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PALEOSEISMIC STUDIES OF THE BOOTHEEL LINEAMENT, SOUTHEASTERN MISSOURI, AND THE CRITTENDEN COUNTY FAULT ZONE, NORTHEASTERN ARKANSAS, NEW MADRID SEISMIC ZONE, CENTRAL UNITED STATES

By

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INTRODUCTION

The New Madrid seismic zone (NMSZ) is the most seismically active region in North America east of the Rocky Mountains and, in the winter of 1811-1812, it was the site of some of the largest historical intraplate earthquakes in the world (Johnston and Kanter, 1990). Extensive scientific studies in the NMSZ during the past two decades have led to major advances in understanding the distribution and characteristics of the seismicity and the structural and tectonic evolution of the New Madrid region. However, despite considerable efforts, reliable geologic data on the recurrence of strong, potentially damaging earthquakes in the NMSZ are limited, inconclusive, and contradictory. The studies described in this report are part of our effort to obtain new paleoseismic data that will refine the existing information on the locations and timing of large prehistoric earthquakes in the region.

Statistical analyses of the historical seismicity (Johnston and Nava, 1985), geodetic data (Liu and others, 1992), and paleoseismic studies in the northern part of the seismic zone (Russ, 1979; Saucier, 1991) have indicated a recurrence interval of about 500-1,100 years for earthquakes that are large enough to produce significant surface deformation. In contrast, studies in other parts of the seismic zone indicate that the recurrence time for major earthquakes may range from more than 1,000 to more than 10,000 years (Saucier, 1989; Wesnousky and Leffler, 1992; Rodbell and Schweig, 1993; Rodbell and Bradley, 1993). Thus, some paleoseismic data indicate a recurrence time of about 1,000 years, yet other data indicate a time of about 10,000 years. Determining the recurrence times for major earthquakes in the New Madrid region is important because this data directly affects seismic-hazard assessments for much of the central United States. If earthquakes similar to the 1811-

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1812 earthquake sequence typically recur at about 10,000-year intervals, then the hazard from these large earthquakes is much less than if the typical recurrence interval is about 1,000 years. Because of the importance of this information, we hoped to identify specific seismogenic faults in the NMSZ and to obtain paleoseismic data on the recurrence of large earthquakes on those faults.

The 1811-1812 New Madrid earthquake sequence included at least three (and probably four) earthquakes of M≥7 within a 2-month time span (Fuller, 1912; Nuttli, 1973; Street and Nuttli, 1984). The ground motion from several of these earthquakes was felt throughout the central and eastern United States (Nuttli, 1973). Today, the occurrence of strong earthquakes similar to those that occurred in 1811-1812 would cause extensive damage throughout a large part of the central U.S. and disrupt numerous major transcontinental lifelines (for example, transportation networks and communication systems) (Applied Technology Council, 1991). Some studies indicate that, because the crust in the central U.S. attenuates seismic energy slowly, major earthquakes in the region may be capable of producing potentially damaging strong ground motion at equal or greater distances compared to seismic events of similar magnitude in the western U.S. (Hanks and Johnston, 1992; Bollinger and others, 1993). Thus, large earthquakes (M≥7) in the New Madrid seismic zone could produce significant shaking hundreds of kilometers away from the epicenter. The large uncertainty in the recurrence time of 1811-1812-type earthquakes complicates the issue of design criteria for major structures and facilities in the region. If the typical recurrence time for 1811-1812-type earthquakes is tens of thousands of years, then it may not be necessary to design structures having a life expectancy of 40 or 50 years to withstand great earthquakes. In contrast, if the typical recurrence time is several hundred years and nearly 200 years have passed since the 1811-1812 earthquakes, then earthquake-resistant designs may be very important. Additional geological data on the recurrence of major earthquakes is useful to evaluate the earthquake hazards associated with the NMSZ.

In this study, our strategy was to locate sites where modern tectonism had deformed shallow, geologically young sediments and to excavate exploratory trenches in which we could document the style and age of the deformation. We concentrated on areas where the U.S. Geological Survey (USGS) had collected high-resolution seismic-reflection data throughout the NMSZ during the past several years. Reflection profiles created from these data provided information about deformed strata that range in depth from approximately 50 to 1,000 m. Several of these profiles contained evidence of faulting and deformation that can be traced upward through most of the Cenozoic strata and possibly into the overlying Quaternary sediments. Along selected parts of these high-resolution lines, the USGS collected additional seismic-reflection data using a 12-gauge shotgun as the energy source; these shotgun data resolved reflectors that are within a few meters of the surface. For our trenching studies, we initially targeted four general areas where the reflection data had been collected and ultimately selected two features to study in detail (fig. 1): (1) the Bootheel lineament, which is a linear feature that extends south-southwest for about 135 km from near New Madrid, Missouri to near Blytheville, Arkansas; and (2) the Crittenden County fault zone (CCFZ) in northeastern Arkansas, which coincides with part of the southeastern margin of the Reelfoot rift. An important aspect of studying the CCFZ is that, although it is not spatially associated with abundant earthquakes, the southeastern margin of the rift is characterized by a low level of seismicity. Furthermore, the CCFZ is located about 25 km from the City of Memphis, which has more than 1 million people in the metropolitan area. A moderate earthquake (M≅5-6) on the CCFZ could cause serious damage in the Memphis area because of its proximity to the city.

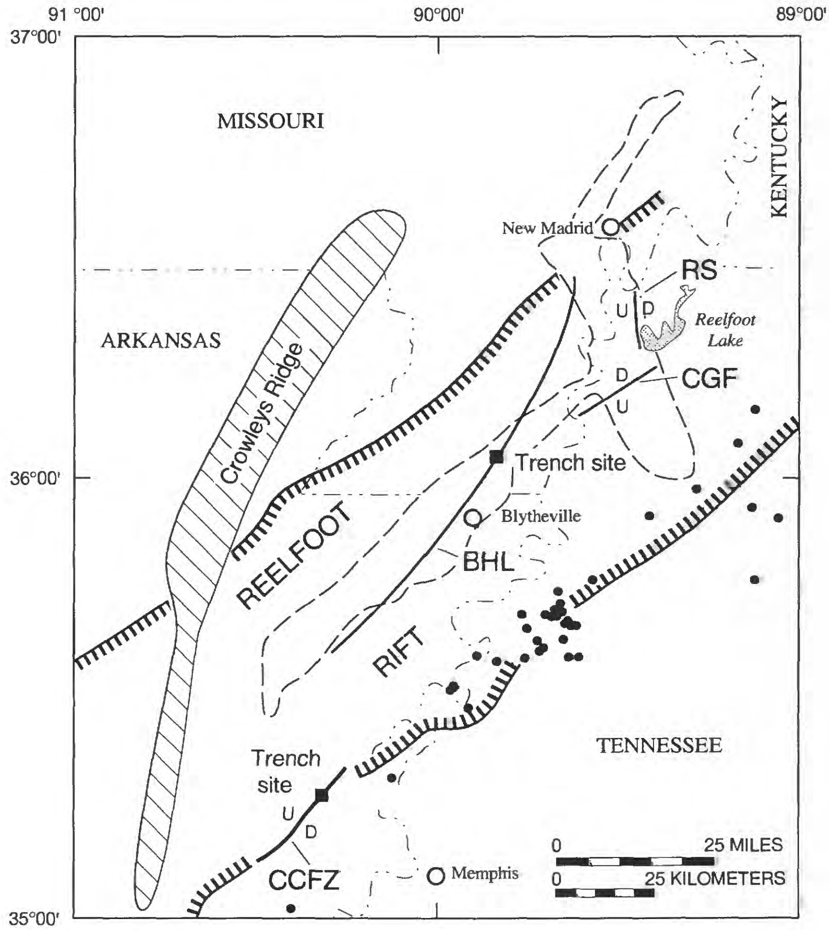

Figure 1. Map of the New Madrid seismic zone in the northern Mississippi embayment. Area within dashed line shows general distribution of concentrated modern seismicity; black dots show scattered seismicity along southeastern boundary of the Reelfoot rift. CGF, Cottonwood Grove fault; CCFZ, Crittenden County fault zone; BHL, generalized location of the Bootheel lineament; RS, Reelfoot scarp.

