USGS-NEHRP Grant G11AP20122 Final Report

Seismological Society of America 2011 Field Trip – Fault Trench Site in the New Madrid Seismic Zone

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Project Period - 04/01/11 through 06/30/11

Abstract

A trench was excavated across the southeastern Reelfoot Rift margin for paleoseismic research purposes and for the 2011 Seismological Society of America national meeting field trip. The trench was parallel to and 6 m southwest of the Oldham trench of Cox et al. (2006). In this 2011 trench, faulted alluvial fan stratigraphy and liquefaction deposits less than 4000 year old were exposed. The trench revealed three tectonic deformation events. The first event (graben formation) and the second event (sand blow, minor faulting, and injection of sand dikes) both post-date a paleosol circa 4000 yr B.P. and pre-date a surficial colluvial soil deposit circa 2000 yr B.P. The third event (minor shallow liquefaction) post-dates the surficial colluvial soil dated at "post-bomb" in this trench but dated as 2120 to 1800 yr B.P. at a deeper level in this unit in the previous Oldham trench. We interpret the deformation in this trench to local faulting at the base of the bluff that was previously imaged in a shallow reflection profile near this site.

Introduction

Subsurface faults along the southeastern margin of the Reelfoot Rift are defined by fault-controlled intrusions, seismic reflection profiles, drill-hole data, and magnetic and gravity data (Hildenbrand et al., 1982; Johnson et al., 1994; Parrish and Van Arsdale, 2004). A linear trend of hypocenters and their focal plane mechanism solutions (Chiu et al., 1997) and paleoseismic trench studies (Cox et al., 2006) along this margin reveal that this is an active fault zone with right-lateral strike-slip movement. In western Tennessee, a prominent scarp and topographic lineament appears to be the surface expression of this southeastern rift margin fault zone (Fig. 1) (Fisk, 1944; O'Leary and Simpson, 1977; Wyatt and Stearns, 1988; Cox et al., 2006). The southern 100 km of this lineament is the bluff-line scarp of the Mississippi River Valley. Linked components of the southeastern rift margin fault complex are most likely the source of the modern seismicity there, and these linked faults have propagated to the surface or near surface along the rift-margin lineament (Cox et al., 2006).

In conjunction with the annual meeting of the Seismological Society of America in Memphis, Tennessee, in April 2011, we excavated a 10-meter long trench in northwest Shelby County 20 km north of the Memphis metropolitan area. Our trench was excavated across the bluff-line lineament of the Mississippi Valley at a site that has previously been documented to be fault controlled. The trench was excavated parallel to and 6 meters southwest of the Oldham trench of Cox et al. (2006). Like the previous trench, the new trench trends down the slope of an alluvial fan at the foot of the valley margin bluff (Fig. 1). The trench revealed fan alluvium (bedded gravel, sand, silt, clay), massive sand we interpret as a sand blow deposit, a buried organic-rich A horizon (paleosol), a surficial organic-rich soil A horizon in gravelly colluvium, faults, and sand dikes (Fig. 2).

Results

We interpret at least three paleoseismic events from features exposed in the trench. This chronology begins with early fan alluviation (units 1 and 2 on Figures 2 and 3), followed by development of a now buried A horizon (unit 3) indicating cessation of fan growth and stabilization of the fan surface (Fig. 3a). Radiocarbon dates from this paleosol (4422 to 4180 yr B.P., AA94447, and 4629 to 4084 yr B.P., AA94448, Table 1) are similar to ages reported by Cox et al. (2006) for this paleosol (4840 to 3900 yr B.P.). This surface was subsequently deformed by formation of a graben (strike 040^{o}) at meter 7 to 9 in the trench (Fig. 3b). This graben was filled with organic-rich sediment from unit 3, and the east side of the graben was collapsed in the southwest trench wall. Had we not excavated the floor of the trench by hand to investigate a linear trend of unit 3 paleosol in the trench floor, we would not have found this graben, and we suspect it was present below the floor of the Oldham trench of Cox et al. (2006). We interpret this graben as a fissure or lateral spread parallel to the strike of a bluff-line fault described by Cox et al. (2006). It is not clear if the collapse of the graben was caused by a later compressive event, either mass wasting or tectonic, or if it accompanied graben subsidence.

The graben and unit 3 paleosol were buried and modified by renewed alluviation (unit 4) and channel scour-and-fill (unit 5) that we interpret as evidence of an increase in erosion and sediment production in the watershed of the fan in response to the local faulting and ground shaking, which accompanied graben formation (Fig. 3c). Before appreciable soil formation could take place, a sand blow (unit 6) buried this active fan surface from meter 3 to the down-fan end of the trench (Fig. 3d). We presume the source of this sand blow is a deeper sand in the fan stratigraphy, and because the sand blow deposit cross-cuts units 3 and 4 in the northeast trench wall, a major vent is probably not far from that trench wall. Ten to fifteen centimeter clasts of the underlying paleosol (radiocarbon ages of 4296 to 4078 yr B.P., AA94445, Table 1) were entrained upward in the vented sand near the presumed vent in the northeast wall. We contend

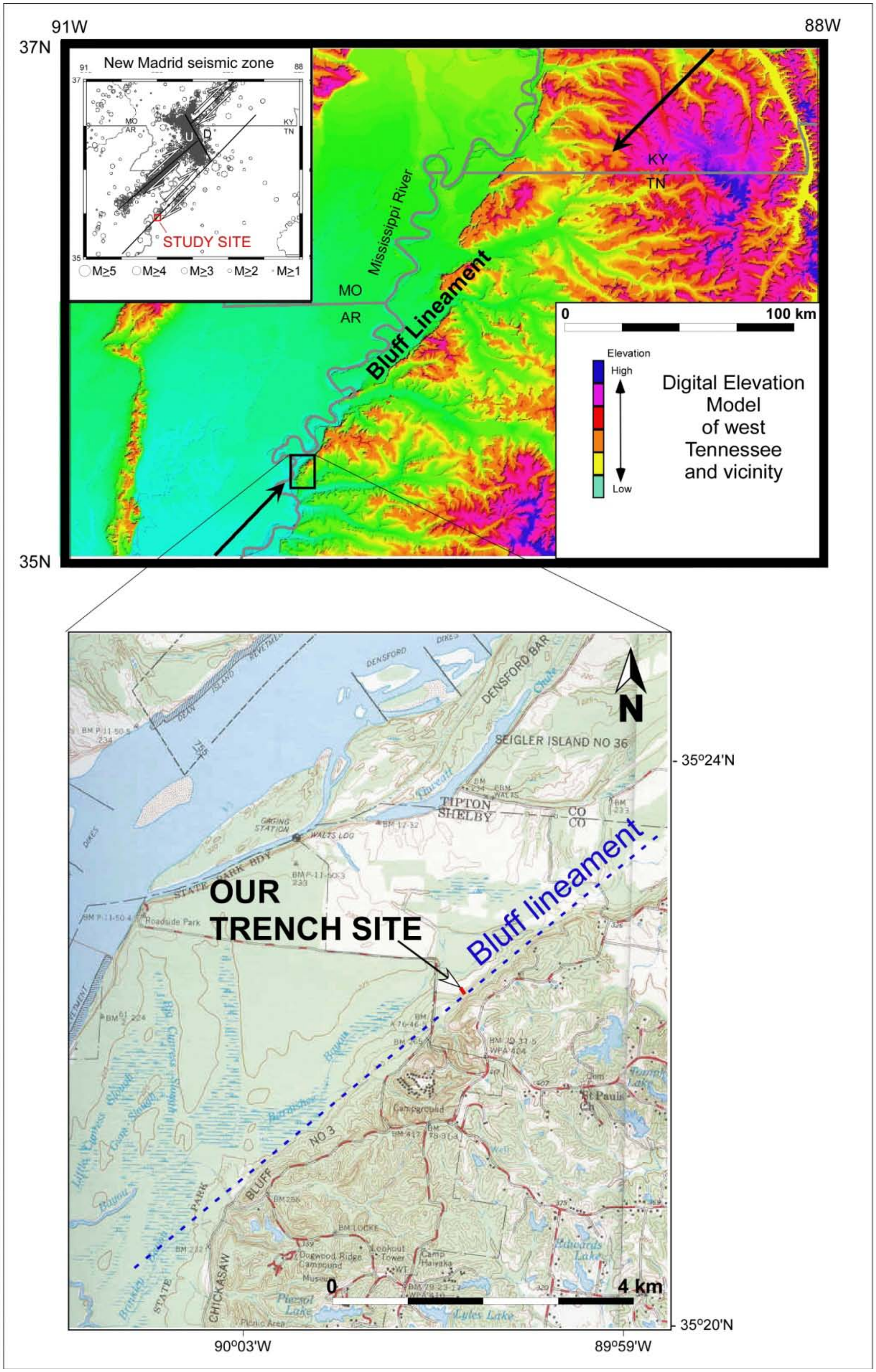

Figure 1. Regional and local map of study area (modified from Cox et al., 2006).

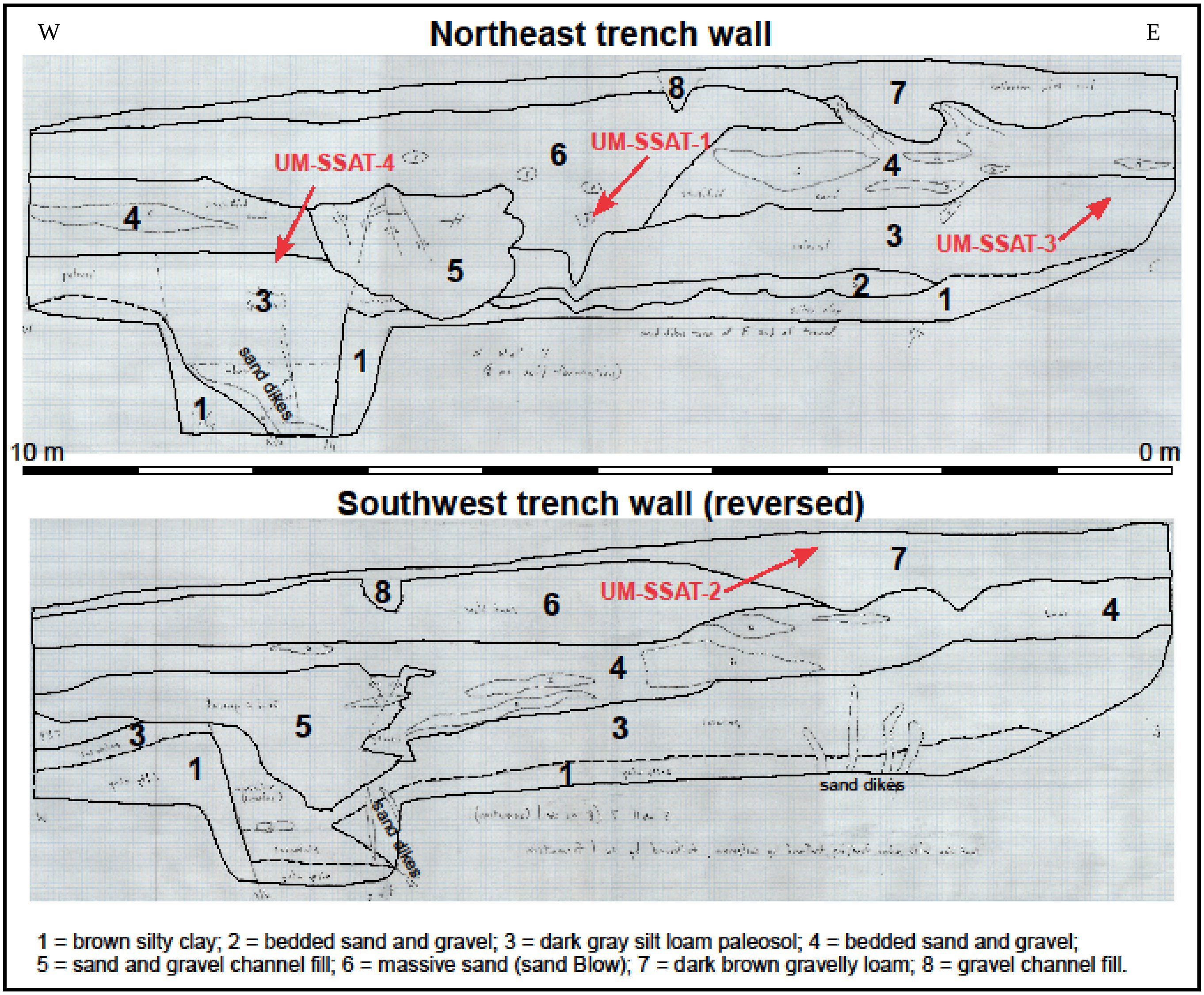

Figure 2. Field logs of trench walls. Dashed line denotes gradational boundary. No vertical exaggeration. UM designates ^{14}C sample locations.

this sand blow records significant local shaking, and in order to minimize the number of deformation events we interpret in the trench, we argue it is coeval with sand dikes at meter 2 to 4 and at meter 7 in the southwest trench wall and at meter 8 to 9 in the northeast wall and with small faults reactivated within and above the graben at meter 6 to 7.5 in the northeast wall and meter 7 in the southwest wall. We base our identification of the sand dikes as liquefaction intrusions on their up-dip pinchouts and a difference in grain size to their host sediment. The small faults follow the 040^{o} strike of the graben, but the sand dikes strike 070^{o}, consistent with extension fractures in the current stress field (Zoback and Zoback, 1991).

