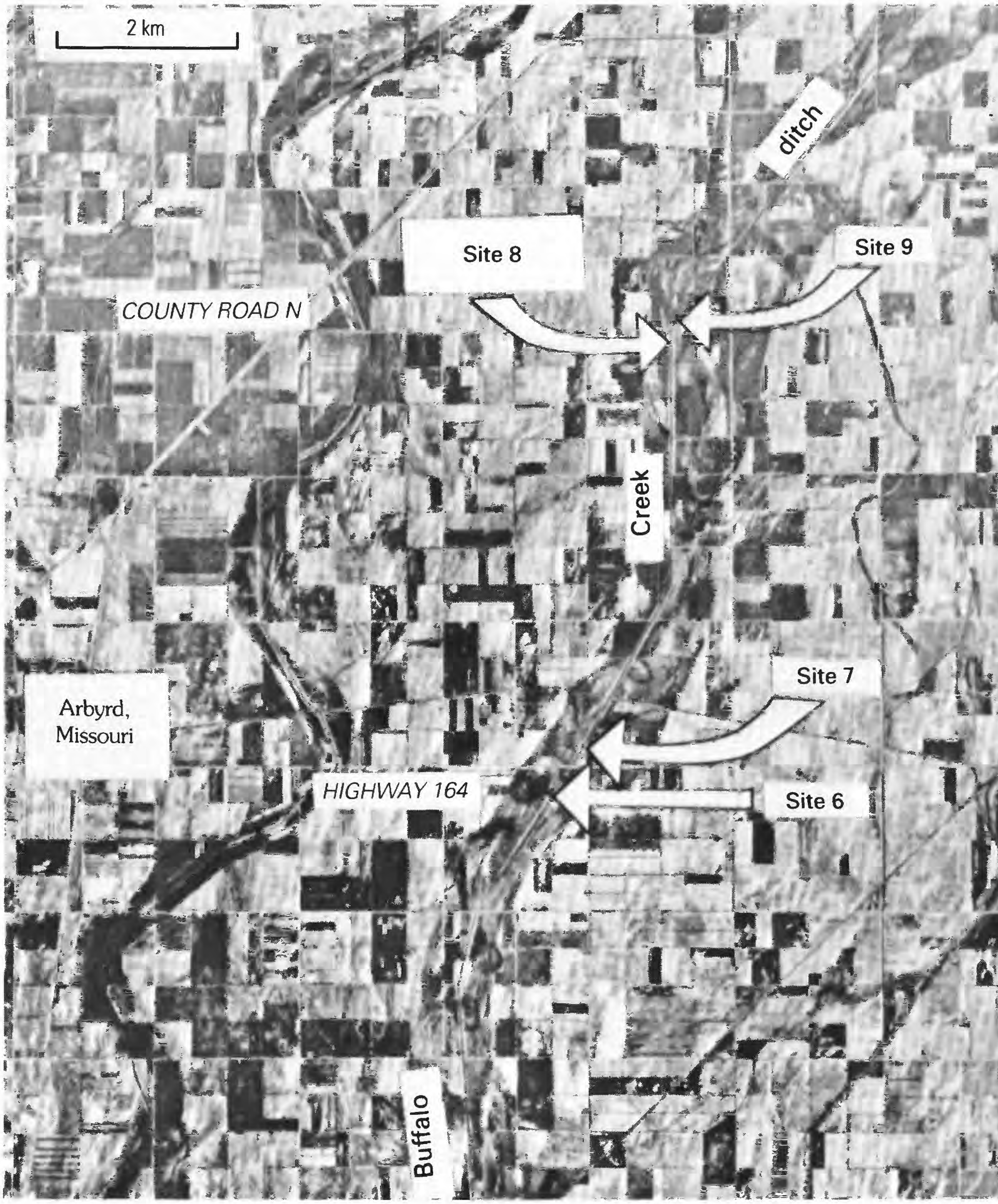


Figure 24. Arbyrd, Missouri, orthophotoquad showing Buffalo Creek ditch following the course of a relict channel on an abandoned braided-stream terrace of late Wisconsin age. Sites 6 through 9 are discussed in the text. North is up on photograph.

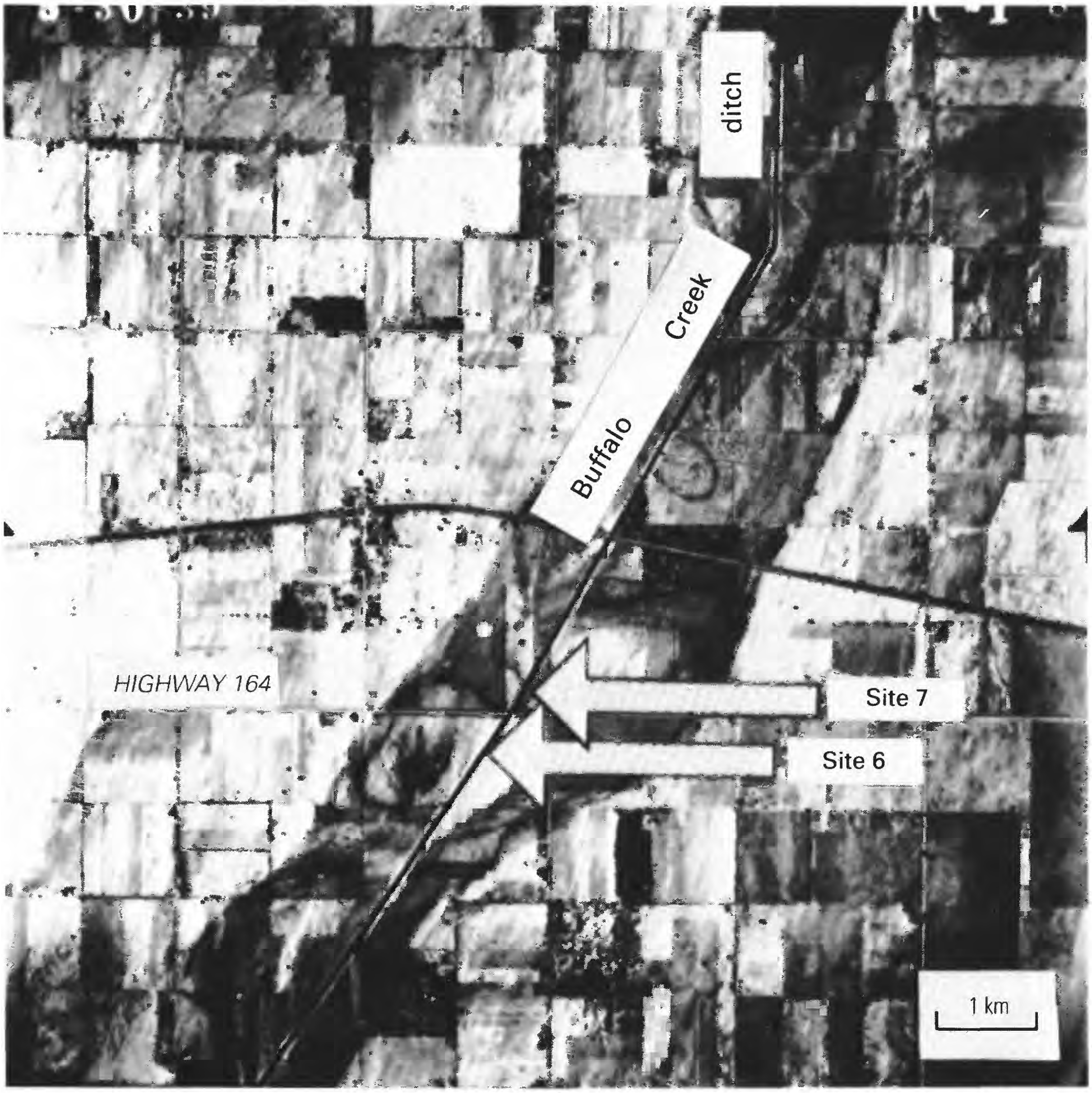


Figure 25. Aerial photograph showing geomorphology in the vicinity of sites 6 and 7 along Buffalo Creek ditch, which follows a relict stream channel of late Wisconsin age. Sites 6 and 7 are discussed in text. North is up on photograph.