PREVIOUS WORK

Paleoseismic studies designed to determine the recurrence intervals of major earthquakes in the NMSZ date back to the late 1970s when Russ (1979) excavated an exploratory trench across Reelfoot scarp, which is along the western margin of Reelfoot Lake in northwestern Tennessee (fig. 1). The 11-km-long scarp is the most prominent tectonic escarpment in the entire New Madrid region. Stratigraphic relations in the trench provided evidence of two pre-1811-1812 earthquakes at the site; the oldest deposits exposed in the trench were about 2,000 years old. Thus, combining the historical record of 1811-1812 earthquakes and the geological evidence of two strong prehistoric earthquakes in the past 2,000 years led Russ (1982) to conclude that major earthquakes have been associated with this structure an average of about 600-700 years during the last two millenia. Recent studies of the scarp by Kelson and others (1992) documented evidence of one prehistoric earthquake that occurred between 200 and 600 years ago. However, the relation between the relatively short scarp and major seismogenic faults in the NMSZ remains unclear. The 1811-1812 earthquakes did not produce a distinct surface rupture on the scarp and, because it is only 11 km long, the faults associated with the scarp probably could not generate major (M≥7) earthquakes. Thus, the significance of Russ' 600-700-year recurrence interval for earthquakes associated with Reelfoot scarp relative to the recurrence of 1811-1812-type earthquakes is uncertain.

Subsequent efforts to identify and trench major latest Quaternary faults in the NMSZ have been unsuccessful. Crone and others (1982) excavated a trench across the surface projection of the Cottonwood Grove fault in western Tennessee (fig. 1) and found 1811-1812 liquefaction features but no evidence of near-surface faulting. This trench was located across the surface projection of the fault, which was first recognized on seismic-reflection profiles. Haller and Crone (1986) trenched a prominent lineament near Blytheville, Arkansas, and likewise, they found abundant 1811-1812 liquefaction features but no evidence of faulting. More recently, Schweig and Marple's (1991) studies of the Bootheel lineament (fig. 1) indicate that this feature probably formed during the 1811-1812 earthquakes, and although their evidence of faulting was inconclusive, they speculate that it may mark the surface trace of a strike-slip fault.

INVESTIGATIONS

THE BOOTHEEL LINEAMENT TRENCHES

The Bootheel lineament was the locus of abundant liquefaction during the 1811-1812 New Madrid earthquake sequence, and even though it does not coincide with any of the modern seismicity trends, it may mark the location of a major fault zone that was active during the New Madrid earthquakes (Schweig and Marple, 1991). We examined several parts of the Bootheel lineament in extreme southeastern Missouri and northeastern Arkansas, and reduced our trenching targets to two potential sites: (1) the Hayti West site, located about 8.8 km west-southwest of Hayti, Missouri, where the lineament is marked by copious amounts of sand that was deposited by liquefaction and by an approximately 1-m-high escarpment, and (2) the Jenkins site, which is about 7.4 km west-southwest of Steele, Missouri, where the lineament is narrow and easily defined. At the Hayti West site, we obtained approval from the farmer and tentative approval from the landowner to excavate a trench. However, contrary to earlier indications, the landowner retracted his approval the day before excavtion was to begin. Because this occurred at such a late date, we could not locate and obtain approval for an alternative site; therefore, we directed our efforts solely to trenches at the Jenkins site (fig. 1).

The general trend of the Bootheel lineament at the Jenkins site is N. 19° E. (019°) and is marked by an area of light-colored, relatively well-drained soil on the west compared to an area of dark-colored, poorly drained soil on the east (fig. 2). The western side of the lineament is about 30 cm topographically higher than the eastern side. The Jenkins site is located in N$^1/_2$NW$^1/_4$SW$^1/_4$ sec. 30, T. 17 N., R. 11 E., Pemiscot County, Missouri (Denton, Missouri USGS 7$^1/_2$-minute topographic quadrangle). The sharp definition of the Bootheel lineament at the Jenkins site allowed us to trench across the entire feature and define stratigraphic and structural differences on both sides of the lineament.

We excavated three subparallel, east-west-trending trenches that are nearly perpendicular to the lineament (fig. 3). The trenches were sequentially numbered from north to south and were spaced approximately 15 m apart. Trench 1, the longest and northernmost trench, was about 73 m long and spanned the entire feature. Trenches 2 and 3 were about 22 m long and 16 m long, respectively, and crossed the part of the lineament where the most prominent liquefaction features are present in trench 1.