An organic-rich soil A horizon (unit 7) developed on the fan surface following venting of the sand blow. The sand blow deposit (unit 6) acted as a barrier to deposition on the fan, and a

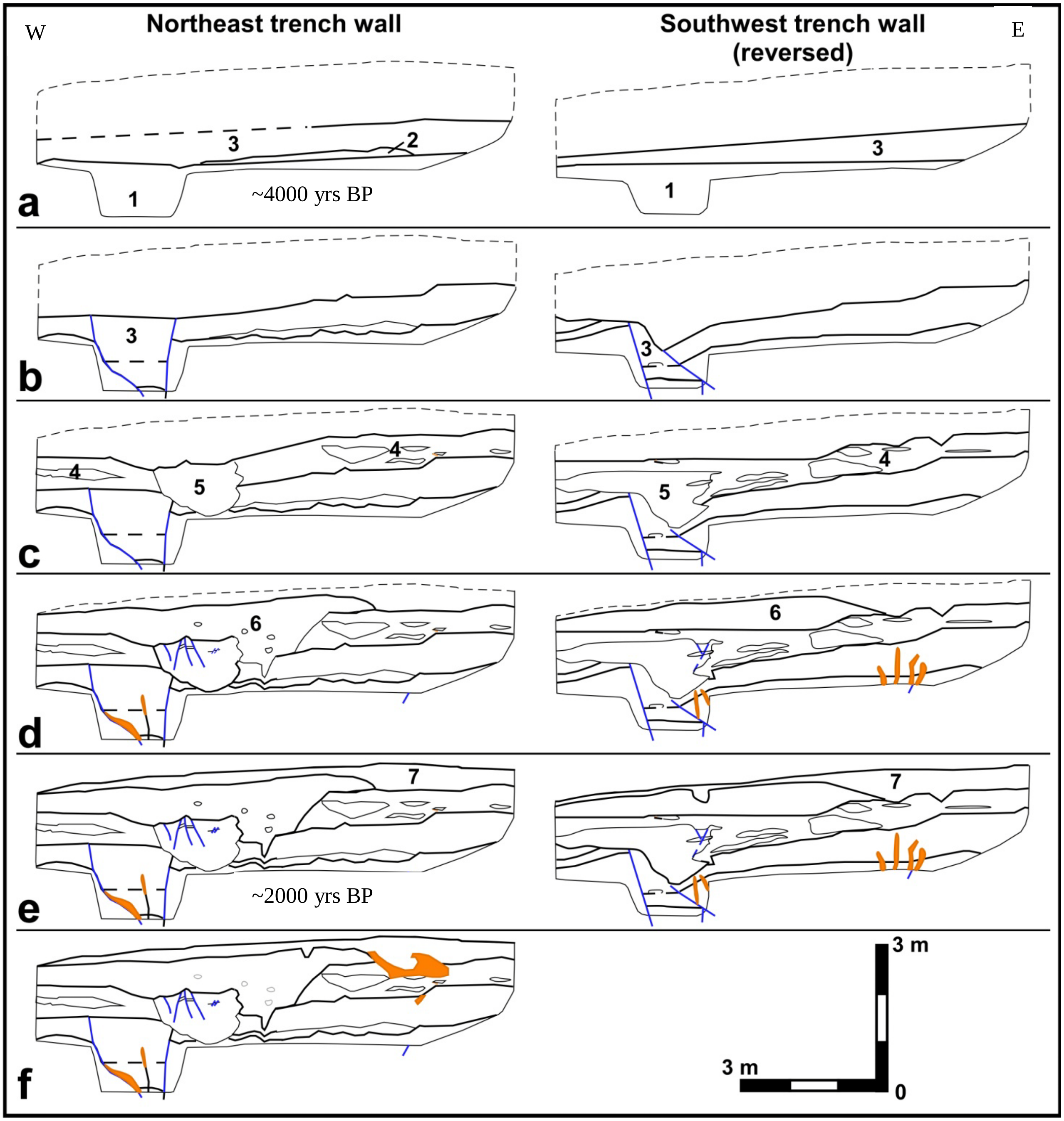

Figure 3. Deformation sequence observed in trench. Blue = fault, orange = sand dike.

thicker colluvial deposit of gravelly A horizon developed upslope of the sand blow (Fig. 3e). The radiocarbon age reported by Cox et al. (2006) for the lower part of this transported soil is 2120 to 1800 yr B.P. We attempted to sample a younger level within this unit in order to better constrain its age, but unfortunately the radiocarbon date was "post-bomb" (AA94446, Table 1).

Sandy alluvium below unit 7 at meter 1.5 to 3 in the northeast trench wall experienced minor liquefaction (Fig. 3f). Cross-cutting relations show this liquefaction post-dates units 6 and 7, and we speculate this event may be coeval with a late stage fissure in the Oldham trench of

TABLE 1. Results of ^{14}C analyses.

Sample*	Lab No.**	Sample Material	Technique	Delta ^{13}C	Radiocarbon age $\pm$ 1σ yr B.P.	Calibrated 2σ age yr B.P.***
UM-SSAT-1	AA94445	Organic sediment	AMS	-26.7	3789+/-39	4296 to 4078
UM-SSAT-2	AA94446	Organic sediment	AMS	-28.1	Post-bomb	
UM-SSAT-3	AA94447	Organic sediment	AMS	-24.5	3888+/-39	4422 to 4180
UM-SSAT-4	AA94448	Organic sediment	AMS	-26.2	3924+/-98	4629 to 4084

* See Figure 2 for sampling locations.
** All analyses conducted by University of Arizona NSF AMS Facility.
*** Determined by calibration curve of Stuiver and others (1998).

Cox et al. (2006). They report that sediment fill of the late fissure was radiocarbon dated at 460 to 260 yr B.P., 220 to 140 yr B.P., and 30 to 0 yr B.P.

A convexity of the fan surface bearing 031^{o} (meter 2.5 on the northeast wall and meter 3 on the southwest wall) is developed in the colluvial deposit and surface A horizon. The convexity follows the zone containing the fault in the Oldham trench of Cox et al. (2006) and the shallow minor liquefaction and deeper sand dikes in our trench from meter 1.5 to 4. This low-amplitude convexity would not persist for more than a few centuries, and we interpret the flexure as possible surface deformation accompanying the last minor liquefaction event.

Conclusions

In contrast to the conclusion of Cox et al. (2006) of one or two paleoseismic events at the study site, we find evidence for three events in this second trench. The first event (graben formation) and the second event (sand blow, minor faulting, and injection of sand dikes) both post-date the paleosol circa 4000 yr B.P. and pre-date the surficial colluvial soil deposit circa 2000 yr B.P. (age from equivalent units in the Oldham trench of Cox et al. 2006), and the last event (minor shallow liquefaction) post-dates the surficial colluvial soil. Our second event is equivalent to the faulting event reported by Cox et al. (2006). On the basis of proximity to the bluff lineament and of northeast strikes of structures observed in the trench, we conclude that the seismic source of these events is a bluff-lineament fault directly below the trench site, as imaged by shallow seismic reflection (Cox et al., 2006).

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Field Trip Guide:
Taking a New Look at the New Madrid Seismic Zone

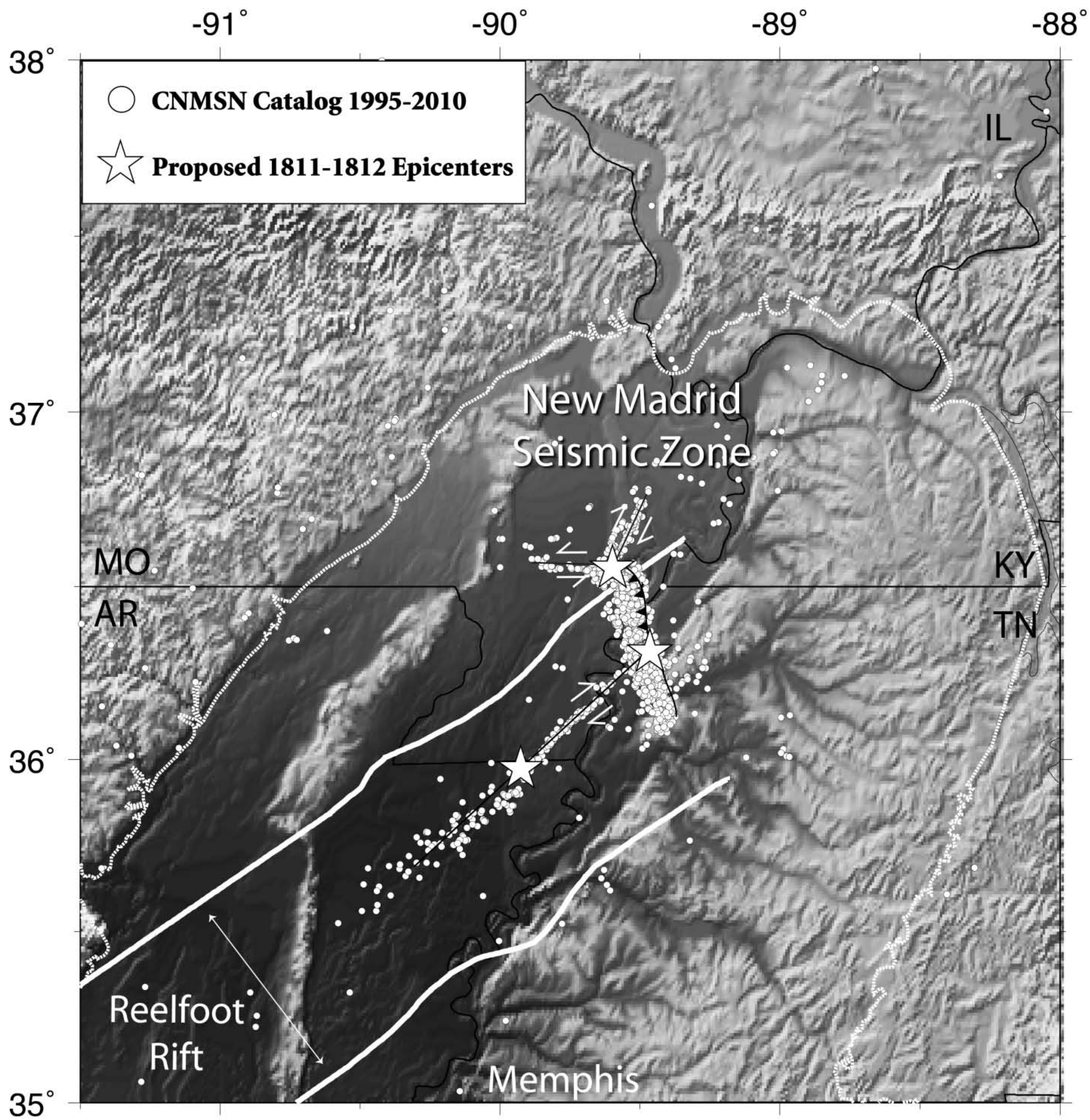

Figure 1: Overview map of the New Madrid Seismic Zone.