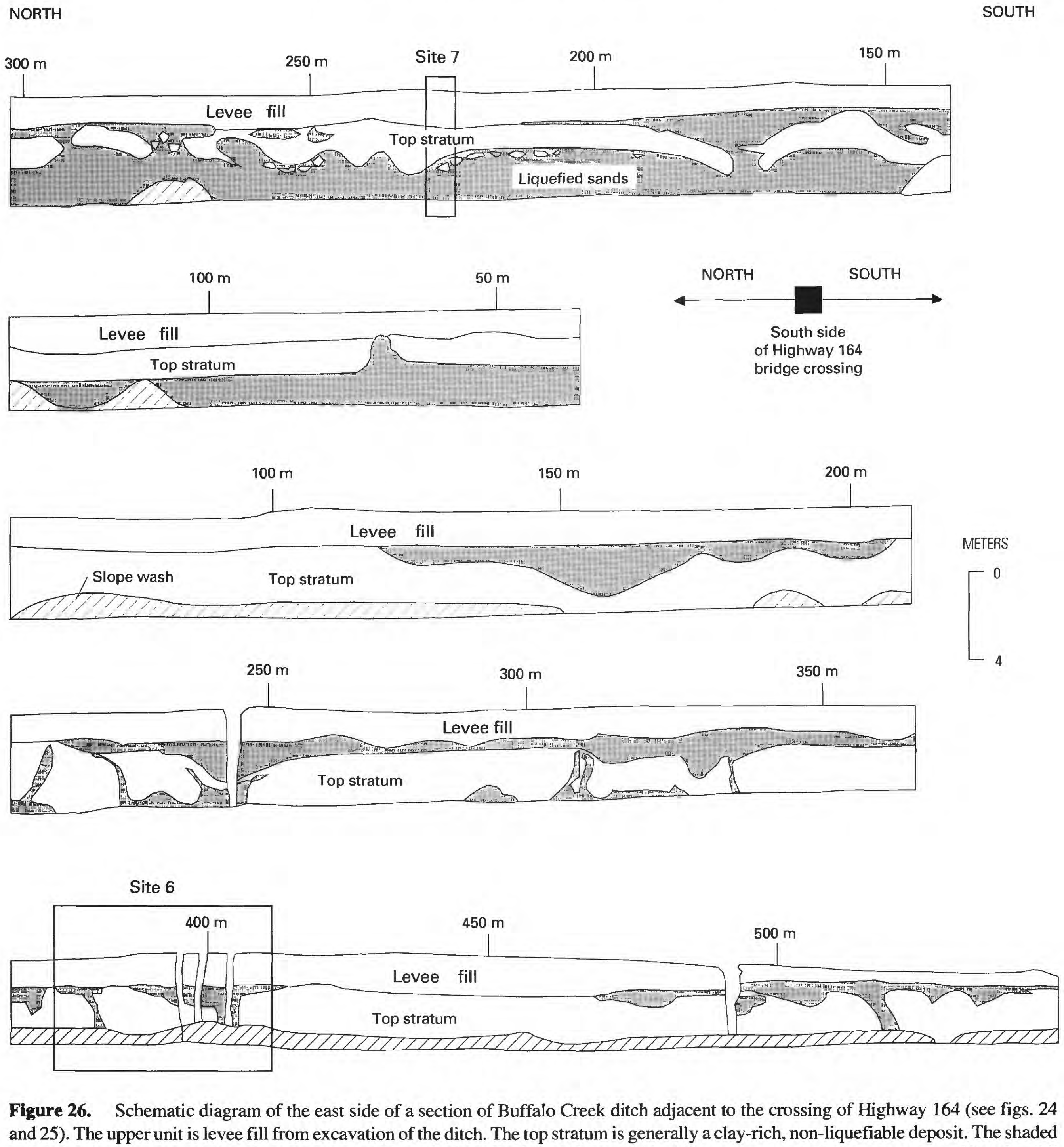


Figure 26. Schematic diagram of the east side of a section of Buffalo Creek ditch adjacent to the crossing of Highway 164 (see figs. 24 and 25). The upper unit is levee fill from excavation of the ditch. The top stratum is generally a clay-rich, non-liquefiable deposit. The shaded unit is fine to coarse sand that shows evidence of liquefaction. Evidence of original bedding is rare beneath the top stratum. Sites 6 and 7 were documented in greater detail and are marked by the solid boxes. Horizontal distances are measured in meters with respect to the south and north sides of the Highway 164 bridge crossing, respectively. Note vertical exaggeration.

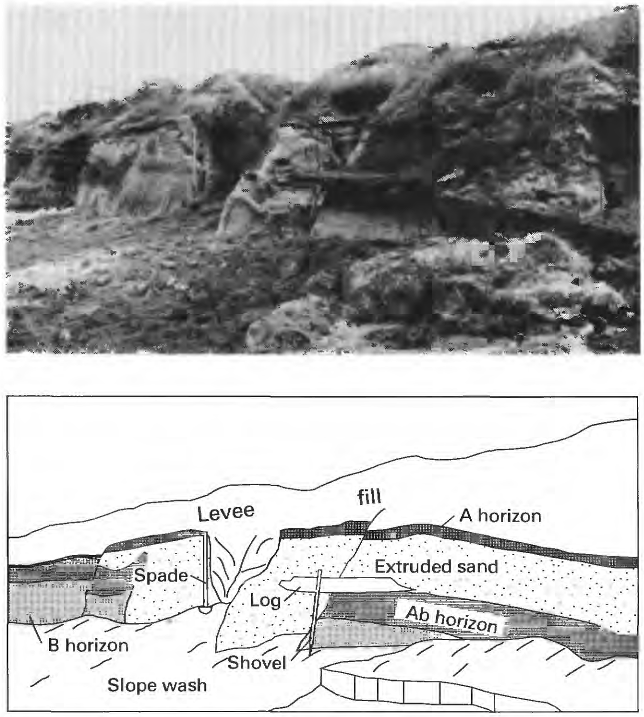


Figure 27. Photograph and schematic diagram of major breach in top stratum at site 6 along Buffalo Creek ditch. The buried log rests on the A horizon developed on the surface at the time of the 1811–12 earthquakes. The Ab soil horizon is a dark-gray, clay loam that averages 20 to 25 cm in thickness and grades downward into the B horizon, which is a light yellowish brown, very fine, sandy loam that extends below the exposure. The A horizon on the extruded sand is an approximately 1-cm-thick, dark-brown, silty clay loam. The sharp color and compositional contrast of this A horizon with underlying sand may be accentuated by the settling out of finer grained clays subsequent to the extrusion of the sands. The extruded sands are light gray to brownish yellow in color, medium to coarse grained, generally devoid of a silt or clay fraction, and contain abundant small clay clasts. Shovel and spade provide scale. A larger scale diagram of the portion of the photograph adjacent to the spade is shown in figure 28.