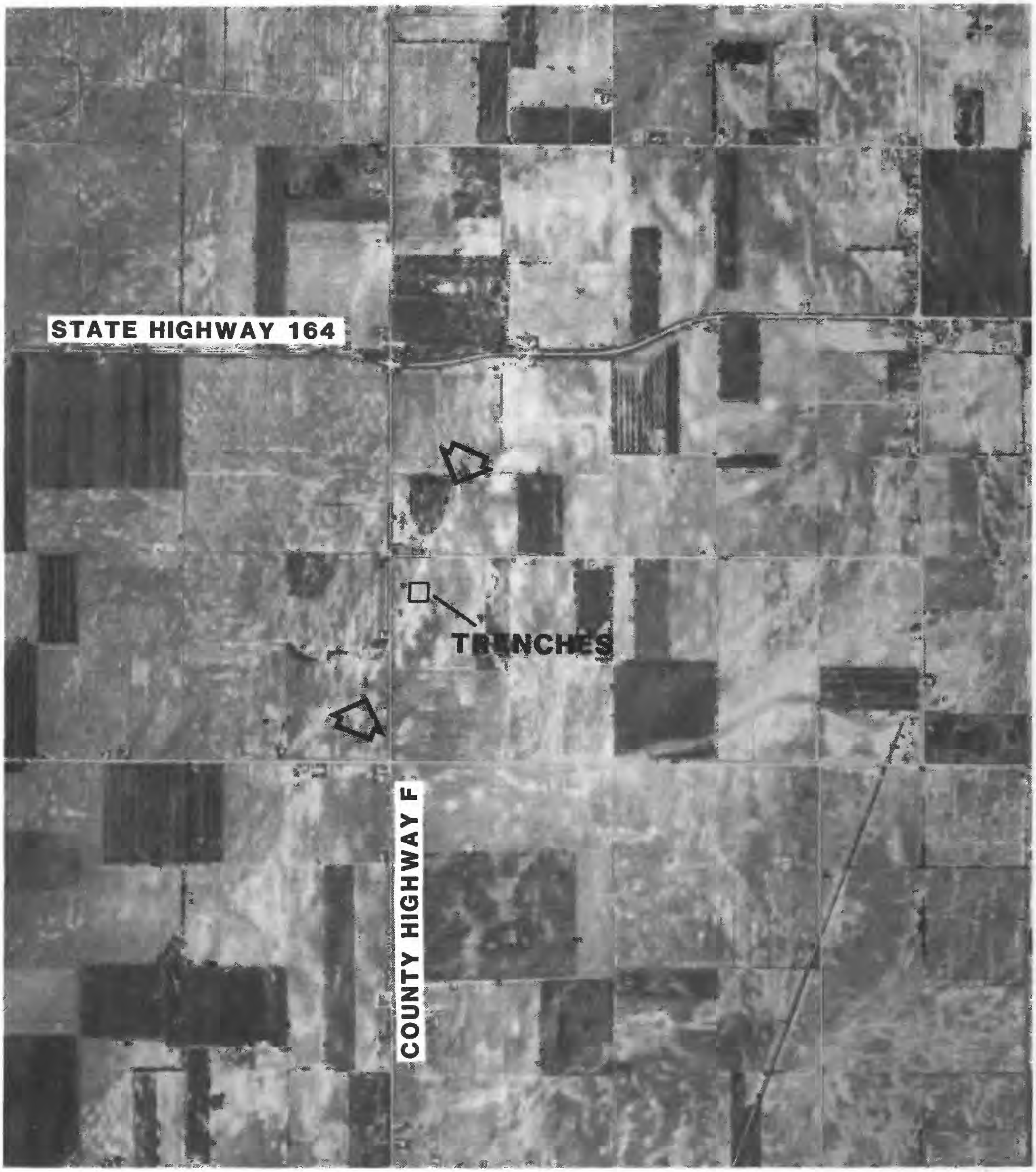

Figure 2. Aerial photograph of Bootheel lineament at the Jenkins trench site. Open arrows show general trend (019°) of the lineament in the area. Box shows location of trenches. Photograph scale is 1:24,000.

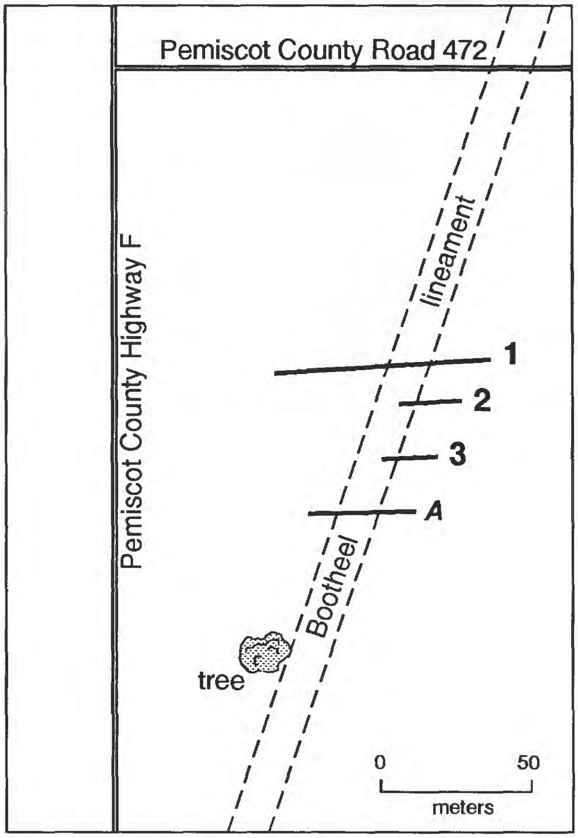

Figure 3. Schematic map of Jenkins trench site showing the general trend of the Bootheel lineament and locations of three numbered trenches discussed in this report. Southernmost trench (labeled *A)* was previously excavated and discussed by Schweig and Marple (1991).

Trench Stratigraphy

The stratigraphy in the trenches consists of a fining-upward sequence of fluvial sediments (units A-C in Bootheel lineament trenches) that are overlain by a sequence of sand-blow deposits (units 1-4 in Bootheel lineament trenches; fig. 4). The lowest unit of the fluvial sequence, unit C, was exposed in the bottoms of all three trenches. The basal deposit in the eastern end of trench 2 is a well-sorted, medium- to coarse-grained quartzose sand, whereas the correlative unit in the western part of trench 2 and in the other trenches is a silty, medium- to fine-grained sand. We interpret the coarser grained sand to be the active channel facies in these fluvial deposts, and the silty sand is a lower energy, distal facies of this unit. Unit C is overlain by a massive, light-gray to very pale-brown, slightly silty, medium- to fine-grained sand (unit B) that is present in all of the trenches. In the eastern end of trench 3, this silty sand grades laterally into a sandy silt. The silt and clay content of the medium- to fine-grained sand increase upward, and the unit grades first into a sandy loam (lower part of unit A) and then upward into a grayish-brown sandy clay loam that has a red-orange mottling (unit A).

We interpret this fining-upward sequence to be deposits from a low-energy meandering stream system. The geometry of the individual mapped units within this sequence provide the basis for our interpretation of these as fluvial deposits. The basal coarse-grained deposits are buried by progressively finer grained overbank and slack-water sediment that filled the abandoned channel and were deposited on the floodplain adjacent to the main channel. In trench 3, the eastward dip of the silty sand and sandy loam (units B and A, respectively) are probably related to the underlying topography of a channel. Based on the geometry of the fluvial units in trench 2, the axis of this channel may be located between the 8-m and 10-m marks on the map of the trench walls. This axis appears to be near the eastern end of trench 1.

The fluvial deposits are overlain by a series of generally well-sorted, light-yellowish-brown to pale-brown, coarse- to fine-grained sands (units 1-4) that are sand-blow deposits (fig. 5). The basal contact of the sand-blow deposits is sharp and planar, although, the erupting sand may have locally eroded the pre-earthquake ground surface. The bulk of the sand-blow deposits is massive, medium- to coarse-grained sand; these massive sand units are separated by a 2- to 4-cm-thick layer of massive to finely laminated sand that contains a small amount of silt (fig. 6). Stratification in the fine-grained sand is distorted and convoluted locally, probably as a result of soft-sediment deformation and dewatering. We interpret the finer grained sands to be deposits that settled out of the mixture of sand and water during lulls in the sand-blow's eruption, although they could also result from coarse-grained sand not being distributed uniformly in a radial pattern around the vent of the sand blow. We do not believe that a significant amount of time elapsed between deposition of the successive coarse-grained sand units because there is no evidence of significant oxidation at the top of the coarse-grained units. Furthermore, if these units had remained at the surface for as little as a few years, then roots from plants growing on the surface would have disrupted the stratification of the fine-sand units. However, the stratification in these deposits is undisturbed.