2011 Seismological Society of America Meeting
Memphis, Tennessee
April 16, 2011

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Acknowledgements
Research presented during this field trip was carried out by many dedicated scientists and graduate students. Research support has come from a variety of funding sources in particular the National Earthquake Hazard Reduction Program managed by the U.S. Geological Survey, the U.S. Nuclear Regulatory Commission, and the National Science Foundation. Special thanks to co-leaders of this field trip Randel Cox, Beatrice Magnani, Nathan (Kent) Moran, University of Memphis/CERI students and staff, and Tish Tuttle of M. Tuttle & Associates, for contributions to this field trip guide and insightful discussions during the field trip. Thanks also to Tish Tuttle for her help organizing the field trip. Thanks to the Ruth Dillahunty family for access to the Yarbro site, to Marion Haynes who assisted in preparing the site, and to SSA for funding to excavate the trenches. Thanks also to the U.S. Geological Survey for funding to develop the Meeman-Shelby site for this field trip.

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Introduction

The New Madrid Seismic Zone (NMSZ) generated a sequence of earthquakes, including three very large (M > 7) mainshocks, in the winter of 1811-1812 and poses a significant seismic hazard to the Central United States (e.g., Johnson and Schweig, 1996; Frankel et al., 1996; Hough et al., 2000; Bakun and Hooper, 2004). Paleoseismic evidence indicates that the NMSZ produced 1811-1812-type events about A.D. 900 and A.D. 1450 suggesting an average recurrence time of 500 years (Kelson et al., 1996; Tuttle et al., 2002; Guccione, 2005). Although less well understood, two earlier New Madrid events have been proposed in 1000 B.C. (Holbrooke et al., 2004) and 2350 B.C. (Tuttle et al., 2005). Holbrooke et al. (2004) suggested that the NMSZ is characterized by active and inactive periods, with inactive periods lasting about 1700 years. Alternatively, the paleoearthquake record may be incomplete prior to A.D. 800.

The NMSZ lies within the Mississippi embayment, a large shallow sedimentary trough initiated during the Cretaceous and interpreted to be due to the passage of the Bermuda hotspot beneath the northeast trending Cambrian age Reelfoot Rift system (Fig. 1) (Cox and Van Arsdale, 2002). The embayment is filled with unconsolidated upper Cretaceous and Cenozoic sediments, with thickness increasing from north to south. The currently active fault system is likely reactivation of rift-related faults (Ervin and McGinnis, 1975). Modern microseismicity is spatially associated with several faults as follows (Fig. 1): (1) the NE trending Cottonwood Grove or Axial right lateral strike slip fault, located along the central axis of the Reelfoot rift; (2) the NW trending Reelfoot fault, is a SW dipping reverse fault; (3) the NNE trending North New Madrid right lateral strike slip fault; and (4) the E-W trending Risco left lateral strike slip fault. These faults are oriented favorably relative to the present east-northeast regional compressive stress field for right-lateral strike slip displacements to occur along northeast oriented faults and for reverse displacements to occur along northwest oriented faults (Zoback and Zoback, 1989). Why the NMSZ generates high levels of microseismicity, while other ancient fault systems also optimally oriented within the present day stress field do not, remains an open question (i.e., Liu and Zoback, 1997; Pollitz et al., 2001; Forte et al., 2007; Calais et al., 2010).

The New Madrid Seismic Zone

The New Madrid earthquakes of 1811-1812 are the largest earthquakes to have struck the conterminous United States in recorded history (Fig. 1, stars). The first main shock occurred at 2:15 a.m., December 16, 1811 (southern star). The two other main shocks occurred on January 23 (northern star) and February 7, 1812 (central star). All three mainshocks have estimated moment magnitudes in the magnitude 7 to 8 range (Johnston, 1996; Johnston and Schweig, 1996; Hough et al., 2000; Bakun and Hooper, 2004). Epicentral Modified Mercalli Intensities (MMI) ranged from X to XII (Street and Nuttli, 1984). Because of the low attenuation of seismic waves in the central United States, these three earthquakes had large (5,000,000 km^2) felt areas (Nuttli, 1982; Nuttli and Herrmann, 1984) and were felt as far away as Boston, Massachusetts (distance of 1,690 km). In addition to the mainshocks, thousands of aftershocks were associated with the New Madrid earthquake sequence, many of which caused damage and were felt along the eastern seaboard (Street and Nuttli, 1984; Johnston, 1996). Since 1812 at least 28 damaging earthquakes, having estimated moment magnitudes between 4.2 and 6.4, have struck the region (Nuttli, 1983; Hamilton and Johnston, 1990; Johnston, 1996).

Although the exact locations of the 1811-1812 New Madrid earthquakes are unknown, their relationship to the northern and southern New Madrid seismic zone is strongly suggested by the isoseismal maps compiled from historical accounts (Nuttli, 1973) and the distribution of ground failures, particularly those related to earthquake-induced liquefaction (Fuller, 1912; Saucier, 1977; Obermeier, 1984; Tuttle et al., 2002) and landslides (Jibson and Keefer, 1988; 1989; 1992). The estimated total area affected by ground failure in 1811-1812 including fissures, sand blows, landslides, and subsidence was about 48,000 km^2 (Fig. 2; Street and Nuttli, 1984; Schweig and Van Arsdale, 1996). Liquefaction of subsurface sand layers resulted in the ejection of sand-bearing water through ground fissures, forming sand blow deposits typically tens of meters in width, hundreds of meters in length, and up to 2 meters in thickness (Fuller, 1912; Obermeier, 1988; Tuttle and Barstow, 1996). Massive bank failures occurred along the Mississippi River, reported to have been choked with trees and the wreckage of boats in certain locations (Penick, 1981). The Reelfoot fault and associated back thrusting probably displaced the bed of the Mississippi River at four locations (Purser and Van Arsdale, 1998). At two locations, one upstream and one downstream from New Madrid, waterfalls or rapids formed in the Mississippi River channel (Penick, 1981; Purser and Van Arsdale, 1998). These displacements in the soft sediments in the river channel were eroded and obliterated rapidly. Landslides along the bluffs bordering the Mississippi River valley occurred from about Cairo, Illinois, to Memphis, Tennessee (Fuller, 1912; Jibson and Keefer, 1988). Eyewitnesses describe the land surface following the earthquakes as being disrupted and in many places uninhabitable (Penick, 1981).

Earthquake Potential of the New Madrid Seismic Zone

In order to understand the hazard that the NMSZ may pose in the future, earth scientists have studied the geological and geophysical record of past earthquakes in the region. These studies have focused on paleoliquefaction features, active faults associated with the Reelfoot Rift fault system, and the sedimentological record of uplift, subsidence, and abrupt changes in the morphology of the Mississippi River. These independent studies have reached similar conclusions that the NMSZ has repeatedly produced large magnitude earthquakes during, at least, the past 4 kyr.

Earthquake-induced liquefaction features, including sand blows and sand dikes, have been studied at more than two hundred sites across the New Madrid region (Fig. 2; e.g., Saucier, 1991, Vaughn, 1994; Li et al., 1998; Tuttle, 1999; Broughton et al., 2001; Tuttle et al., 2002 and 2005). During these investigations, the locations, sizes, and sedimentary characteristics of historic and prehistoric liquefaction features were documented and organic samples collected for radiocarbon dating of the liquefaction features, and thus the earthquakes that formed them. Both historic and prehistoric sand blows were found to be compound structures, composed of multiple, fining upward units, suggesting that they formed during earthquake sequences including several very large earthquakes (Saucier, 1989; Tuttle et al., 2002). The age estimates of sand blows across the region cluster around A.D. 1810 ± 130 years, A.D. 1450 ± 150 years, A.D. 900 ± 100 years, interpreted to represent the timing of New Madrid earthquakes (Fig. 3). In addition, large sand blows that formed in 2350 B.C. ± 200 years were found at several sites in northeastern Arkansas and southeastern Missouri and attributed to an earlier New Madrid event (Tuttle et al., 2005).

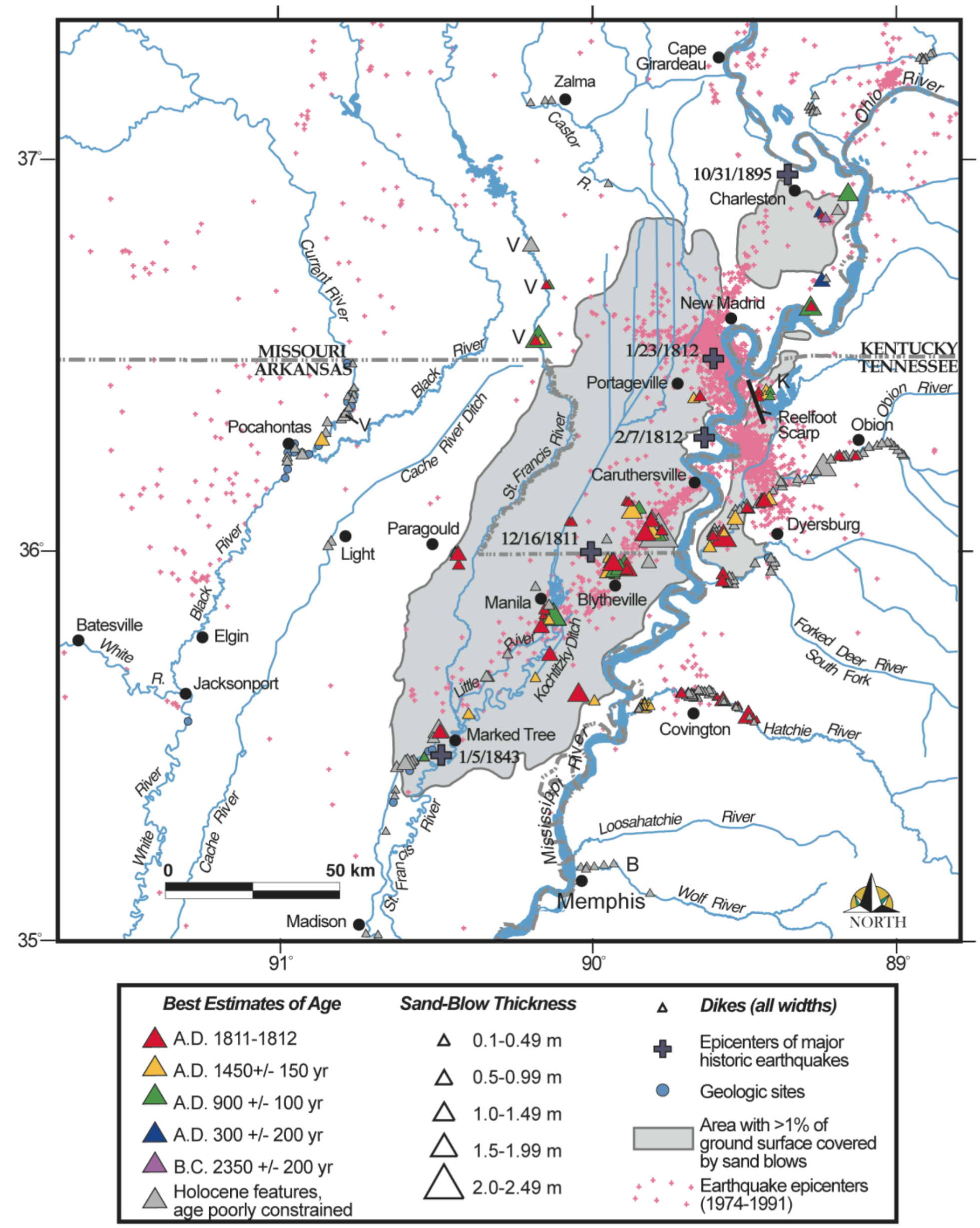

Figure 2. Map showing locations, age estimates, and measured sizes of sand blows and sand dikes in the NMSZ (modified from Tuttle et al., 2002).