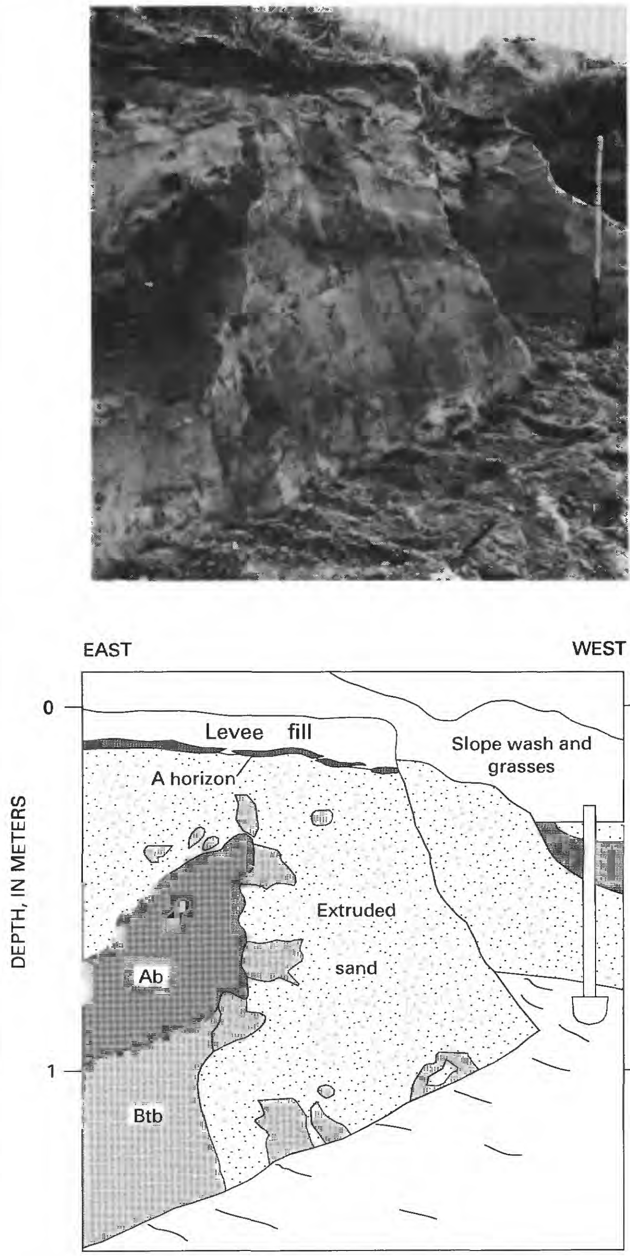
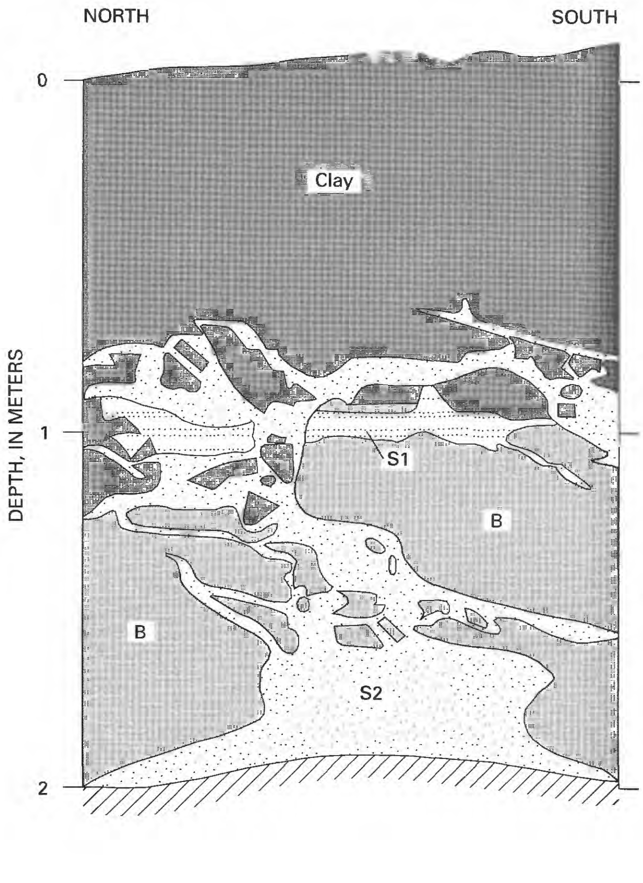


Figure 28. Photograph and schematic diagram of the portion of site 6 adjacent to the spade shown in figure 27. This figure further illustrates the character of soil development on the top stratum and extruded sand. View is to the south.