We interpret the detailed stratigraphy and lateral thinning of the vented sand-blow deposits adjacent to the dikes to be evidence of at least two major eruptive phases (fig. 6). Units 4 and 3 were deposited during the first phase. Unit 4 is a medium- to fine-grained, light-yellowish-brown, slightly silty sand that was deposited during the onset of the initial eruption. The primary deposits from the

Figure 4. View of trench 2 across Bootheel lineament at the Jenkins trench site. Light-colored sand body in upper part of trench is sand-blow deposit that pinches out near eastern end of trench. Main sand-blow dike in this trench is in left-center of photograph; see figure 5 for detailed view of dike. Flags on string lines are 1 m apart. View is to the northeast.

Figure 5. Detailed view of dike 3 in trench 2 at the Jenkins trench site. The 50-cm-wide dike is in the bottom-center of the photograph. Sand-blow deposits are light-colored sediment in upper part of trench; underlying fluvial deposits are dark-colored sediment. Note lack of significant soil-horizon development in the top of the fluvial deposits. The top of the fluvial deposits is vertically offset 50-55 cm across the dike. Horizontal string lines are 1 m apart.

first eruptive phase are pale-brown, well-sorted, medium- to coarse-grained sand that contains less than 5 percent granule-size grains and clay clasts as large as 10 cm in diameter (unit 3). We believe that unit 4 was deposited during the vigorous early phase of the eruption. Unit 2 is a 2- to 4-cm-thick, well-sorted, fine-grained sand that separates coarser grained units above and below. We interpret this fine-grained sand to be the sediment that settled out of suspension when the vigorous activity of the first eruption subsided. Alternatively, unit 2 could have been deposited during a brief time when the strongest flow of sediment and fluid were diverted in a direction away from the trench. However, because the general stratigraphy of the sand-blow deposits is similar in all three trenches, we believe that the fine-grained sand represents a lull in the activity between separate eruptive events. Unit 1 is a massive to well-stratified, well-sorted, medium- to fine-grained sand that contains concentrations of small (~5 mm) lignite fragments located along bedding planes. We interpret this to be the primary deposit from the second eruptive phase. The upper part of unit 1 is now part of the modern plowed zone (unit Ap) that has been modified by agricultural activity.

The overall thickness of the sand-blow deposits vary greatly along the length of the trenches; they are thickest where large sand-blow dikes cut the fluvial deposits, and they thin rapidly outward from the dikes (fig. 4). The coarse-grained units contain scattered clay clasts, which are fragments of the fluvial deposits (units A and B) that were ripped up during the sand-blow eruption and were incorporated in the liquefied sand (fig. 6). The clay clasts (as large as 10 cm in size) were transported more than 6 m from the nearest major sand-blow feeder dike. As we discuss below, we attribute these liquefaction deposits to the 1811-1812 earthquakes.

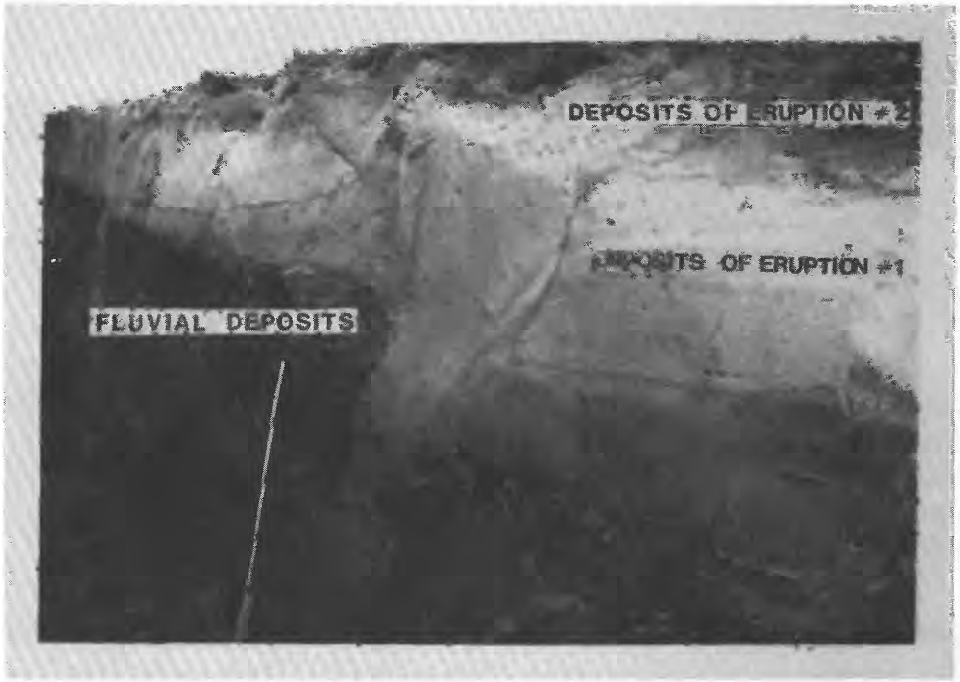

Figure 6. View of dike 3 in trench 1 at the Jenkins trench site showing stratification of sand-blow deposits. The main throat of the dike is outlined by slightly darker fine-grained sand. Coarse-grained sand from two major eruptions is separated by finer grained layer. Note westward thinning of sand away from the vent. Also note westward dip of dike and vertical offset (28 cm) on top of fluvial deposits. View is to the west.

Three lines of geologic evidence indicate that the fluvial deposits are late Holocene in age. First, the Jenkins site is located about 2 km west of Pemiscot Bayou, which defines the western limit of the modern Mississippi River meander belt. The bayou is still permanently flooded in places and local farmers report that it was navigable only a few decades ago. This implies that the bayou is a young, unfilled, abandoned channel. Any site, such as the trench site, which is within a few kilometers of a major active channel of the Mississippi River, would certainly receive significant amounts of sediment during annual flooding of the river. This circumstantial evidence suggests a late Holocene age for the fluvial deposits.

The second line of evidence is the poorly developed soil overlying the fluvial deposits (top of unit A; fig. 5), which marks the paleoground surface at the time the liquefied sand was erupted. Soil-horizon development on this surface is very weak, and the best indicator of soil development is a slight darkening of color in the upper part of unit A, which likely is caused by an increase in organic matter in a buried A/B horizon. No textural changes or distinct soil structures are present in the upper part of the fluvial deposits, which would indicate that this surface was subaerially exposed for a significant period of time (a few thousand years).

The third line of evidence of a late Holocene age for these deposits is the presence of human artifacts in the fluvial deposits. Unit B in trench 2 (at 14-m mark on map of trench 2; also fig. 4) contained evidence of a prehistoric hearth from which we collected small fragments of charcoal and two fragments of pottery. We found two additional pottery fragments in unit B near the 12-m mark. Two of the pottery fragments are composed of sand-tempered pottery, which is characteristic of the Middle and Late Woodland Native American culture in this part of the Mississippi Valley (J.H. Ray, Center for Archaeological Research, Southwest Missouri State Univ., 1993, written commun.). Another fragment has been tentatively identified as being composed of shell-tempered clay in which the shell fragments have been dissolved; as a first approximation, shell-tempered pottery is representative of artifacts from the Early Mississippian Native American culture. Archeological studies throughout the region have established the general time spans of these pottery styles. The Middle and Late Woodland artifacts typically date from 1 A.D. to about 700-800 A.D.; the Early Mississippian artifacts were made by cultures that were active in the region about 800-1,000 A.D. Thus, the presence of these pottery fragments indicates that the fluvial deposits exposed in the trench are about 1,000-2,000 years old.