There is a close spatial correlation of both historic and prehistoric sand blows with the NMSZ, which was interpreted as the source of earthquakes responsible for most of the liquefaction features (Tuttle, 1999; Tuttle et al, 2002). Also, the size and spatial distributions of historic and prehistoric sand blows were found to be strikingly similar, suggesting that the prehistoric earthquakes were similar in location and magnitude to the 1811-1812 mainshocks (Fig. 2). The Ambraseys (1988) relation between moment magnitude and epicentral distance to farthest surface manifestation of liquefaction (~240 km to farthest sand blows) suggests that the largest of the 1811-1812 earthquakes was of **M** ≥ 7.6. Although the limit of the paleoliquefaction fields have not yet been determined, the similarity in the size and spatial distribution of prehistoric sand blows with historic sand blows suggests that the A.D. 900 and A.D. 1450 events are likely to have included at least one earthquake of **M** ≥ 7.6 (Tuttle, 2001). Geotechnical testing and analysis of liquefaction potential carried out at several liquefaction sites near Blytheville, Arkansas, and Steele, Missouri, found that sediments are not especially susceptible to liquefaction and that an earthquake of **M** ≥ 7.5 would be required to induced liquefaction at all of the sites (e.g., Schneider and Mayne, 2000). Taken together, the liquefaction data indicate that the NMSZ generated sequences including very large, **M** 7 to 8, earthquakes every 500 years on average during the past 1,200 years. The estimated uncertainties on the timing of each New Madrid event allow for the recurrence time of New Madrid events to be as short as 160 years and as long as 1200 years (Cramer, 2001).

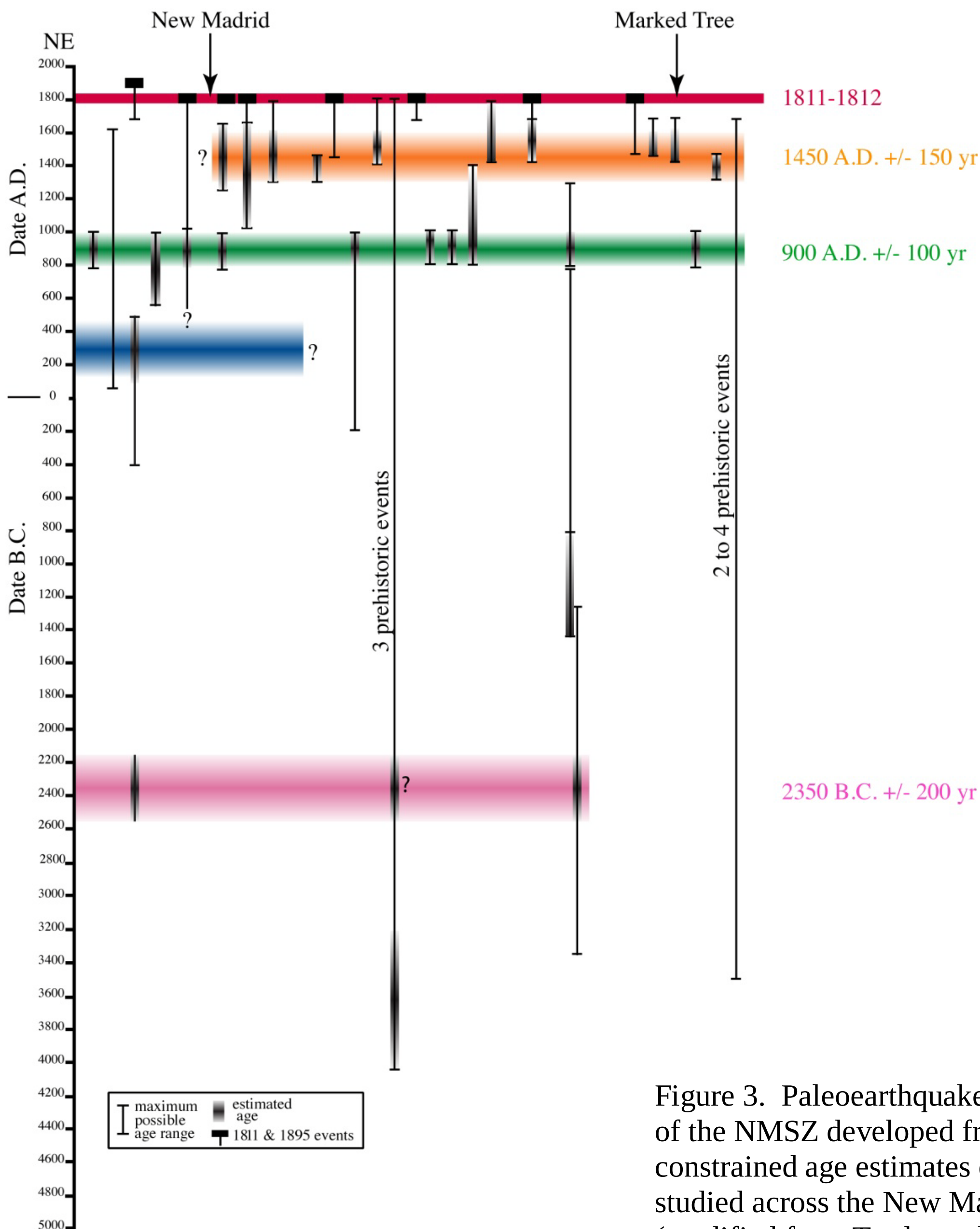

Figure 3. Paleoearthquake chronology of the NMSZ developed from well-constrained age estimates of sand blows studied across the New Madrid region (modified from Tuttle et al., 2002).

Displacement histories across the Reelfoot and Ridgely faults revealed in seismic reflection data also suggest that multiple major earthquakes may be typical of the New Madrid seismic zone (Van Arsdale et al., 1998). Trench investigations at sites along the Reelfoot scarp found evidence for three deformation events, including the 1812 event, associated with the Reelfoot fault during the past 1200 years (see Stop D; Russ, 1982; Kelson et al., 1996). The results of the fault studies were in agreement with the paleoliquefaction studies (Figs. 2 and 3).

This field trip focuses on the NMSZ, historical accounts of the effects of the 1811-1812 earthquakes, and recent seismological, geological, and geophysical results that pertain to the hazard posed by faults associated with the Reelfoot Rift fault system. Field trip stops include a site of earthquake-induced liquefaction and ground failure, Reelfoot Lake, Reelfoot scarp, a continuous GPS monitoring station, a creek exposure of near-surface stratigraphic units, and (Mississippi River stage permitting) a trench along the eastern margin bluff line near Memphis. (Fig. 4). Significant time has been allotted for participants to examine geologic features and to discuss recent findings with investigators.

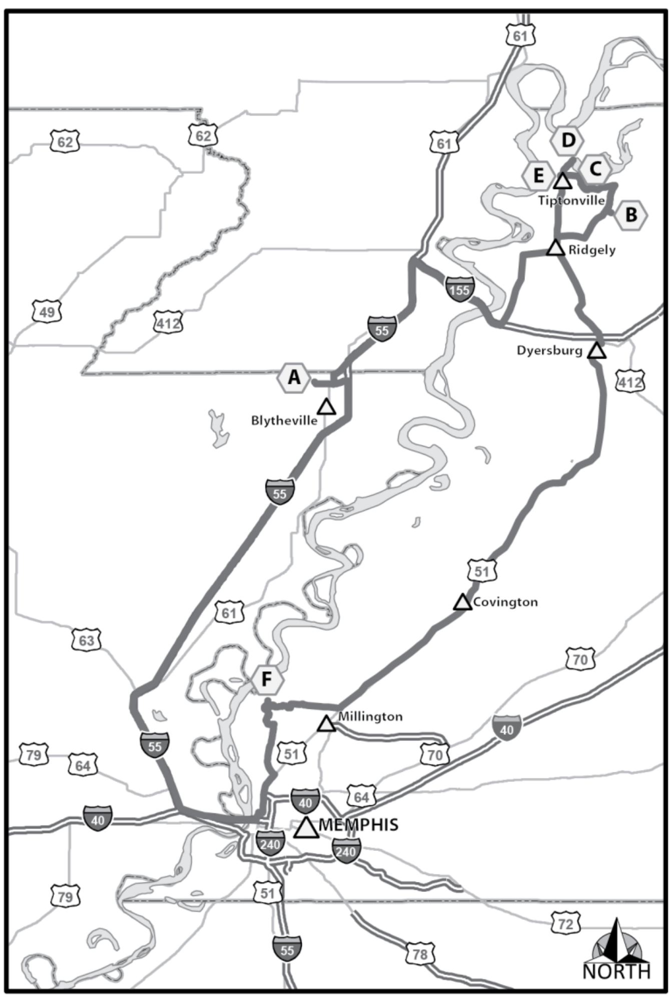

Figure 4. Map of field trip stops A-F.

A. Earthquake-induced liquefaction and related ground failure

B. Shallow stratigraphy of the region, Pawpaw Creek exposure

C. Reelfoot Lake at Blue Bank

D. Reelfoot Scarp, Tiptonville Dome, and Lake County Uplift

E. Seismic and geodetic networks, GPS station LCHS, Lake County High School

F. Trench exposure near Meeman-Shelby Forest

Stop A: Site of Earthquake-Induced Liquefaction and Ground Failure near Blytheville, AR (contributed by M. Tuttle)

Yarbro excavation and Ruth Dillahunty trench are located in close proximity to the Blytheville fault zone and about 3 km east of the Bootheel lineament that are thought to have ruptured during the December 16, 1811 mainshock and its two largest aftershocks (Fig. 2; Johnston and Schweig, 1996). The site occurs in the Holocene meander belt of the Mississippi River and along the southern bank of the Pemiscot Bayou, that reportedly “blew up” during the New Madrid earthquakes (Fig. 5; Penick, 1981). Many large sand blows formed in this area during the 1811-1812 earthquakes and are still visible on satellite images and in plowed fields today.

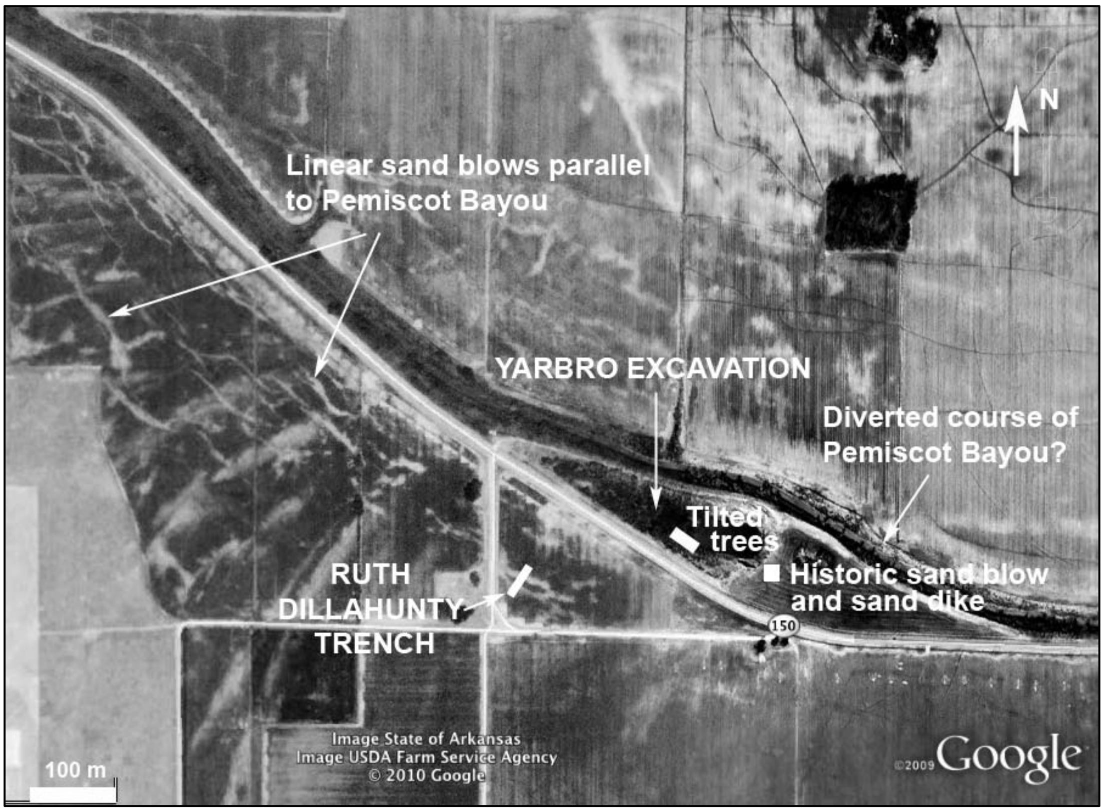

Figure 5. Google Earth satellite image of Yarbro excavation and Ruth Dillahunty trench site along southern bank of Pemiscot Bayou north of Blytheville, Arkansas. Northwest-southeast oriented sand blows parallel to and within 300 m of bayou, as well as possible diversion of course of bayou, may be related to lateral spreading towards the channel.