NORTH
SOUTH
0
1
2
DEPTH, IN METERS
Clay
S1
B
B
S2

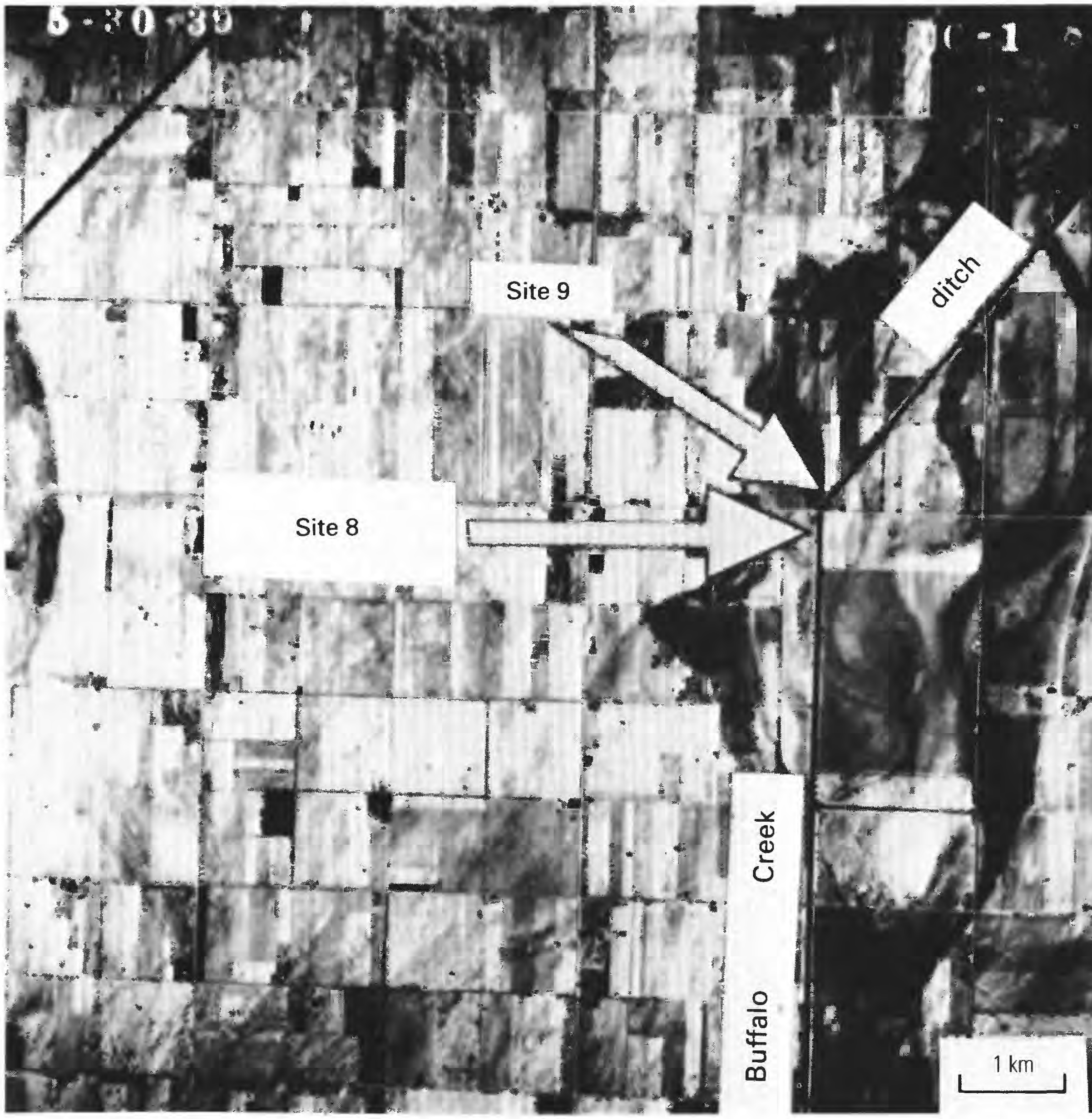


Figure 30. Aerial photograph of Buffalo Creek ditch showing sites 8 and 9, which are south and north of Missouri County Road N bridge crossing, respectively. The articulated remains of a stout-legged llama (*Paleolama mirifica*) were unearthed at site 8. Both sites are located in a relict channel on an abandoned late Wisconsin braided-stream terrace. North is up on photograph.

Figure 29 (facing page). Photographs and schematic diagram of site 6 along Buffalo Creek ditch showing the erosion at the base of the top stratum due to the liquefaction and flow of underlying sands, which most likely took place during the 1811–12 earthquakes. Lower photograph and schematic diagram show central part of upper photograph. See text for discussion.

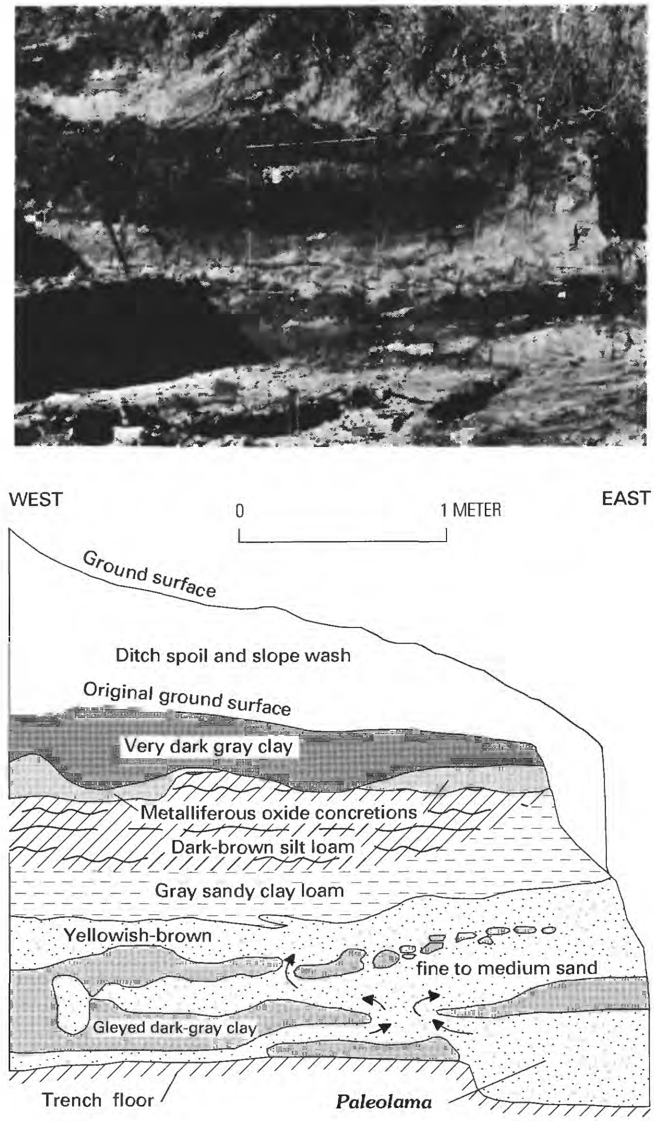


Figure 31. Photograph and schematic diagram of site 8, Buffalo Creek ditch. A 1-m grid, shown on the photograph, shows the location of the schematic diagram. Small survey flags at base of excavation mark the location of skeletal remains of a *Paleolama mirifica*. A radiocarbon date places the age of 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.