Charcoal fragments from the hearth have been radiocarbon dated and confirm the age of the fluvial deposits that was inferred from the artifacts. An accelerator mass spectromety age determination indicated that the charcoal fragments are 1,508±64 radiocarbon years old (Geochron sample GX-19872-AMS). When dendrochronologically corrected for variations in atmospheric carbon isotopes, the likely age of these fragments is between 1,313-1,419 yr B.P. (Stuiver and Reimer, 1993).

We believe that the sand-blow deposits exposed in the trenches formed during the 1811-1812 earthquakes, based on the late Holocene age of the underlying fluvial deposits and the lack of significant oxidation, mineral alteration, and pedogenesis in the sand-blow deposits (except for the Ap horizon).

Structural Features

Large sand blows and their feeder dikes are the main structural features in the trenches. We found no evidence of faulting or brittle deformation that we attribute to tectonic activity. Each trench exposed at least one large feeder dike; the largest of these was dike 3 at the 19.5-m mark in trench 2 (trench maps, figs. 4 and 5), which was a maximum of about 50 cm wide. The dikes broke through the fluvial deposits during the eruptions and vented a mixture of sand and water onto the ground surface. The thickest sand deposits are near the vents directly above the major dikes. The maximum thickness of the liquefied sand deposits is 1.25 m adjacent to dike 3 in trench 2.

In the fluvial deposits, the attitude of the sand-blow dikes range from nearly vertical (dike 4 at 14-m mark, trench 1) to about 45° (dike 1 at 1.5-m mark, trench 3). The strikes of the dikes vary considerably. Some of this variation may reflect true changes in the overall strike of the dikes, but part of it may result from the sinuosity of the dikes, which we could see in the plan view for the dikes that crossed the floors of the trenches. The strikes of the dikes range from N. 8° W. (352°) to N. 24° E. (024°) and are subparallel to the local trend of the Bootheel lineament (019°).

In contrast to the clustered orientations of most sand-blow dikes, dike 5 at the 53.3-m mark in the western part of trench 1 strikes approximately N. 40° E. (040°) and has a unique stratigraphy. It is approximately 20-35 cm wide, which is similar to other major dikes in the trenches, but little if any liquefied sand rose upward through this feature onto the ground surface because the fluvial deposits in this part of the trench extend to the present-day surface. The sediment filling this dike is unique compared to the other dikes because, rather than being generally massive and homogeneous, it contains well-stratified, fine- and coarse-grained sand interbedded with silty clay loam that appears to be derived from the surrounding fluvial sediments. We do not believe that this is a sand-blow dike, rather we interpret it to be an infilled fissure that was originally open and was subsequently filled with sediment that washed in from the surface and was transported laterally along the fissure. We believe that the sediment was transported in the fissure in a manner similar to that described by Holzer and Clark (1993), although we found no evidence that the sediment-laden fluid in this fissure reemerged at the surface and formed sand boils.

In trenches 1 and 2, the top of the sequence of fluvial deposits is vertically offset across three of the largest dikes (dikes 2 and 3 in trench 1 (fig. 5), and dike 3, trench 2 (fig. 5)). In all cases, the east side of the dike is downthrown, and the stratigraphy of the sand-blow deposits shows that virtually all of this differential displacement occurred during the initial eruption. The maximum vertical offset of the fluvial units is 50-55 cm across dike 3 in trench 2 (fig. 5); we measured 13 cm of offset across dike 2 (trench 1) and 28 cm across dike 3 (trench 1) (fig. 6). We found no *direct* evidence that these vertical offsets are related to tectonic faulting, and in the absence of such evidence, the simplest and preferred explanation for these offsets is that they were caused by differential subsidence, which resulted from the huge volume of sand that was removed from below. Despite the lack of evidence of tectonic faulting, speculation about a relation between these offsets and contemporary tectonism is discussed in the following section of this report.

We found no evidence of lateral slip across the sand-blow dikes. Abrupt changes in the thickness of stratigraphic units across faults are commonly used as evidence of lateral slip. Minor changes in the thickness of fluvial units are present across some dikes, but these changes are the result of fluvial depositional processes and minor erosion of the ground surface during the sand-blow eruption. We do not believe that the thickness changes are either large enough or consistent enough between different dikes to be used as evidence of lateral slip.

At least two of the dikes did not break the upper contact of the fluvial deposits in the plane of the trench walls (dike 4, trench 3; dike 1, trench 1). These relations are not convincing evidence of a liquefaction event that predates the massive sand-blow deposits. These two dikes are probably contemporaneous with the sand-blow deposits. The relatively large size of dike 4 (in trench 3) and the fact that its upper part extends to within less than 15 cm of the top of the fluvial deposits suggest that the dike probably connects with vented sand deposits out of the plane of the trench wall. Dike 1 (in trench 1) is very thin and may have been too small to intersect the ground surface at the time of the earthquake.

Interpretation and Discussion

An important result of this study is the absence of conclusive evidence of faulting associated with the Bootheel lineament. Without this evidence, it is difficult to directly associate features in the surficial deposits along the lineament with underlying seismogenic faults, including those that may have slipped during the 1811-1812 earthquakes. This lack of evidence in surficial deposits is not entirely surprising considering two factors. First, the Quaternary deposits and underlying Cenozoic and upper Mesozoic rocks are unconsolidated to poorly consolidated and have a cumulative thickness of more that 1 km. As a result, it is difficult for fault offsets at depth to propagate through these deposits and produce visible deformation at the surface. Secondly, the surficial deposits exposed in the trenches are young, probably 1,000-2,000 years old and probably have not been subjected to multiple large earthquakes that could have caused a detectable amount of surface deformation. Thus, the ages and characteristics of the surficial deposits in this area limit the likelihood of finding evidence of brittle failure (faulting).

Despite the lack of clearly documented faulting, the orientation of the sand-blow feeder dikes and the infilled fracture might be the near-surface expression of tectonic strain that is induced by the regional stress field. The origin of the Bootheel lineament is uncertain, but Ellis and Schweig (1992) speculate that it may be an incipient right-lateral strike-slip fault. If the lineament is the product of a right-lateral shear couple that is being deformed in the current stress field, then the orientations of the feeder dikes and infilled fissure should correspond to the orientation of features that form in a right-lateral wrench fault system (fig. 7) (Wilcox and others, 1973). Modern deformation in the New Madrid region is being driven by a maximum horizontal compressive stress that is oriented N. 80° E. (080°) (Zoback and Zoback, 1989). The local trend of the Bootheel lineament in the study area is about 019°. The three largest dikes have strikes between 004° and 013°, and the average strike of the dikes is 012° (range of 352° to 024°) (fig. 7). The feeder dikes are nearly perpendicular to the maximum compressive stress direction, which implies that, if slip occurred on features with these orientations, it would be mainly reverse faulting with a small component of right-lateral slip. It is interesting to note that the three large feeder dikes across which the fluvial deposits are vertically displaced all have steep westward dips (~75°-87°) and a down-to-the-east sense of displacement.