The Holocene meander belt of the Mississippi River is composed of channel and point bar deposits of medium to coarse sand and abandoned channel deposits of silt and clay (Guccione, 1987; Saucier, 1994). Clayey back swamp deposits predominate in the western portion of the meander belt. Natural-levee deposits, which typically consist of thinly bedded fine sand and massive sandy silt to clayey silt, occur between the active portion of the meander belt and the backswamp (Guccione, 1987; Saucier, 1994). The Pemiscot Bayou, the largest and youngest of the four distributaries of the Mississippi River recognized in the northern Lower Mississippi Valley, extends from its distributary node near Caruthersville, Missouri to its confluence with the

St. Francis River near Marked Tree, Arkansas (Saucier, 1994). About 5,000 years B.P., the Pemiscot Bayou captured about 25% of the Mississippi River discharge and remained active for about 2,500 years, developing a 1.5-5 km wide meander belt with associated point bar, overbank, and abandoned channel-fill deposits (Guccione et al., 1999). The meandering distributary never fully avulsed (or captured more than 40% of the main river discharge) and the channel was largely infilled by 2,200 years B.P. (Guccione et al., 1999). During the past few decades, portions of the channel are periodically cleaned and dredged by the U.S. Army Corps of Engineers as part of the extensive system of ditches that drain the Mississippi River floodplain.

Yarbro excavation is currently an inactive borrow pit from which sand was mined in the 1990s for use primarily in construction of house foundations (Fig. 5). The source of the sand was very large sand blows that had formed during the 1811-1812 earthquakes as well as an earlier event (Tuttle, 1999). The borrow pit was excavated adjacent to the dredged channel of the Pemiscot Bayou. In the 1990s, earthquake-induced liquefaction features, including large sand blows and related sand dikes were exposed in the northeastern, southeastern, and southwestern walls of the borrow pit as well as in walls of islands within the pit and in the pit floor (Figs. 5 and 6). The liquefaction features were logged, measured, and dated and the results combined with those from many other liquefaction sites across the region to estimate the timing, locations, magnitudes, and recurrence times of earthquakes generated by the NMSZ (Figs. 2 and 3; Tuttle et al., 2002). Those interested in detailed descriptions of liquefaction feature studied at this site are referred to Tuttle (1999).

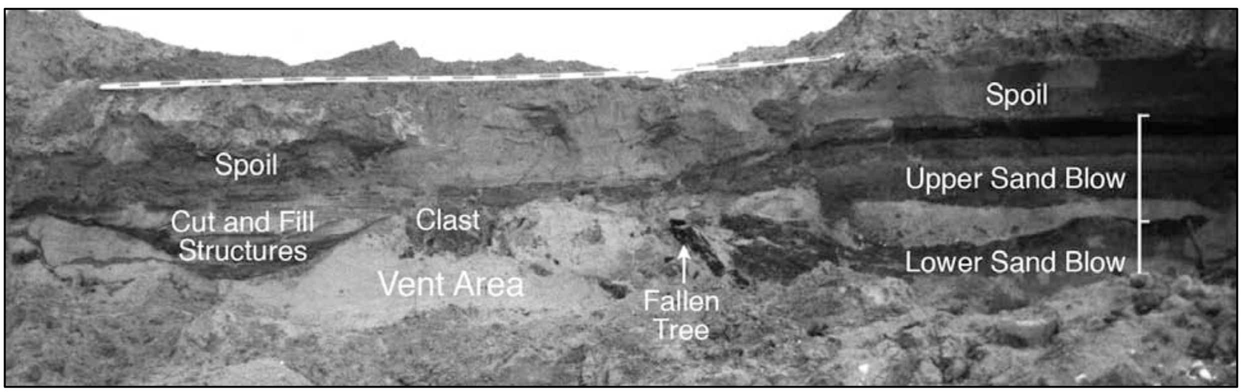

Figure 6. Photograph of two generations of sand blows and vent area exposed in the southeast end of the excavation in the 1990s. Notice soil developed in top of lower sand blow. White and gray intervals on stadia rod represent 10 cm.

During the site investigation in the 1990s, two stacked sand blows, and the vent area of the upper sand blow, were exposed in the southeastern wall of the borrow pit (Figs. 5 and 6). The upper sand blow, thought to have formed during the 1811-1812 earthquakes, was up to 2 m thick and composed of interbedded silty, very fine sand, fine sand, and medium sand with many pieces of lignite and silt clasts. The lower sand blow was about 30 cm thick, of limited lateral extent, and composed of medium sand containing clasts. A 12 cm thick A horizon had developed in the top of the lower sand blow indicating that it had formed during an earlier event.

In the vent area, the lower sand blow was cross-cut by a sand dike of medium sand characterized by nearly vertical flow structure and containing many clasts, some ranging up to 1.2 m in diameter. The sand dike, through which sand-bearing water erupted to the surface, may be about 6 m wide, trends about S75°E, and is roughly parallel to and about 80 m from the channel of Pemiscot Bayou. On either side of the large feeder dike, the paleosols buried by the sand blows dipped towards the dike. Tree trunks exposed near the southwestern wall of the pit were rooted in a paleosol, buried by sand blows, and tilted 16 to 18° from the vertical towards the large feeder dike (Fig. 7). The dip of the paleosol and the tilt of the trees towards the feeder dike suggest that subsidence of the ground surface accompanied venting of sand-bearing water as the result of liquefaction of subsurface sediment. A cross-section developed from coring data indicates that the ground surface subsided about 2 m during the historic events (Guccione et al., 1996). Given that the site is located adjacent to the Pemiscot Bayou, it is likely that lateral spreading toward the channel was involved and may have contributed to the severity of ground failure and formation of the very large feeder dike and sand blows (Tuttle, 1999). As seen on satellite images of the area, many linear sand blows or sand fissures parallel to and within 300 m of the Pemiscot Bayou support the interpretation that lateral spreading occurred along the bayou (Fig. 5).

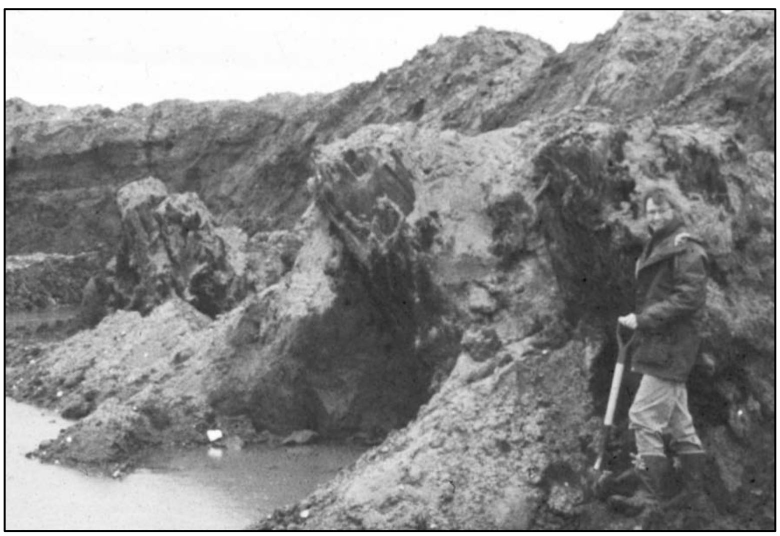

Figure 7. Photograph of *in situ* tree trunks that were buried by sand blow deposits and tilted towards large feeder dike probably as result of subsidence.

The Ruth Dillahunty trench was excavated across one of the linear sand blows that probably formed as the result of lateral spreading towards the Pemiscot Bayou (Figs. 5 and 8). The sand blow is not obvious on the ground surface because a fairly thick soil has developed in the top of the sand blow; however, it is recognizable because of its affect on crops. Crops growing in sand blows and sand dikes, which have low-moisture holding capacity, often wilt and die during the summer months. The liquefaction features exposed in the trench are relatively small, compared to those that were exposed in Yarbro excavation, which actually makes it easier to observe critical relationships. The buried soil horizon (IIA) is crosscut by two sand dikes (54 and 11 cm wide) and is displaced downward by about 1 m across the dikes. The sand blow is composed of 4 major depositional units (labeled 1 - 4), three of which fine upward, probably resulting from 4 large shocks in a closely timed sequence of earthquakes. The sand blow is overlain by a 28+ cm thick soil horizon, including plow zone) of silty to sandy loam (A) suggesting that the sand blow predates the 1811-1812 earthquakes. Depositional units 7 and 8, as well as the upper portion of unit 4, are probably related to another nearby sand blow (Fig. 5).

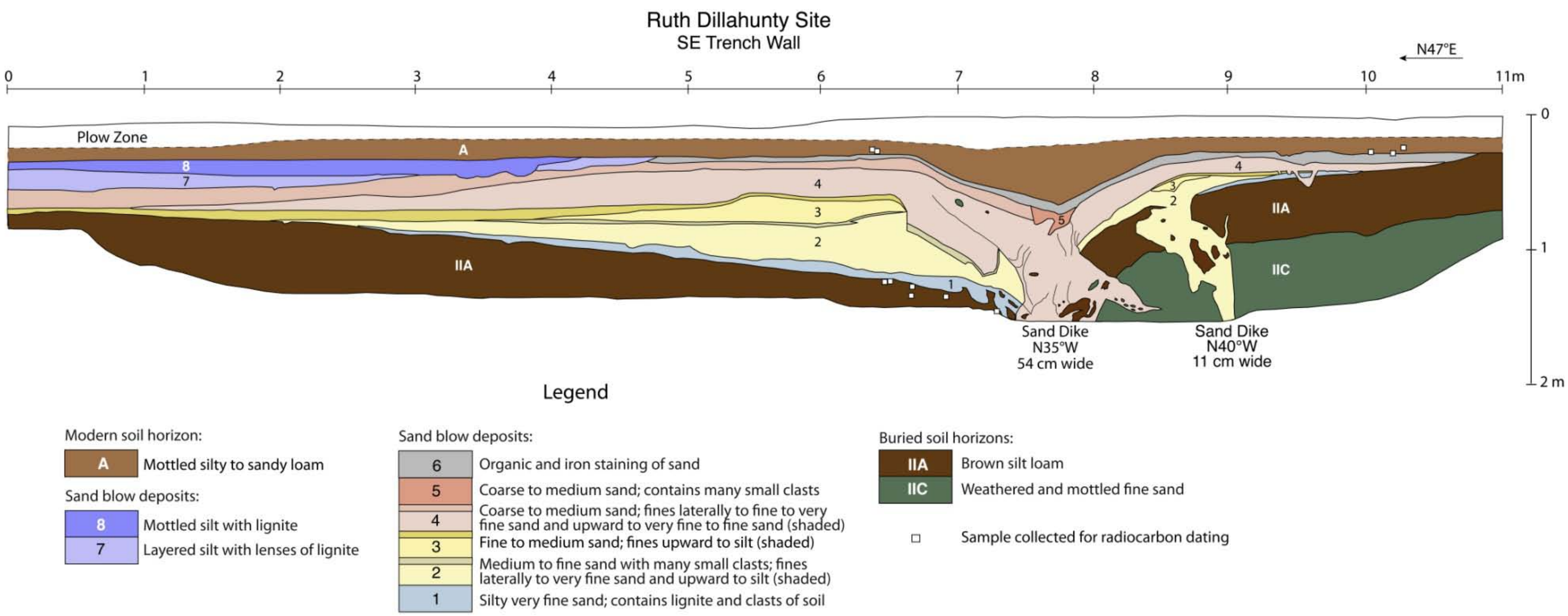

Figure 8. Trench log of compound sand blow and related sand dikes exposed in trench wall at Ruth Dillahunty site. Compound sand blow is composed of 4 major depositional units with no soil development in between suggesting that it formed during 4 earthquakes clustered in time. Thickness of soil devloped in top of sand blow suggests it predates 1811-1812 earthquakes. Layers towards northeastern end of trench may be influenced by and related to venting from nearby subparallel dike. Logged by M. Tuttle and M. Haynes, Sept. 12-13, 2010.