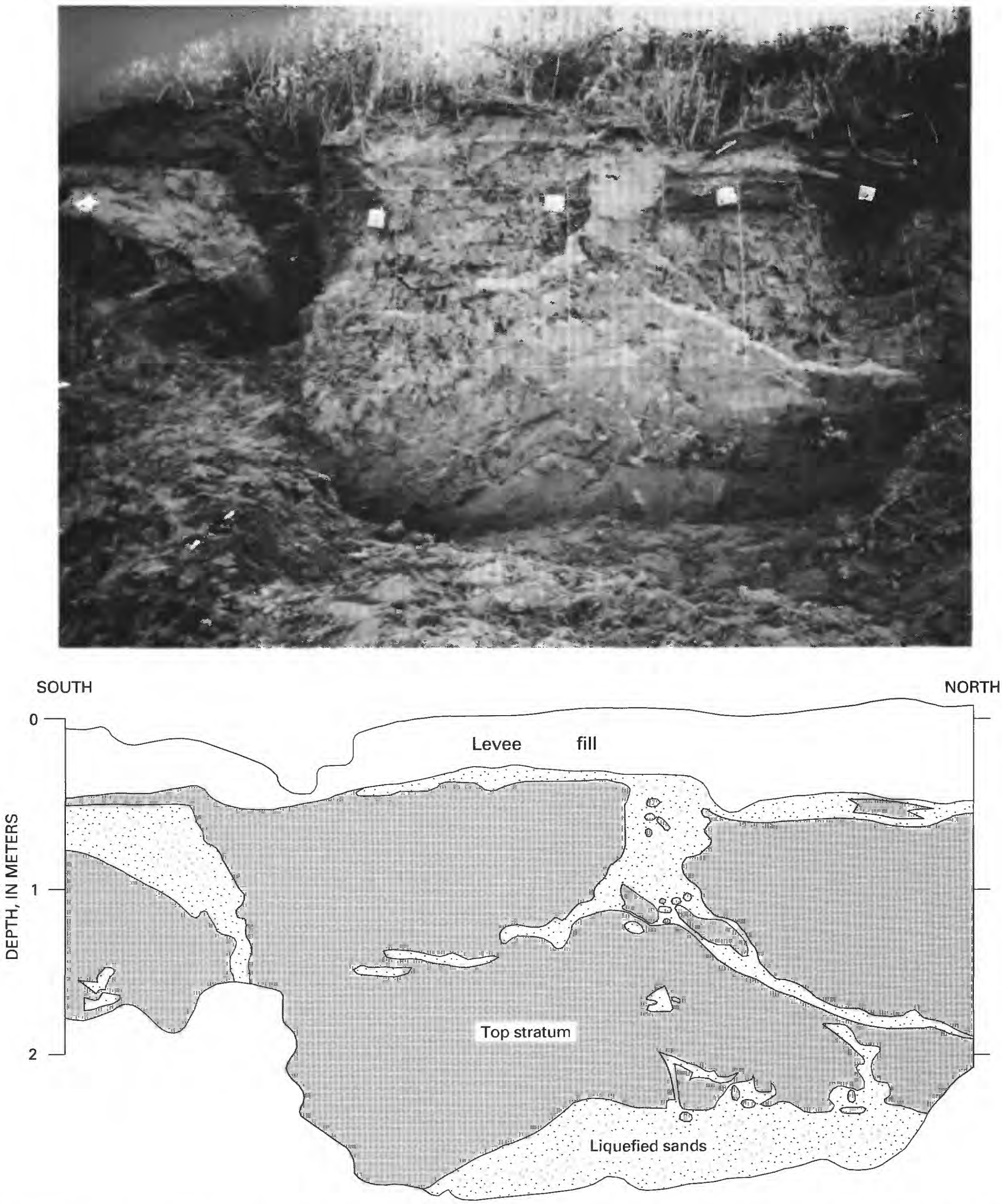


Figure 32. Photograph and schematic diagram of site 9 showing breach of clay loam top stratum by small dikes along Buffalo Creek ditch near Missouri County Road N. String grid in photograph indicates 1-m intervals.

Figure 33. Reexcavation of the Stateline and Bell Fountaine ditches produced about 5 m of vertical exposure, although sides of the ditches had a relatively shallow slope. The drag line in the distance provides a measure of scale, and the width of the ditch prior to reexcavation is visible in the distance.

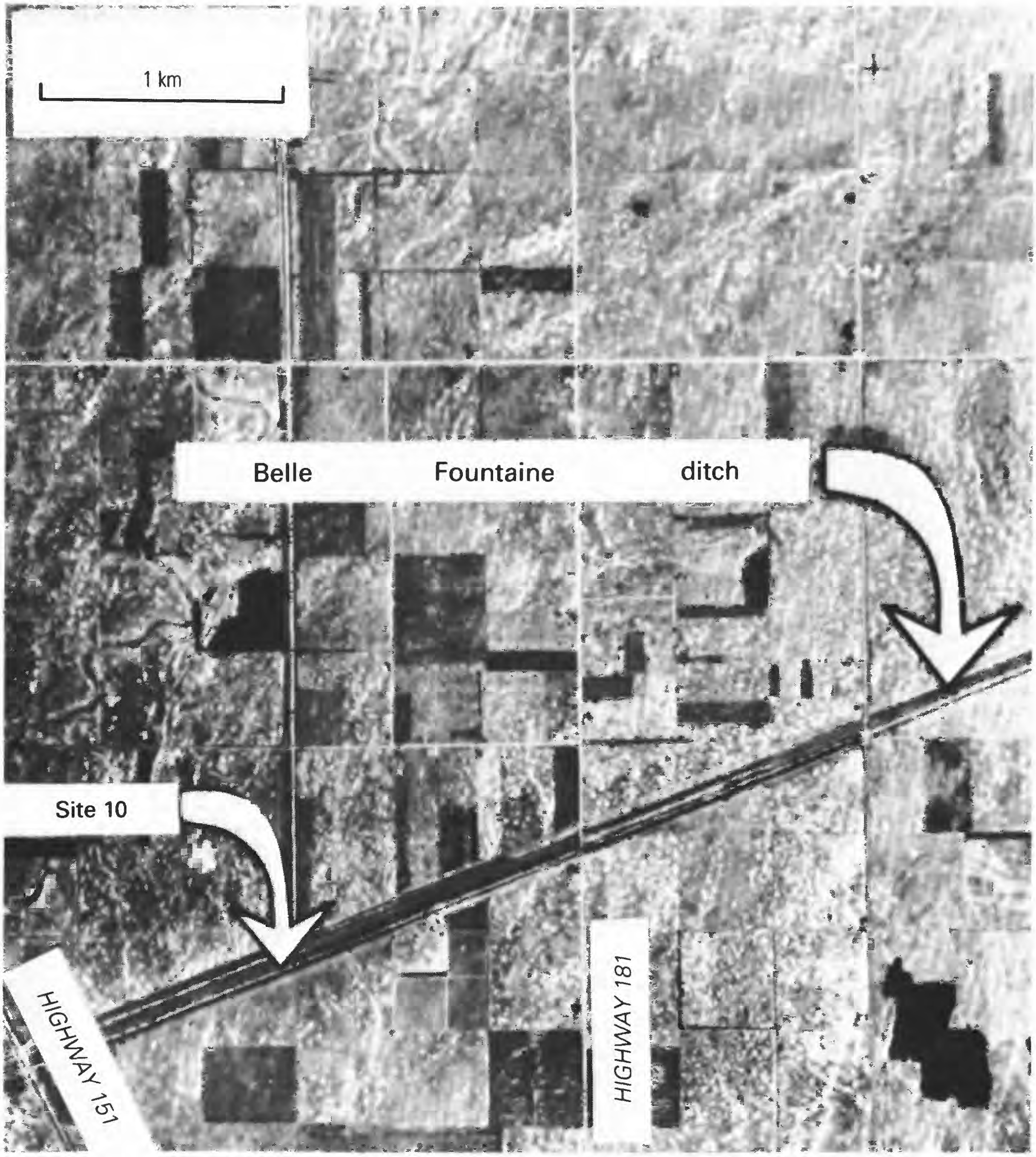


Figure 34. Portion of the Denton, Missouri, orthophotoquad showing site 10 along Belle Fountaine ditch surrounded by numerous sand blows in the adjacent fields. North is up on photograph.