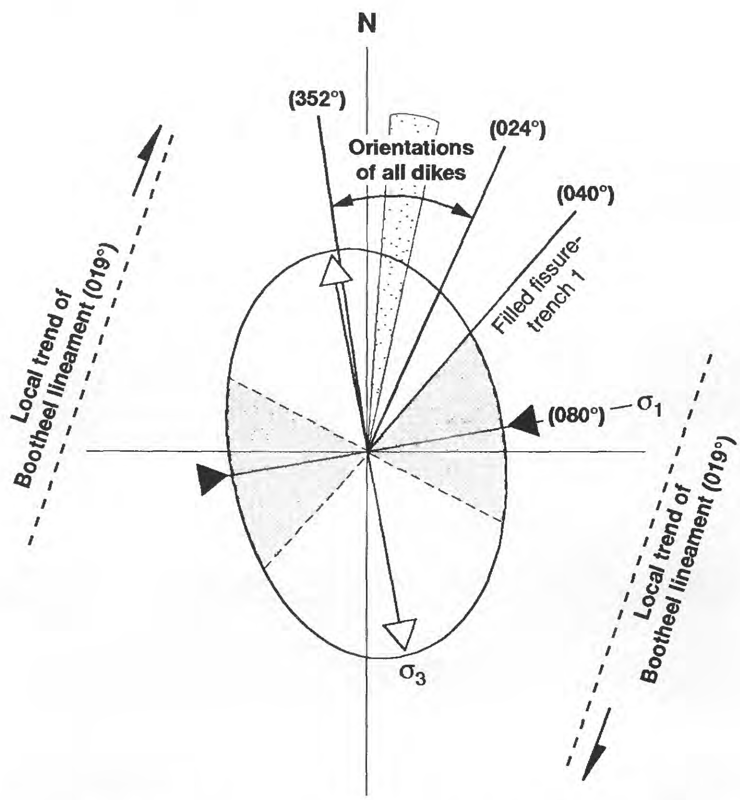

Figure 7. Diagram of strain ellipse for right-lateral shear system that has same orientation as Bootheel lineament at Jenkins trench site. Orientation of maximum horizontal compressive stress (σ_1; indicated by solid triangles) is about 080° in the New Madrid region (Zoback and Zoback, 1989). Line with open triangles, orientation of minimum horizontal compressive stress (σ_3). Shaded areas are tensional quadrants; structural features that have strikes in these quadrants will have a component of extension. Orientations of sand-blow dikes range from 352° to 024°; orientations of strikes of major dikes (stippled pattern) are 004°-013°.

The westward dip and sense of displacement are consistent with reverse faulting. Although clearly speculative, these relations could be interpreted as evidence that the major feeder dikes were intruded along incipient reverse faults.

At first glance, this speculation appears to create a mechanically enigmatic situation because, if these feeder dikes correspond to reverse faults, then the slip planes of these faults would undergo compression, which would inhibit the injection of liquefied sand along the fault plane. However, compression on the fault plane would be greatest during the few minutes of active shaking. When the shaking subsided, the strength of the compressional forces acting on the fault plane would diminish greatly, especially in surficial deposits that have an unconfined upper surface. In contrast to the 1-2 minutes of the strong shaking associated with large shocks, liquefaction can occur for many hours after an earthquake. We hypothesize that, during an earthquake, compression produced cracks in the fluvial sediments and formed incipient reverse faults. These cracks created relatively weak zones in the sediment along which liquefied sand could flow during the hours following the earthquake.

It is also interesting to note that the feature we interpret as an infilled fracture has a strike of 040°, which places it in a quadrant of the strain ellipse (fig. 7) that would have a component of tension. Tensional conditions would favor the formation of extensional features, such as open fissures.

We emphasize that the preceding discussion is indeed speculative because we failed to find clear-cut evidence of differential slip to corroborate this deformation model. Nevertheless, we offer this hypothesis with the hope that it might stimulate additional studies, such as trenching across paleochannels that are cut by the lineament to determine its origin.

At the Jenkins site, pervasive liquefaction is the main earthquake-related process associated with the lineament. The large quantity of liquefied sand that was erupted onto the preearthquake ground surface may have caused differential subsidence of as much as 50 cm across several of the largest dikes. The stratigraphy of the sand-blow deposits is evidence of two major eruptions that occurred close in time. These two eruptive episodes could have been caused by the first two of the three large earthquakes that occurred in 1811-1812 (the December 16 and January 23 events), whose epicenters are estimated to be about 10 and 35 km, respectively, from to the Jenkins site (Nuttli, 1979; Obermeier, 1989). Even though the February 7, 1812 event may have been the largest earthquake, its epicenter was located more than 50 km from the site.

The geologic evidence from the trenches we have described here suggests that, during the past approximately 1,500 years, liquefaction has occurred at this site only during the 1811-1812 earthquakes. Furthermore, the extensive liquefaction that did occur here in 1811-1812 indicates that site conditions were very favorable for liquefaction. Given the apparent favorable conditions but lack of evidence of prehistoric liquefaction, we conclude that the site has not been subjected to sustained shaking as strong as that which occurred in 1811-1812 for at least 1,500 years.

This conclusion is consistent with the results of paleoliquefaction studies in some parts of the New Madrid seismic zone, but differs with findings from other parts of the seismic zone. Similar to our results, studies of late Pleistocene fluvial terraces along the Obion River in western Tennessee failed to find convincing evidence of prehistoric liquefaction in deposits that are about 20,000 years old (Rodbell and Schweig, 1993; Rodbell and Bradley, 1993). In contrast, recent studies at two sites south of the Jenkins site in extreme southeastern Missouri and across the border in northeastern Arkansas (Schweig and others, 1993; Tuttle and others, 1993) revealed that at least one prehistoric liquefaction event occurred in the area about 1,000-1,300 years ago. Furthermore, studies of paleoliquefaction features near New Madrid, Missouri, indicate that as many as two prehistoric liquefaction events occurred in the past 2,000 years in the area northeast of the Jenkins site (Kelson and others, 1992; Russ, 1979; Saucier, 1991; Schweig and others, 1993).

The simplest hypothesis that reconciles the apparent contradictory evidence states that multiple seismic source zones exist within the New Madrid region and each one is capable of generating moderate to strong earthquakes. A strong earthquake originating in a single source zone would cause strong ground motion and liquefaction in a localized area. This notion of individual source zones is consistent with the current paleoliquefaction data and with the occurrence of at least three major earthquakes in 1811-1812. However, the close timing of the 1811-1812 events may have been unusual and may not represent the typical temporal pattern of earthquakes in the region. The currently available paleoliquefaction data is best explained by the occurrence of single strong events generated by specific source zones; the time span between the events from a single zone might be a few thousand years.

It is clear that our present understanding of the distribution and timing of strong prehistoric earthquakes in the New Madrid region is too incomplete and inadequate to accurately characterize the long-term behavior of the seismic source zones. Additional studies are needed throughout the region to develop a large enough geologic database to confidently establish a regional paleoearthquake chronology. Each of these studies provides an important fragment of information, which eventually will lead to a better understanding and assessment of the seismic hazards in the New Madrid seismic zone.