Stop B: Shallow stratigraphy of the region, Pawpaw Creek Exposure
(contributed by R. Van Arsdale)

The NMSZ is in the northern part of the Mississippi embayment, a broad trough opening to the south, whose axis coincides approximately with the Mississippi River. The embayment fill consists of Cretaceous sediments unconformably overlying Paleozoic bedrock and capped by Tertiary and Quaternary sediments. Embayment formation initiated during the late Cretaceous and has been interpreted as having been caused by the passing of the Mississippi Valley over the Bermuda Hotspot (Cox and Van Arsdale, 1997; 2002). Subsequent sedimentation has largely been controlled by changes in sea level. In the Mississippi River valley, Quaternary (~ past 2 million years) surficial sediments reflect cyclic glacial and interglacial climates and associated glacial outwash.

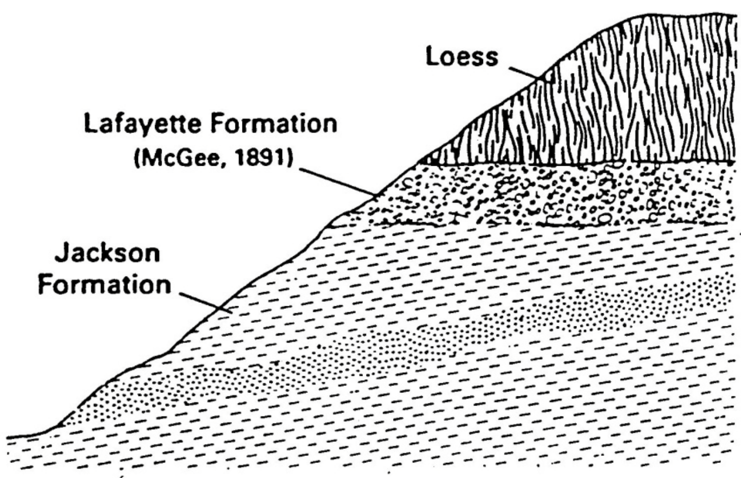

Figure 9. Generalized stratigraphy of bluffs east of Mississippi River in field trip area (from Jibson and Keefer, 1988).

The stratigraphy in the bluffs along the Mississippi Valley in the area of this trip is shown in Figure 9. The Eocene/Oligocene Jackson Formation is beneath the Mississippi River alluvium and at the base of the bluff in most of the trip region; exposures are as thick as 50 m. The composition of the Jackson Formation is highly variable; it generally comprises discontinuous layers of shallow-water marine clays and silts that are a few centimeters to tens of meters thick. In some areas the Jackson Formation contains clean uncemented sand more than 10 m thick interbedded with soft clays. The Plio-Pleistocene Lafayette Formation (Upland Complex) lies unconformably on the Jackson Formation (Autin et al., 1991; Van Arsdale et al., 2007). These fluvial sands and gravels are as thick as 20 m but may be locally absent. The deposits are uncemented in many areas, but a few localities contain concretionary beds as thick as 2 m. The bluffs are capped by 3 to 45 m of Pleistocene loess, which lies unconformably on the Upland Complex and locally on the Jackson Formation; the average loess thickness is 15 m. Loess is wind-blown silt from Mississippi River sediments deposited during glacial cycles. It commonly forms vertical faces that are supported because of a clay binder, calcareous cement, or both. The loess thins eastward and pinches out approximately 100 km east of the bluffs.

Approximately 1.7 miles east of the Mississippi Valley bluffs is a beautiful stratigraphic exposure in a 25 m high cut bank of Pawpaw Creek. At the bridge, walk about 100 m south to the exposure. Exposed in this cut bank are 5 m of Jackson Formation, overlain by 7 m of Upland Complex, which is in turn overlain by 12 m of loess. These thicknesses are approximate since the section has not been measured at this site. This exposure illustrates the near-surface stratigraphy that is characteristic of the bluff line from Mississippi through Kentucky.

Stop C: Reelfoot Lake at Blue Bank
(contributed by R. Van Arsdale)

Perhaps the feature most commonly associated with the 1811-1812 earthquakes is Reelfoot Lake; it fills a broad, shallow, irregular depression about 20 km long (measured SW to NE) by about 6 km wide. Maximum lake depths are about 5 m; the average depth is only about 2 m. The lake and surrounding marshes cover approximately 100 km^2. Although several historical accounts attribute the formation of Reelfoot Lake to the 1811-12 earthquakes, the association of the lake with old river channels and the presence of discontinuous bayou levees indicates that much of the region was probably covered by oxbow lakes before 1811 (Russ, 1982); however, Russ cited drowned baldcypress trees, partially eroded Indian mounds, and submerged trees marking old land-grant boundaries as evidence that the lake enlarged significantly during the 1811-12 earthquakes.

Baldcypress tree rings were collected to assess the impact of the 1811-12 earthquakes and, in particular, to determine if there is a tree-ring response to the formation of Reelfoot Lake. Forty-eight living baldcypress trees were sampled in Reelfoot Lake with one to four cores taken from each tree (Stahle et al., 1992; Van Arsdale et al., 1998). The annual rings were dated to their exact year of formation.

As illustrated in Figure 10 (top), there is a dramatic tree-ring response to the coseismic inundation of Reelfoot Lake. Tree-ring indices fluctuate around a value of 1.0 from 1685 to 1990 with a major growth surge from 1812 through 1819. Ring widths are variable for 1812 with some being very narrow and others very wide. By 1813 all the trees in the data set have extremely wide rings and the 1814 mean index value is the largest ever recorded in a baldcypress tree-ring chronology (Stahle et al., 1992). A second coseismic response in the Reelfoot Lake tree rings is a major decrease in the ratio of latewood to earlywood. This is visually apparent in the cores as a change to a lighter toned core at 1812 that continues to 1990. (Latewood or summerwood is the darker cells that terminate the annual growth layers of many mid-latitude trees). Thus, coseismic inundation resulted in a longer earlywood growing season, the virtual elimination of late summer droughts, and a much curtailed latewood growing season. A third coseismic response observed in the Reelfoot cores is the numerous cracks and breaks in the pre-1812 portions of the cores as compared to the solid post-1812 portions. It appears that many of the trees were physically damaged during the 1811-12 earthquakes.

The Reelfoot Lake chronology is one of a number of baldcypress chronologies in the Mississippi Valley (Van Arsdale et al., 1998). Most of these chronologies lie outside the meizoseismal area of the 1811-12 earthquakes. From these unaffected chronologies a baldcypress regional chronology has been made (Fig. 10, bottom). Comparing the Reelfoot chronology with the regional chronology, and the individual chronologies that went into the regional chronology, reveals that Reelfoot Lake is the only tree-ring site that shows this growth surge. It should also be noted that the St. Francis sunklands of northeastern Arkansas (not visited on this field trip) also were affected by these earthquakes (Fig. 10, middle). However, the St. Francis sunklands baldcypress experienced a major growth suppression that lasted for 45 years.

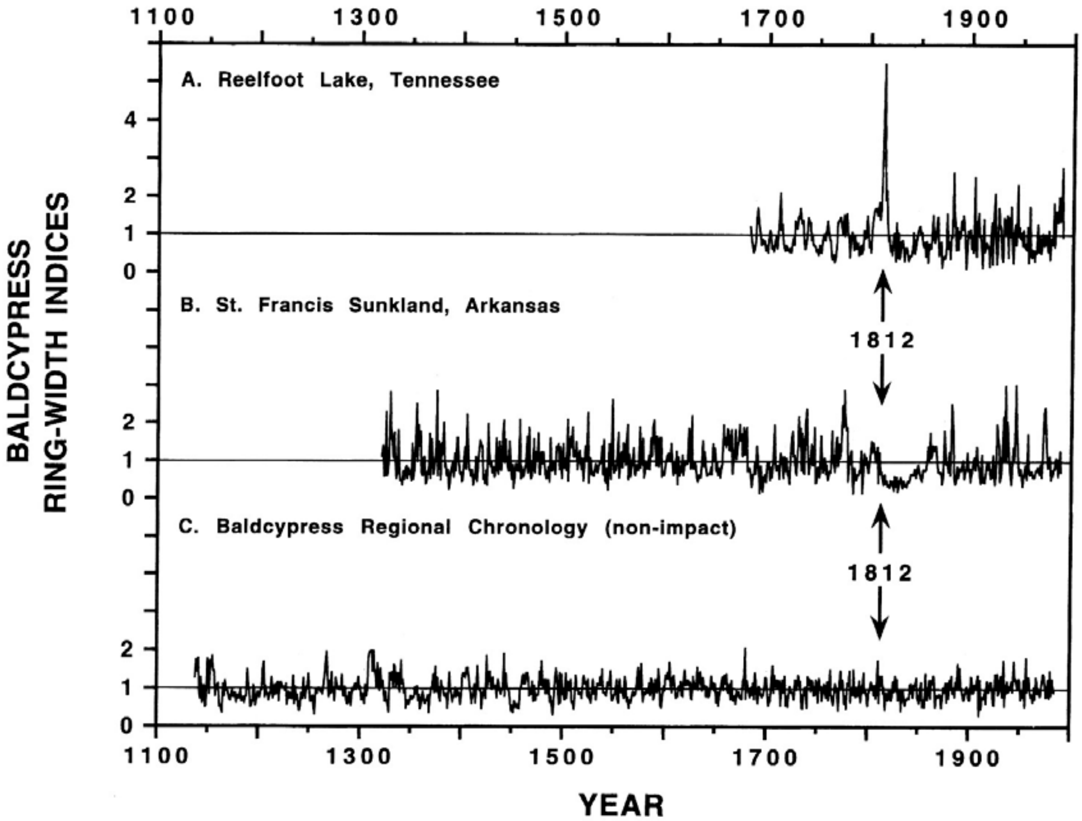

Figure 10. Baldcypress tree-ring chronologies from Reelfoot Lake, Tennessee (A), St. Francis sunkland, Arkansas (B), and regional chronology based on four baldcypress chronologies in central Arkansas (C). These mean ring-width chronologies are dimensionless indices of growth for each year and are based on samples of exactly dated ring-width time series. Note unprecedented growth surge at Reelfoot Lake that peaked in 1814 and prolonged growth suppression at St. Francis sunkland following New Madrid earthquakes of 1811-1812. These tree-growth anomalies within the New Madrid seismic zone are not evident in the regional chronology from central Arkansas (C) (from Van Arsdale et al., 1998).

Stop D: Reelfoot Scarp, Tiptonville Dome, and Lake County Uplift
(contributed by R. Van Arsdale)

The Reelfoot fault is believed to extend from New Madrid, Missouri, to near Dyersburg, Tennessee (Van Arsdale et al., 1999) (Fig. 1). However, the Reelfoot scarp is formed in Holocene Mississippi River alluvium from the southern margin of Reelfoot Lake to the Kentucky bend. The scarp faces east, is 3 to 10 m high, and has slope angles ranging from 1 to 6 degrees, which is significant and visible on the smooth alluvial plain. West of the scarp, the Tiptonville dome rising as much as 10 m above the surrounding flood plain, is the highest part of the larger Lake County uplift, which has maximum dimensions of 50 km by 23 km. The Reelfoot scarp is interpreted to be a consequence of fault-propagation folding (Van Arsdale et al., 1995; Kelson et al., 1996), whereas the Lake County uplift and Tiptonville dome are believed to be due to fault-bend folding (Purser and Van Arsdale, 1998; Van Arsdale, 2000) (Fig. 11).