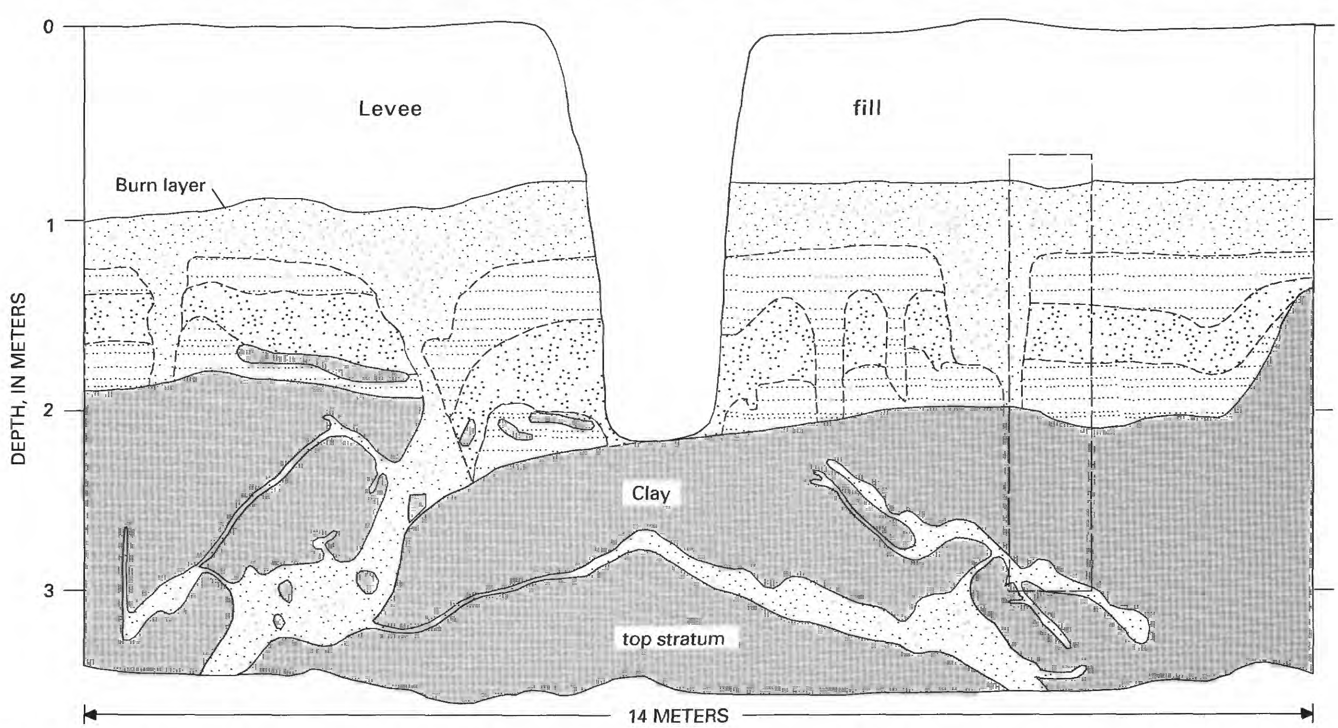


Figure 35. Photograph and schematic diagram of exposure at site 10, Belle Fountaine ditch. Sand vented onto the surface through dikes in the clay top stratum form a layer about 1 m thick. Internal contacts (dashed) within the ejected, very fine to fine sands (dotted and stippled) indicate four distinct episodes of venting, all of which are most likely due to the 1811–12 earthquake sequence. The dashed box is the location of the larger scale photograph in figure 36 that shows details of the internal stratigraphy of vented sand. String grid in photograph indicates 1-m intervals. See text for further discussion.

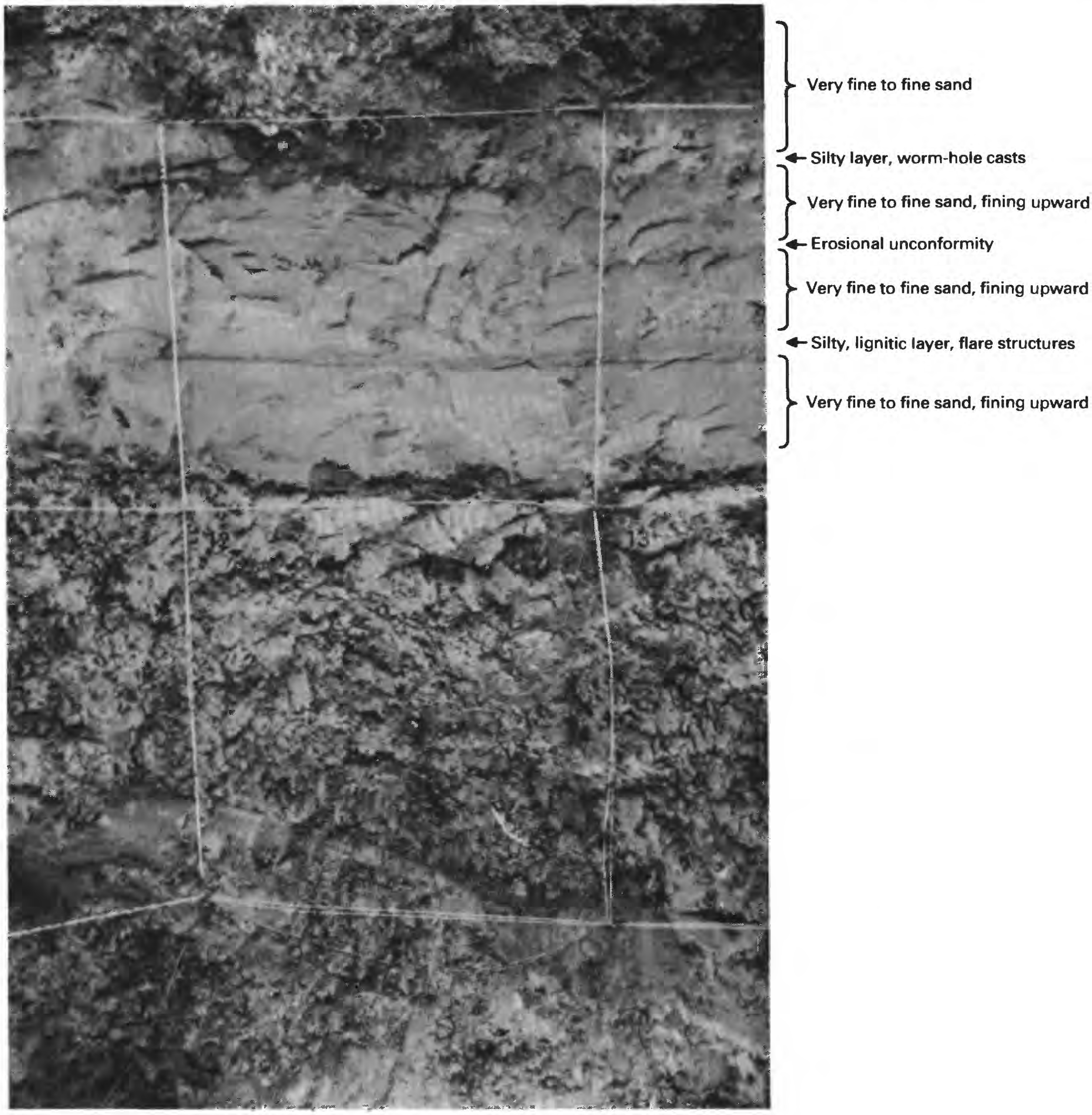


Figure 36. Photograph of part of exposure shown in figure 35. Four distinct layers of yellowish-brown sand are visible. Contacts between the sand layers are marked by a concentration of silt and lignite, abrupt changes in grain size, and the presence of flare structures and worm casts. The three lower packages show fining-upward sequences. The contact between the levee fill and sand has been disturbed, but pedogenesis appears minimal at the uppermost contact of the sand. The contacts between the sand packages are interpreted to reflect brief hiatuses between separate episodes of venting resulting, possibly, from the earthquakes of the 1811–12 sequence. String grid in photograph indicates 1-m intervals.