CRITTENDEN COUNTY FAULT ZONE TRENCH

The Crittenden County fault zone (CCFZ) (fig. 1) was a primary target for trenching because previous geophysical studies had shown evidence of deformation in very shallow sediments. The fault zone was originally recognized on the basis of data from two drill holes that were only about 600 m apart. The drill holes showed 78 m of offset at the top of Paleozoic rocks and progressively less offset in shallower stratigraphic horizons. Vibroseis™ and Mini-Sosie™ reflection data show that deformation associated with the CCFZ can be traced upward to depths as shallow as the base of the Quaternary sediments (Crone, 1992; Luzietti and others, 1992); seismic-reflection data that used shotgun and jackhammer energy sources allow the deformation to be traced confidently to within 30 m of the surface (Williams and others, 1993; fig. 8). The results of reprocessing these data indicate that deformation may be as shallow as 6-7 m (Williams and others, 1993). Thus, exploratory trenches, which are typically about 3 m deep, might expose shallow deformation associated with the fault zone.

We chose to excavate the CCFZ trench in the area between the two drill holes that originally revealed the presence of the fault. The combined Mini-Sosie, shotgun, and jackhammer reflection data delimit the location of shallow deformation to within a few tens of meters. Thus, the geophysical studies at this site greatly increased the likelihood finding evidence of young deformation in the trench.

The CCFZ trench was located in NW$^1/_4$NW$^1/_4$SE$^1/_4$, sec. 22, T. 8 N., R. 7 E., Crittenden County, Arkansas (Heafer, Arkansas 7$^1/_2$-minute topographic quadrangle), and was one-half mile west of Arkansas State Highway 50. The trench was 49 m long and averaged 2.5-3 m deep.

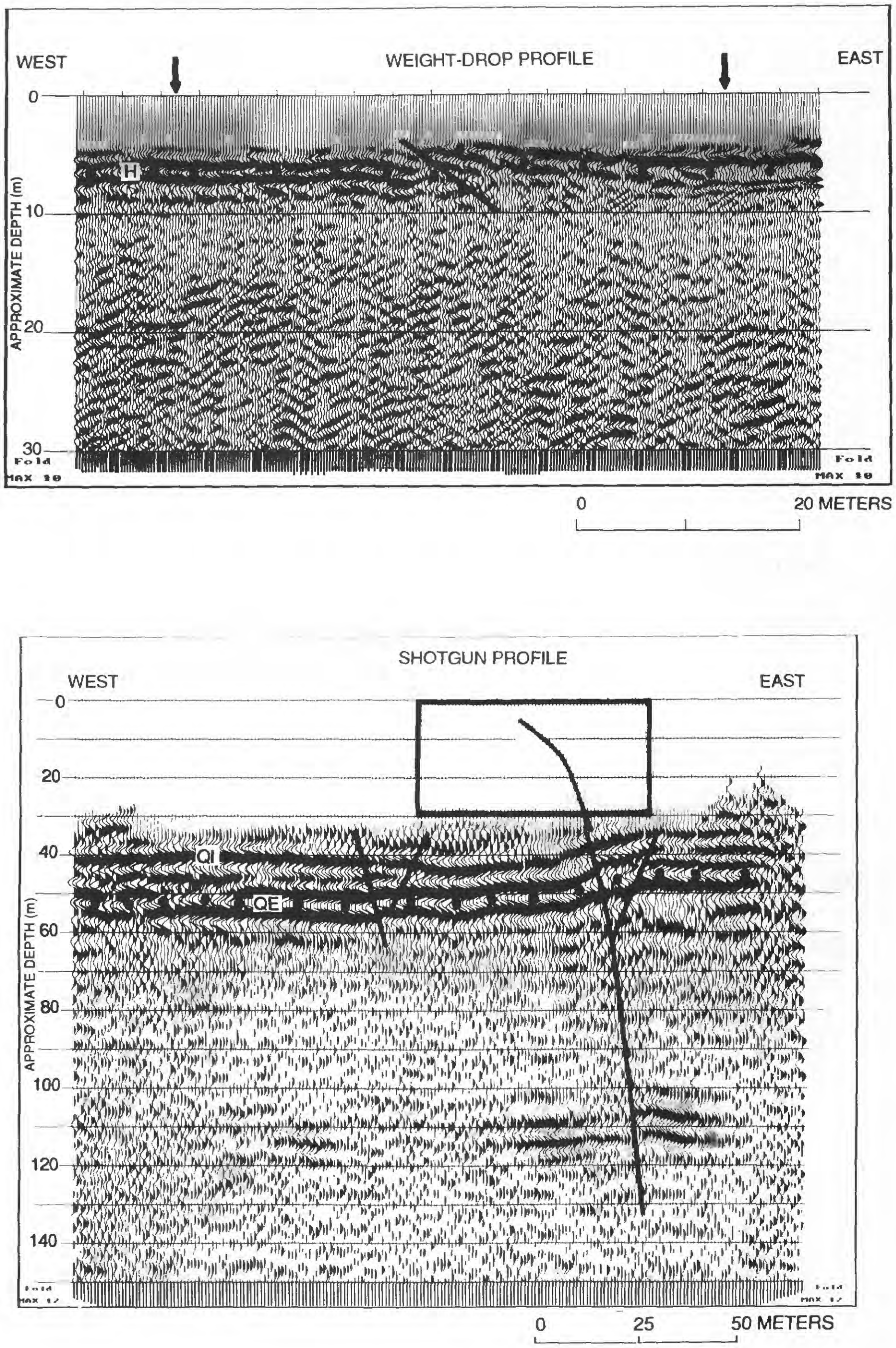

Figure 8. Depth sections of weight-drop and shotgun-reflection profiles across Crittenden County fault zone in northeastern Arkansas. Solid lines show interpreted locations of faults. Shotgun profile shows deformation in Quaternary alluvium as shallow as about 30 m below surface; weight-drop profile shows deformation as shallow as about 7 m below surface. Solid box in upper part of shotgun profile shows area covered by weight-drop profile. Solid arrows at top of weight-drop profile show eastern and western extent of trench. QE, contact between Quaternary and Eocene sediments; QI, reflection from lower Quaternary sediments; H, unidentified reflector probably of Holocene age. Horizontal and vertical scales of profiles are approximately equal. Profiles provided by R. A. Williams, USGS, Denver.

The trench site is within the Holocene-age Mississippi River meander belt, an area of gently undulating topography that contains abandoned channels, natural levees, and crevasse splays. Surficial deposits in Crittenden County are almost exclusively Mississippi River alluvium, mostly silt and clay, although sandy deposits are present adjacent to abandoned channels (Gray and Ferguson, 1974). Soils in these deposits are weakly to moderately developed because the surficial deposits are geologically young. The county soils map assigns the soils at the trench site to the Sharkey silty clay and the Tunica clay soil series, both of which are formed on poorly drained sediments (Gray and Ferguson, 1974). Sharkey soils are formed on thick clayey deposits, and the Tunica soils are formed on thin clayey sediments that overlie coarser grained sediment. The deposits at the trench site are so young that pedogenesis has not visibly disrupted laminations in fine-grained sand and silt that are less than 1 m beneath the surface.

Trench Stratigraphy

The deposits that were exposed in the Crittenden County trench are predominantly silt, but contain various amounts of sand and clay. We interpret these to be low-energy fluvial sediments that were deposited in overbank and slack-water depositional settings, and we divide them into two groups (fig. 8). The stratigraphically lowest group (unit 5) is light-gray to grayish-brown silty clay loam, which was exposed in the eastern end of the trench. This silty clay loam grades downward into a gray, fine sand. To the west, the unit changes facies and is subdivided into three parts: (1) a lower, yellowish-brown fine sand that is mottled very pale brown (unit 5c); (2) a middle, very pale brown loamy sand that is mottled dark-yellowish-brown (unit 5b); and (3) an upper, yellow silt loam that is mottled and stained with iron oxide and some manganese oxide (unit 5a).