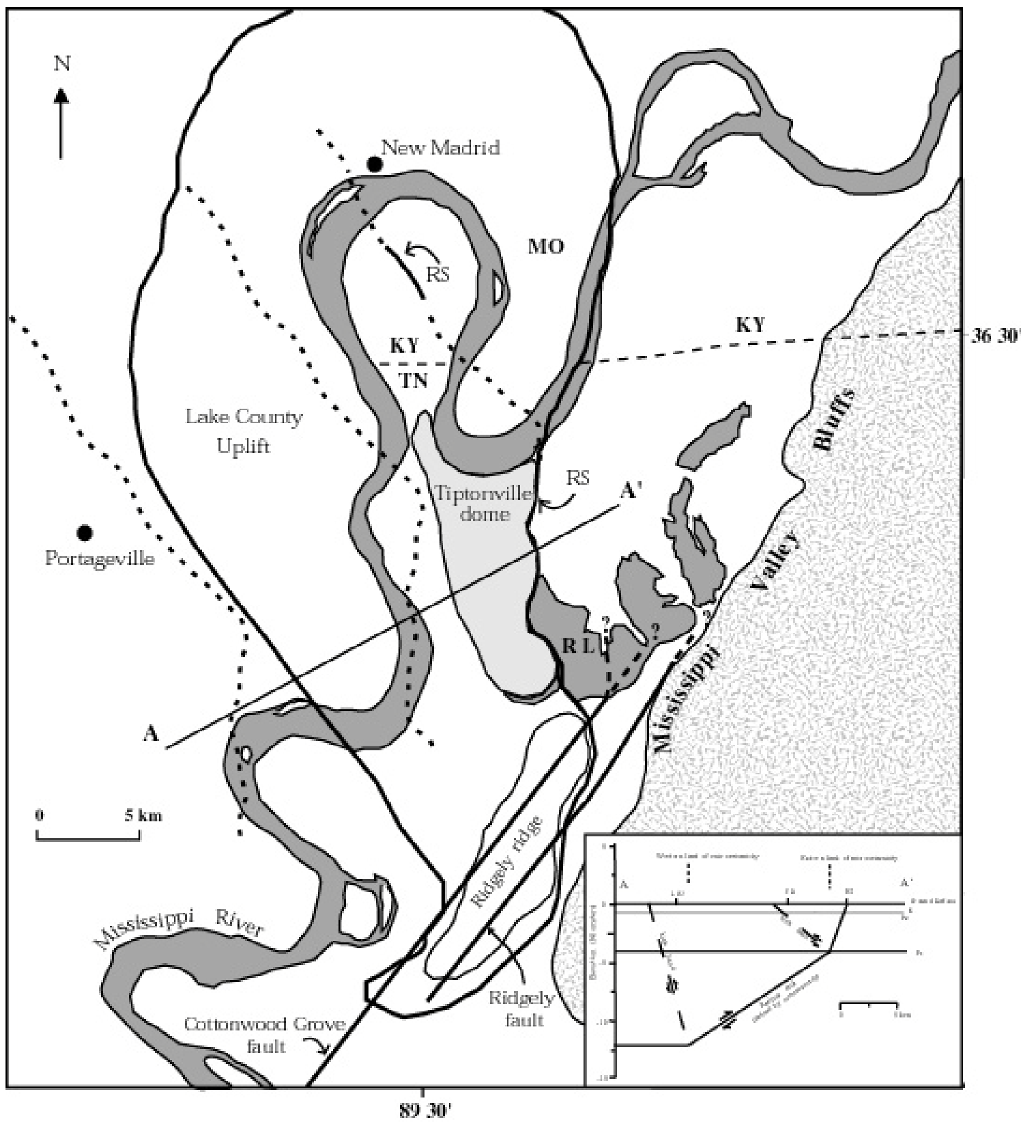

Figure 11. The Lake County uplift and vicinity. The solid line marks the boundary of the Lake County uplift as defined by Russ (1982), and the dotted lines are locations of the Reelfoot fault and proposed kink bands (back-thrusts) on the west side of the Tiptonville dome and Lake County uplift. Line A-A' is the line of cross section in inset. RS = Reelfoot scarp, RL = Reelfoot Lake. K = top of Cretaceous, Pz = top of Paleozoic, Pc = top of Precambrian, LCU = Lake County uplift western margin, TD = Tiptonville dome western margin, RS = Reelfoot scarp (from Purser and Van Arsdale, 1998)

To help constrain the number and timing of late Holocene large-magnitude earthquakes, numerous trenches across the scarp have been opened to investigate scarp-derived colluvial deposits related to deformation. A 90-m-long, east-west oriented trench was excavated across the Reelfoot scarp approximately 60 m west of the western margin of Reelfoot Lake at Champey Pocket near Reelfoot Lake's south shore by Kelson et al. (1992). Stratigraphic relations and age-estimates best support the interpretation that the unweathered liquefaction-related features exposed in the trench are a result of the 1811-1812 earthquakes, and that the scarp-derived colluvial deposits are a result of a prior event. Radiocarbon analyses show that this penultimate event occurred between about A.D. 1310 and A.D. 1540. Stratigraphic evidence of a third event about A.D. 900 is present but equivocal. Liquefaction-related features included sand dikes and sills that intrude into the levee and overbank deposits, and a possible older extrusive sand deposit. Charcoal and archeological artifacts from a deposit inset into and overlying the levee deposits suggest that they are older than about A.D. 800 to 900. Charcoal from the overbank deposits yielded an age-estimate of ca. A.D. 1310 $\pm$ 90; charcoal from the overlying colluvial deposits yielded an age-estimate of ca. A.D. 1540 $\pm$ 90.

Distinct marker beds within the levee deposits define a broad monocline that parallels the ground surface and exhibits more than 5 m of down-to-the-east vertical separation. This fold consists, in part, of four smaller-scale flexures each having amplitudes of about 1 m. Associated with these flexures are numerous west-dipping normal faults that have a total net vertical separation of about 0.4 m in a down-to-the-west sense, which is opposite in sense to that exhibited by the scarp and the silty marker beds. We interpret that these faults are related to extension in the crest of the monocline, and that the monocline represents deformation above a west-dipping reverse fault that reaches or approaches the ground surface east of the trench and the base of the scarp. At the trench site, this interpretation places the surface projection of the fault near the western margin of Reelfoot Lake.

Scarp height at field trip stop E, coincident with the Proctor City Trench site, is 8 m (Fig. 12). Two trenches located approximately 10 m apart were excavated across the scarp at this site by Kelson et al. (1996), and more recently by Champion et al. (2001). Most of the deformation in the trench is monoclinal folding but a graben was exposed near the top and steepest part of the scarp (Fig. 12). Three episodes of faulting within the last 2,400 years were revealed in these trenches. These events occurred between A.D. 780 and 1000, between A.D. 1260 and 1650, and during A.D. 1812. Each event had a slightly different style of deformation. The oldest event formed a small graben in the hanging wall of the fault that was only a few tens of centimeters deep. The second most recent event resulted in 1.3 m of throw in the graben in conjunction with updip propagation of the reverse fault and scarp development. The 1812 earthquake produced minor faulting on the graben, major folding of fluvial strata across the scarp, and abundant liquefaction (Kelson et al., 1996). These trenches provide good constraints on the earthquake history of the Reelfoot fault and illustrate the utility of using hanging wall grabens in the dating of thrust fault deformation. An S-wave seismic reflection profile conducted across the scarp prior to trench excavation by James Harris revealed a west-dipping reverse fault. When trench HST1 was excavated the fault projected to the surface at distance 13 m where a reverse fault was revealed (box labeled Area of Figure 7 in Fig. 12).

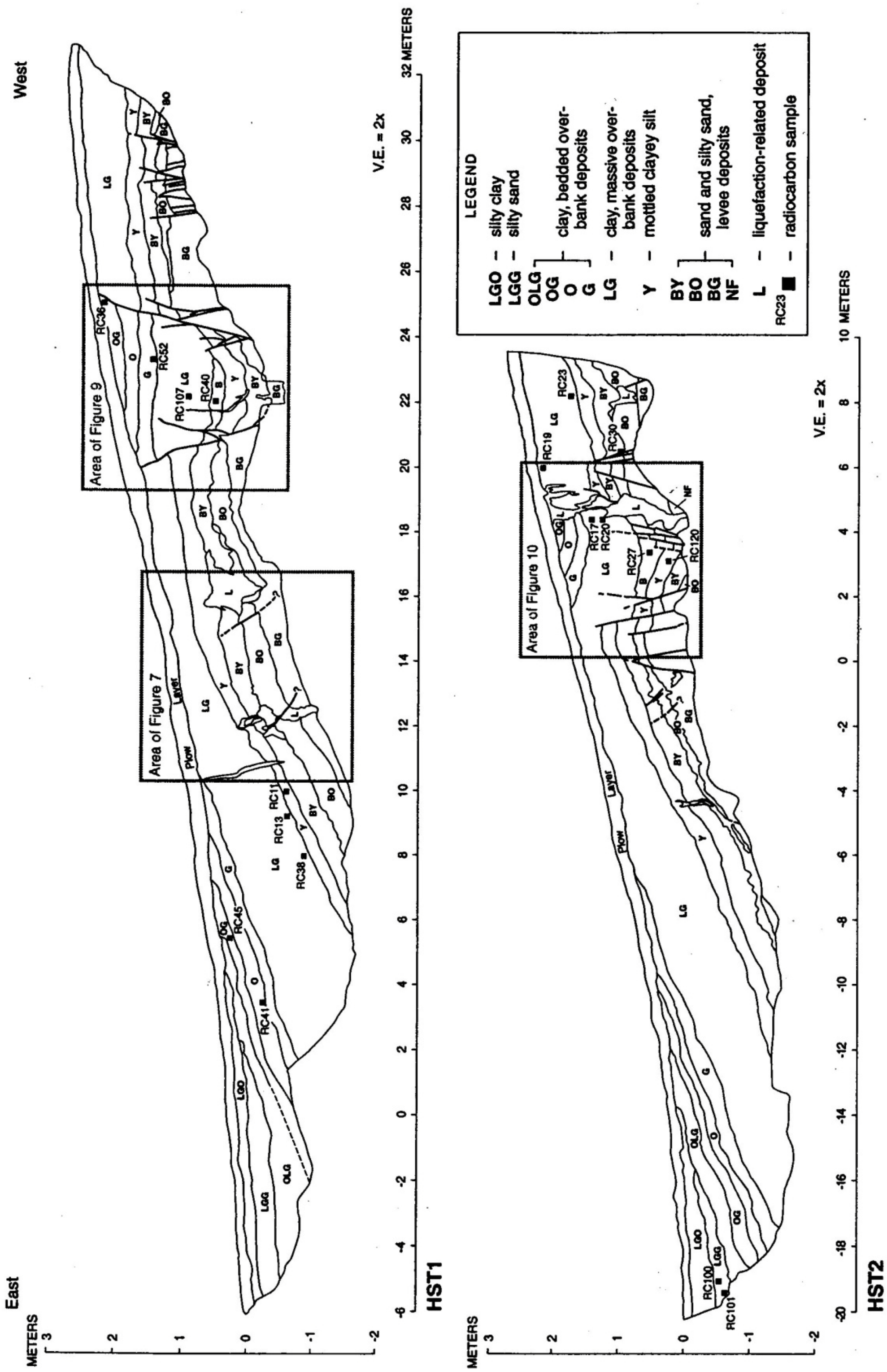

Figure 12. Generalized logs of southern walls of trenches HST1 and HST2 at the Proctor City site (A) (from Kelson et al., 1996).