Figure 37. View to the northwest along the Exit 4 ditch in southeastern Missouri. Car at left edge of view is on Interstate 55. Site 11 is the excavation behind the person standing in the ditch.

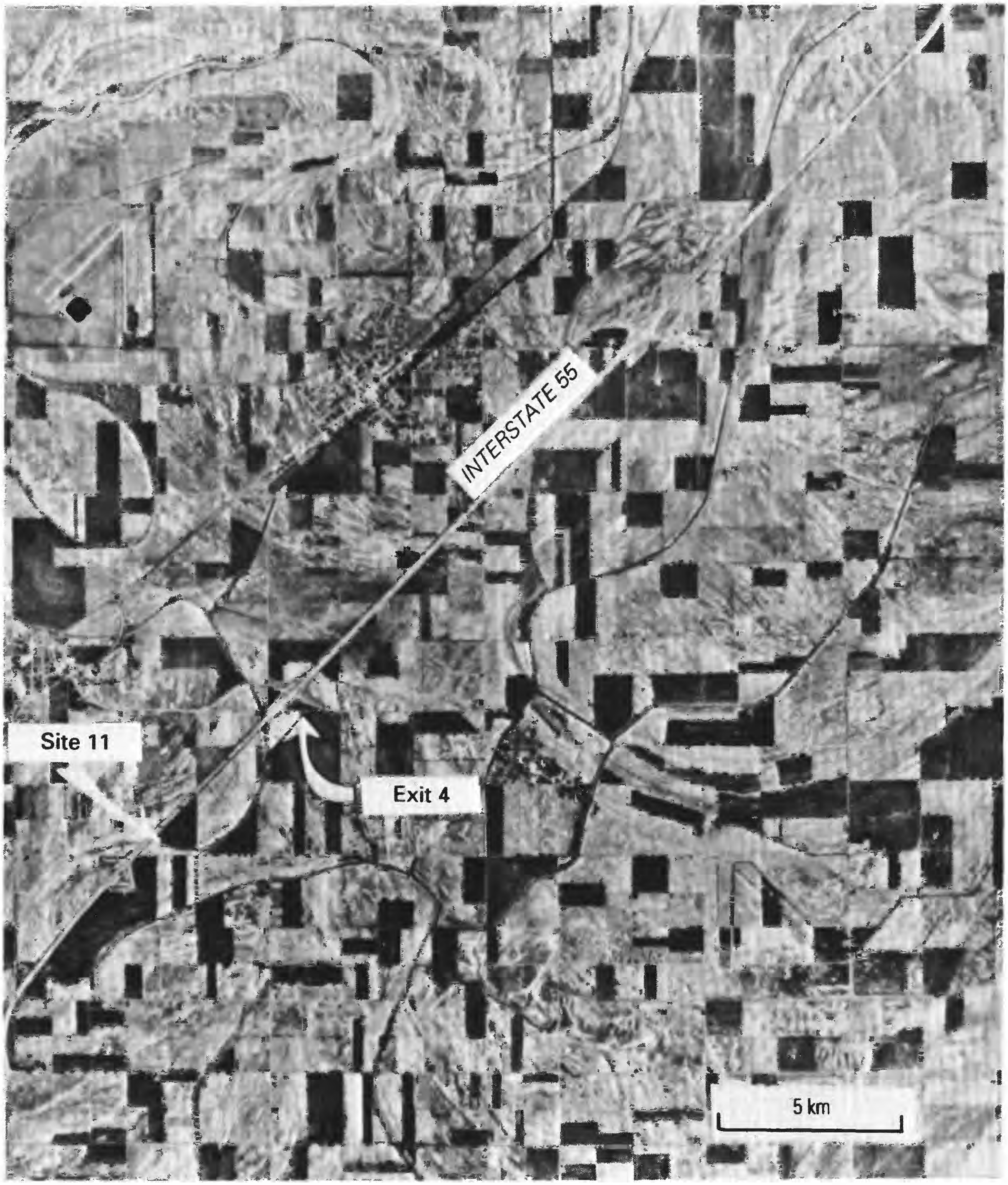


Figure 38. Portion of Steele, Missouri, orthophotoquad showing location of Exit 4 ditch and numerous abandoned meander scars of the Mississippi River system. Holland, Mo., is located directly above the site 11 label. North is up on photograph.