The upper group of sediments (units 1-4) in the trench is composed of silty clay, silty clay loam, and silty loam. Unit 4 is a dark-grayish-brown silty clay to silty clay loam that is generally massive but contains laminae of very fine sand and silt. We interpret this to be a quiet-water deposit. Unit 4 is as much as 20 cm thick in the eastern end of the trench, but pinches out near the 42-m mark in the trench.

Unit 3 is a finely laminated, light-gray silt to very fine sand that contains yellow mottles. Individual laminae are typically a few millimeters thick. The basal contact of unit 3 is sharp, but locally the boundary between units 3 and 4 is marked by a 3-cm-thick zone of alternating laminae that are texturally similar to the two adjacent units. We interpret unit 3 to be a slack-water deposit that accumulated in a slightly higher energy environment than that of the underlying clayey deposits. Unit 3 is as much as 23 cm thick in the eastern end of the trench, and, similar to unit 4, it pinches out to the west near the 44-m mark.

Unit 2 is a light-gray to dark-grayish-brown clay to silty clay that we believe was deposited in an environment similar to that of unit 4. It has a moderate, prismatic pedogenic structure throughout. The ped faces, which formed as a result of this structure, are devoid of clay films, but have smoothed, striated surfaces that probably resulted from differential movement during repeated shrinking and swelling. No primary stratification was visible in this deposit. The entire unit contains scattered 1- to 2-mm-size manganese- and iron-oxide nodules, but the nodules are more common in the upper part. The unit is slightly less that 40 cm thick in the eastern end of the trench, and, similar to the underlying units, it thins markedly to the west, but it does not pinch out.

Unit 1 is a very pale brown silt loam to silty clay loam that has a moderate platy structure in the upper 25 cm and grades downward to a moderate prismatic structure. The unit is massive, but the structure that has formed from pedogenesis has not destroyed the primary depositional fabric. The upper half of the unit is mottled with iron oxide. The lower 15-20 cm of the unit consists of interstratified laminae of units 1 and 2. This unit also thins considerably to the west. This unit was probably deposited in a slack-water environment similar to that of unit 3.

The shallowest mapped unit in the trench is the plowed zone (unit Ap), which has been repeatedly disturbed by farming.

Structural Features

We found no evidence of faulting, brittle deformation, or liquefaction in the trench. With the exception of units 3 and 4 (discussed below), all mapped units were continuous along the entire trench, although facies changes produced a large textural change in unit 5.

The most significant structural feature in the trench is the pinch out of units 4 and 3 near the 42- and 44-m marks, respectively (fig. 9), and the westward thinning of units 1 and 2. These relations are evidence that the top of unit 5 is an unconformity, which separates the two groups of deposits. About 1.2 m of relief is present on the unconformity (fig. 10). Units 1-4 were deposited on this nonplanar surface, and, as they were deposited, they onlapped onto the unconformity to the west. As deposition continued, the topographic relief on the unconformity was buried, and units 1 and 2 draped over the unconformity.

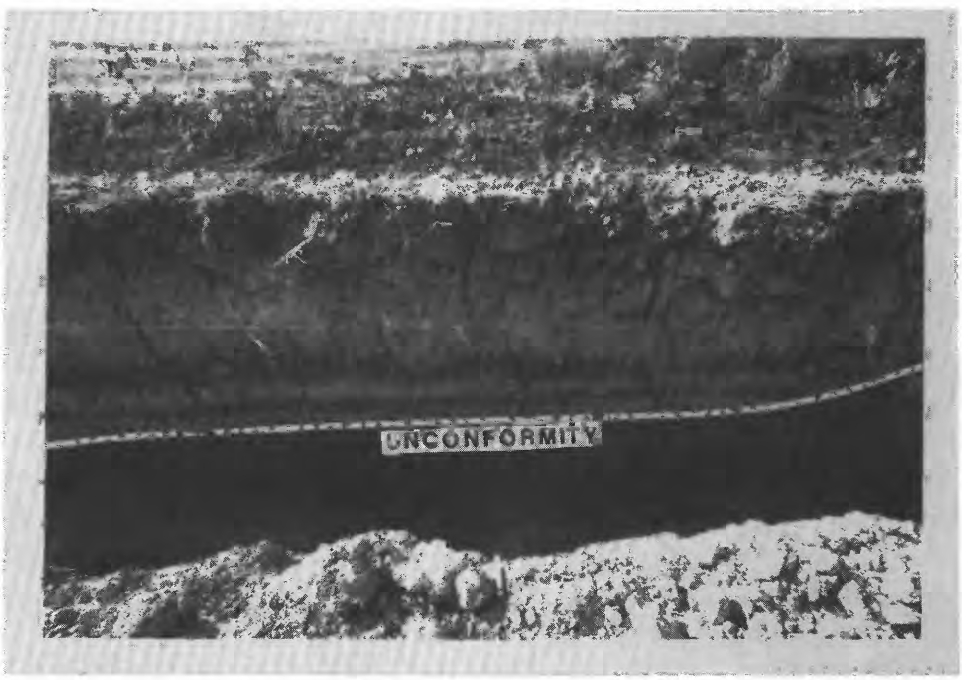

Figure 9. View of south wall of Crittenden County trench between 32 and 36 m. Note that stratigraphic units rise to the west (right) with respect to horizontal string lines. Units above unconformity thin to the west. Horizontal string lines are 1 m apart.

Figure 10. View (looking west) of topography on unconformity in south wall of Crittenden County trench. Note the progressive rise of stratigraphic units to the west with respect to horizontal string lines. Top of dark-gray unit in bottom of trench is an unconformity. Light-colored units directly above unconformity thin and pinch out to the west. String lines are 1 m apart.

During the original mapping of the trench, we recognized the significance of the relief on the unconformity. We realized that it would be valuable to extend the trench farther west to determine if the relief on the unconformity was related to a localized ridge or if it was a monoclinal feature. Therefore, when the excavation equipment returned to backfill the trench, we extended the western end of the trench by about 7 m, which allowed us to briefly examine the character of the unconformity. The stratigraphic units in the western extension remained essentially horizontal, which indicates that the unconformity defines a monoclinal warp at the scale of the trench.

Interpretation and Discussion

Data from the CCFZ trench do not provide absolute evidence about the origin of the monocline; in the absence of evidence of faulting, the most reasonable interpretation of this feature is that it marks the margin of a paleochannel that was later filled with fine-grained sediment. Much of the modern landscape of Crittenden County resulted from fluvial processes, and river channels with several meters of relief are common. Thus a fluvial origin for the feature is a likely interpretation for the feature.

However, the coincidence of the monocline with the deformation located a few meters below the bottom of the trench indicates that this feature might be related to deeper structural features. If the relief on the unconformity is related to deformation in the underlying sediments, then the seismic-reflection data links the relief to crustal-scale faults along the southwestern margin of the Reelfoot rift. Because such a link would have tremendous implications for earthquake hazards in the region, it is clear that better knowledge of the deformational history of the rift margins is needed to adequately assess the seismic hazards in the New Madrid region.

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