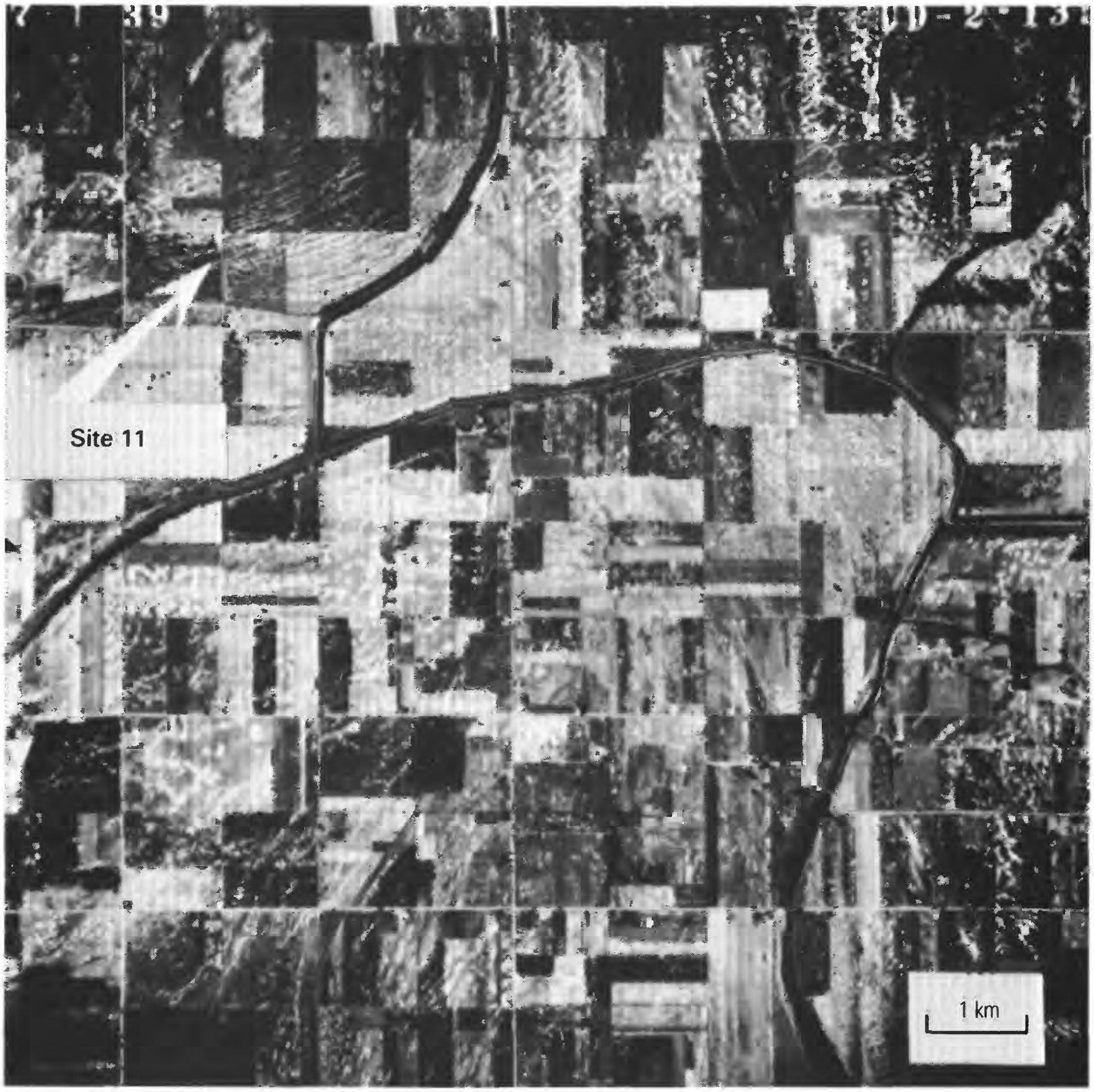


Figure 39. Aerial photograph showing location of site 11 along Exit 4 ditch with sharp white lineations caused by liquefaction and extrusion of sand along trend of abandoned point-bar deposits.

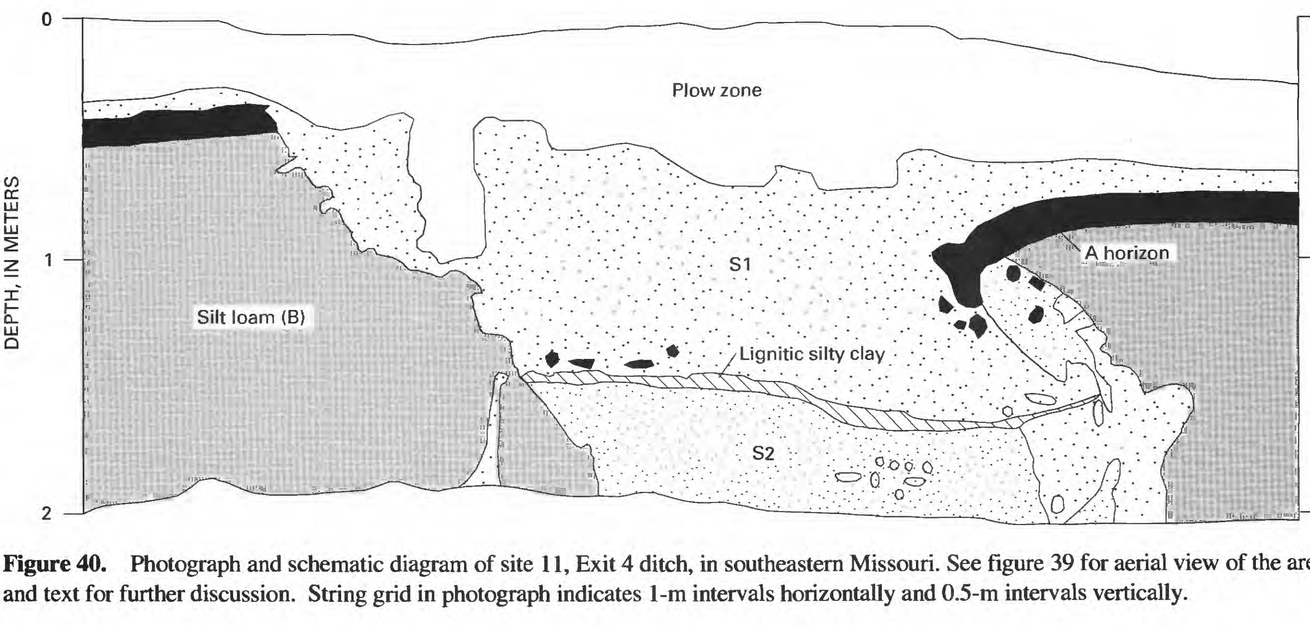


Figure 40. Photograph and schematic diagram of site 11, Exit 4 ditch, in southeastern Missouri. See figure 39 for aerial view of the area and text for further discussion. String grid in photograph indicates 1-m intervals horizontally and 0.5-m intervals vertically.

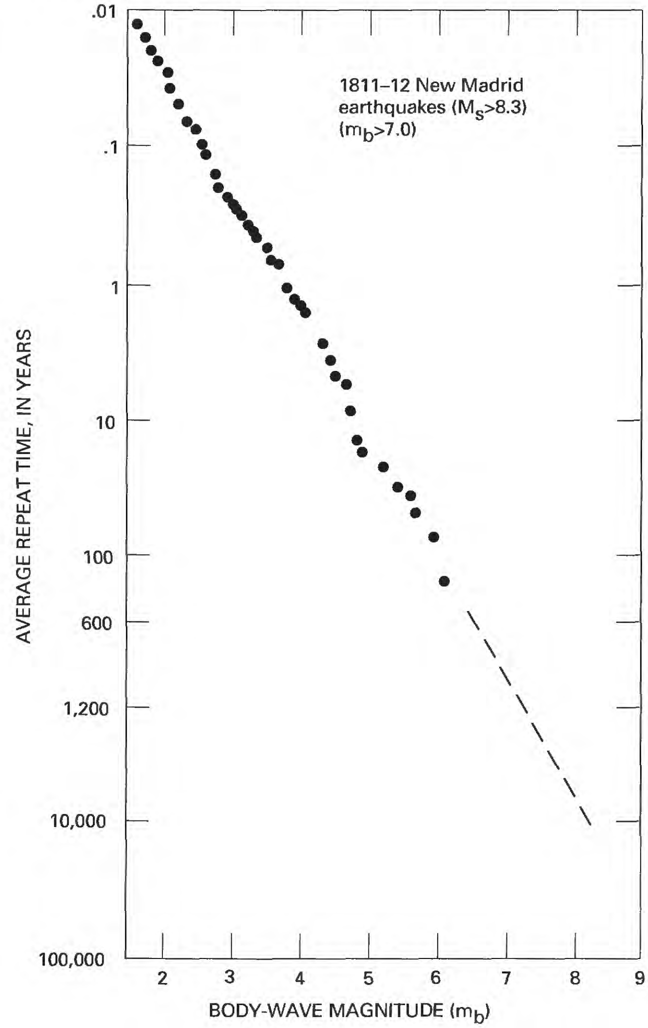


Figure 41. Average repeat time of earthquakes of size greater than or equal to a given body-wave magnitude (m_b, solid dots) for the New Madrid seismic zone (adapted from Johnston and Nava, 1985). The largest earthquake reported during the period since 1811–12 is $m_b = 6.2$. Extrapolation (dashed line) of earthquake statistics covering the period since 1811–12 implies a 550- to 1,100-yr repeat time for 1811–12-type earthquakes ($M_s > 8.3$). The lack of geologic evidence for widespread paleoliquefaction may reflect a significantly longer repeat time, on the order of 5,000 to 10,000 yr or more, for such events in the region.

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