Stop E: Seismic and Geodetic Networks, GPS station LCHS, Lake County High School (contributed by H. DeShon)

The US Geological Survey, Saint Louis University (SLU), and the Center for Earthquake Research and Information (Univ. of Memphis) fund and/or maintain seismic and geodetic networks in the New Madrid region. The current continuously recording seismic network is known as the Cooperative New Madrid Seismic Network (CNMSN). The network consists of 3-component short-period and broadband instrumentation, and CERI maintains the earthquake catalog derived using this network (Fig. 13). Approximately 200 earthquakes are recorded per year within the NMSZ by the CNMSN. Prior to the CNMSN, the Central

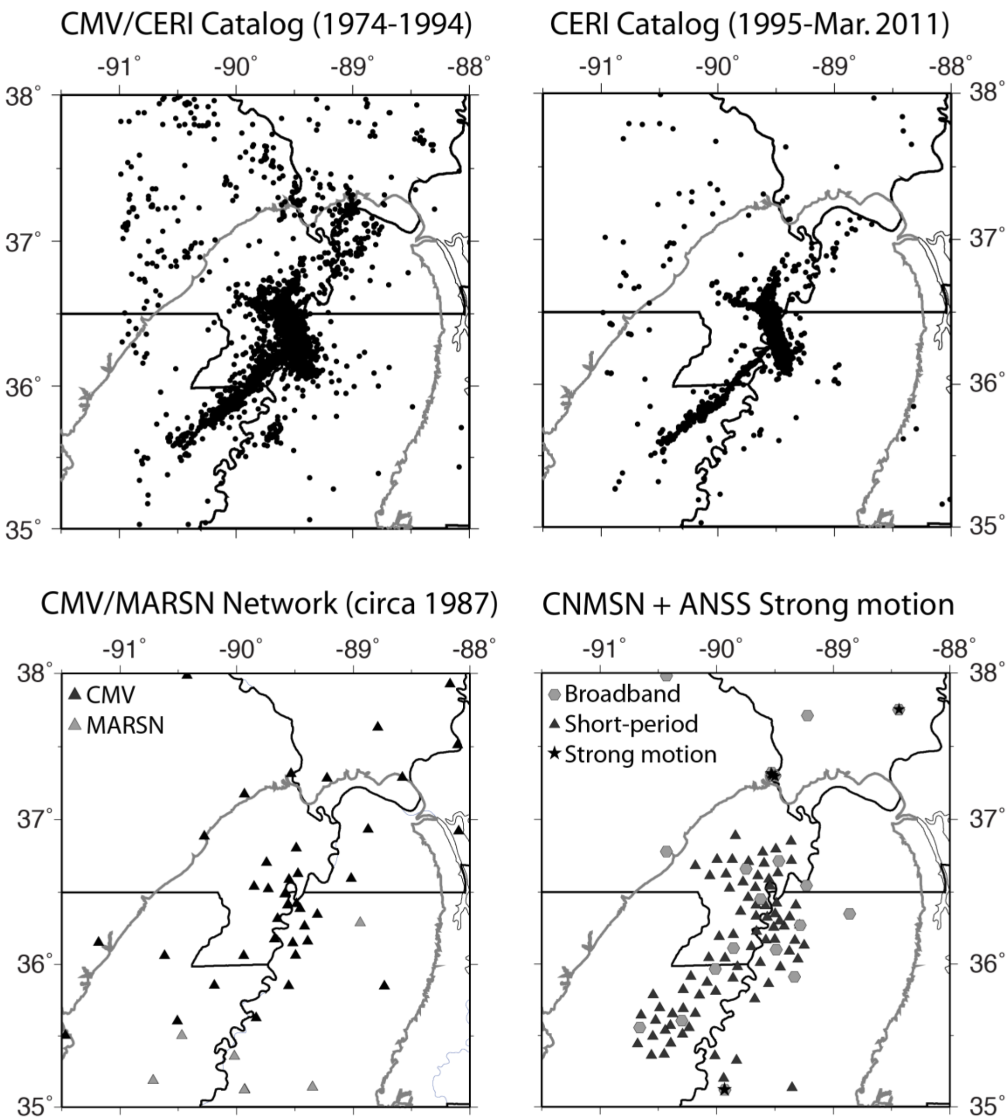

Figure 13: (top) TEIC and CERI catalog earthquake locations (black circles). The Mississippi embayment (gray) is shown for context. (bottom) The TEIC network and current CNMSN network. Stations are color-coded and shaped by type. Strong motion stations that are part of the ANSS network are also shown (stars).

Mississippi Valley (CMV) bulletin reported hypocenters using arrivals recorded by SLU's CMV network and CERI's Memphis Area Regional Seismic Network (MARSN). These networks were primarily vertical component stations that yielded poor depth constraints on resulting earthquake locations. Figure 13 shows the CMV/MARSN and CNMSN networks and related catalogs in order to illustrate the differences in station coverage and epicentral accuracy. Though the CNMSN catalog does not cover as many years, the image of the seismic zone has sharpened significantly due to the decreased uncertainties and increased accuracy of the absolute locations. Numerous high-resolution earthquake location studies using CNMSN catalog data (Csontos and van Arsdale, 2008; Dunn et al., 2010; Powell et al., 2011) or temporary seismic networks, such as the PANDA project, now exist for this region (Chiu et al. 1992, Pujol et al., 1997; Dunn et al., 2010; Powell et al., 2011).

Geodetic measurements have been made, and the interpretation and modeling of the resulting measurements debated, in the NMSZ since the early 1990s. Surface deformation rates as measured by campaign and continuous Global Positioning System stations are on the order of <0.2 mm/yr across the entire seismic zone (Newman et al., 1999; Calais and Stein, 2009). Smalley et al. (2005), however, reported that two continuous stations located on either side of the Reelfoot fault showed a relative convergence of ~2.7±1.6 mm/yr. The relatively short-time period of continuous recording in the region, large GPS station spacing, and uncertainty analysis using a different GPS processing package led Calais et al. (2005) to question this result. The GPS array in mid-America (GAMA) network of continuous stations has since been expanded (Fig. 14), and continuous recording continues to help resolve spatio-temporal resolution issues. The continuous recordings are just reaching the 10-year mark.

LCHS, the site we visit on the field trip, was installed September 2008 to help improve resolution across the Reelfoot fault. The signal is sampled at 30 sec, 1 Hz, and 5 Hz. All 30 second GAMA data is archived at CERI and the UNAVCO Facility and is available from the UNAVCO Facility Archive (UFA). 1 Hz data are archived at CERI and available upon request; 1 Hz data are downloaded/archived/available by the UFA on PBO triggers. 5 Hz data are archived at CERI and the UFA and is downloaded/archived/available by the UFA on PBO triggers. Monumentation of GAMA stations vary. Original GAMA stations are primarily I-beam monuments. LCHS is a deep pile monument.

Some researchers would argue that the present day surface deformation can't be resolved or that it is less than the uncertainty (Calais and Stein, 2009 and references therein). Such low surface deformation has been interpreted to mean that New Madrid is no longer active (e.g., Stein, 2010), but other scientists think that the rate of surface deformation may not be directly related to present-day seismicity rates, as it more likely may be at plate boundaries. Currently, there is no accepted model that accounts for both the low rate of present-day surface deformation and the 500 yr recurrence time of large New Madrid events estimated from the 1200-yr-long paleoseismic record. In the most recent version of the National Earthquake Hazard maps, the paleoseismic-based recurrence estimates are more heavily weighted than the geodetic-based estimates (Petersen et al., 2008).

Figure 14: GAMA continuous GPS stations (place markers). All data is available for download via UNAVCO. Network is maintained by Robert Smalley, CERI.

Stop F: Trenching just north of Meeman-Shelby Forest
(contributed by R. Cox)

The trench at Stop F reoccupies the Oldham trench site of Cox et al. (2006) that revealed faulting related to the southeast margin of the Reelfoot rift. An alignment of hypocenters and their focal plane mechanism solutions along this rift margin indicates it is an active fault with right-lateral strike-slip sense (Chiu et al., 1997). The southeastern rift margin is expressed as a series of collinear scarps across western Tennessee, and shallow reflection profiles, coring, and trenches show late Quaternary faulting along this lineament (Williams et al., 2001; Cox et al., 2006). Cox et al. (2006) collected push-cores along a transect across a bluff lineament just north of Meeman-Shelby Forest, near the Boat-ramp Road seismic profile (Figs. 15, 16, and 17). These cores revealed a tapering wedge of clay within an alluvial fan that suggests down-to-the-northwest displacement across two faults (>1 m separation on each) (Fig. 17A). Cox et al. (2006) excavated a 42 m trench adjacent to the core-hole line (Fig. 17B), and a vertical N57^{o}E-striking fault with ~0.5 m of down-to-the-northwest displacement was exposed in the trench at meter 36.

This fault displaces a paleosol with ^{14}C ages of ~4000 yr BP, and organic-rich sediment from the base of a graben depression over the fault has a ^{14}C age of ~2000 yr BP. We interpret this faulting event to have been slightly before 2000 yr BP. Fissuring and subsidence adjacent to the fault in the down-dropped block suggest an extensional component that may be due to co-seismic sliding. This fault is at the expected surface projection of the southern-most fault revealed in the Boat-ramp Road profile (Fig. 16), but the sense of throw is different. Thus, we postulate that throw changes rapidly along strike of the fault (consistent with strike-slip movement) or vertical displacement in the trench may be due to co-seismic sliding away from a strike-slip surface rupture. Organic-rich fill of a small fissure at meter 29.8 in the southwest trench wall yielded a ^{14}C age that can accommodate the 1811-1812 New Madrid earthquake sequence. The re-excavation of this site for this fieldtrip is planned to include trenching parallel to the fault in an attempt to observe strike-slip offset of alluvial fan channels.

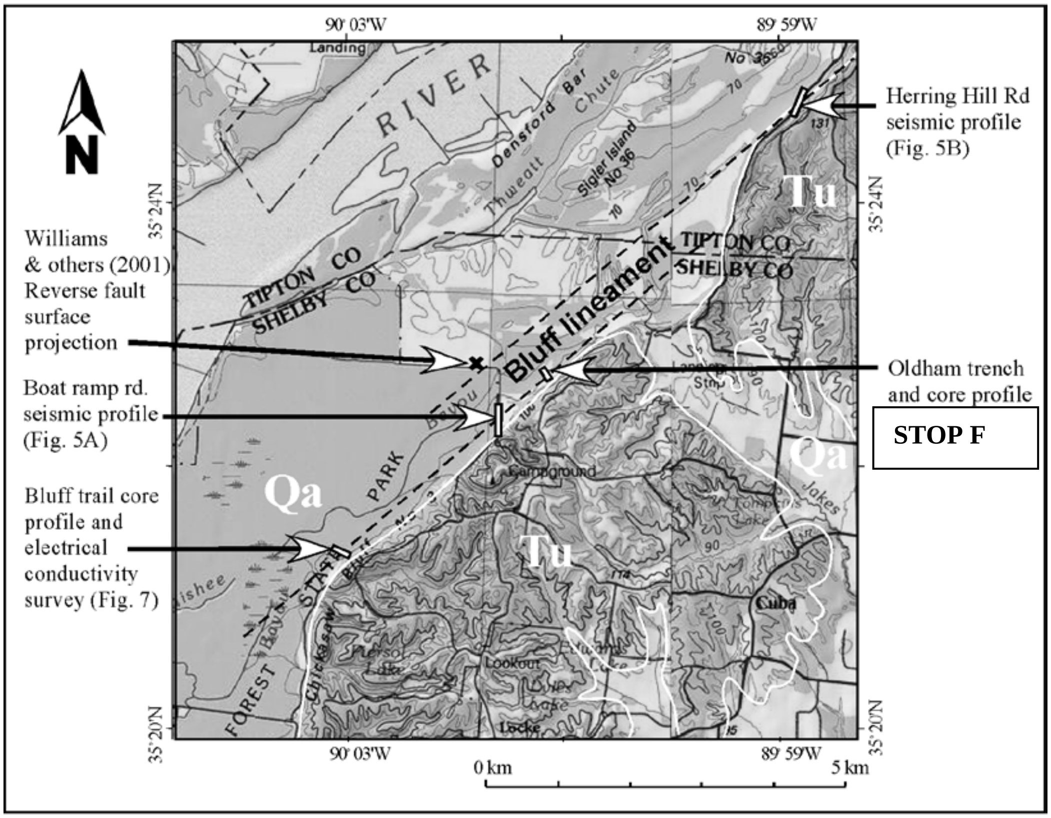

Figure 15. Surficial geology of Meeman-Shelby Forest State Park Investigation Sites. White line: boundary between Quaternary alluvium (Qa) and Tertiary uplands (Tu). Figure 4 from Cox et al. (2006).

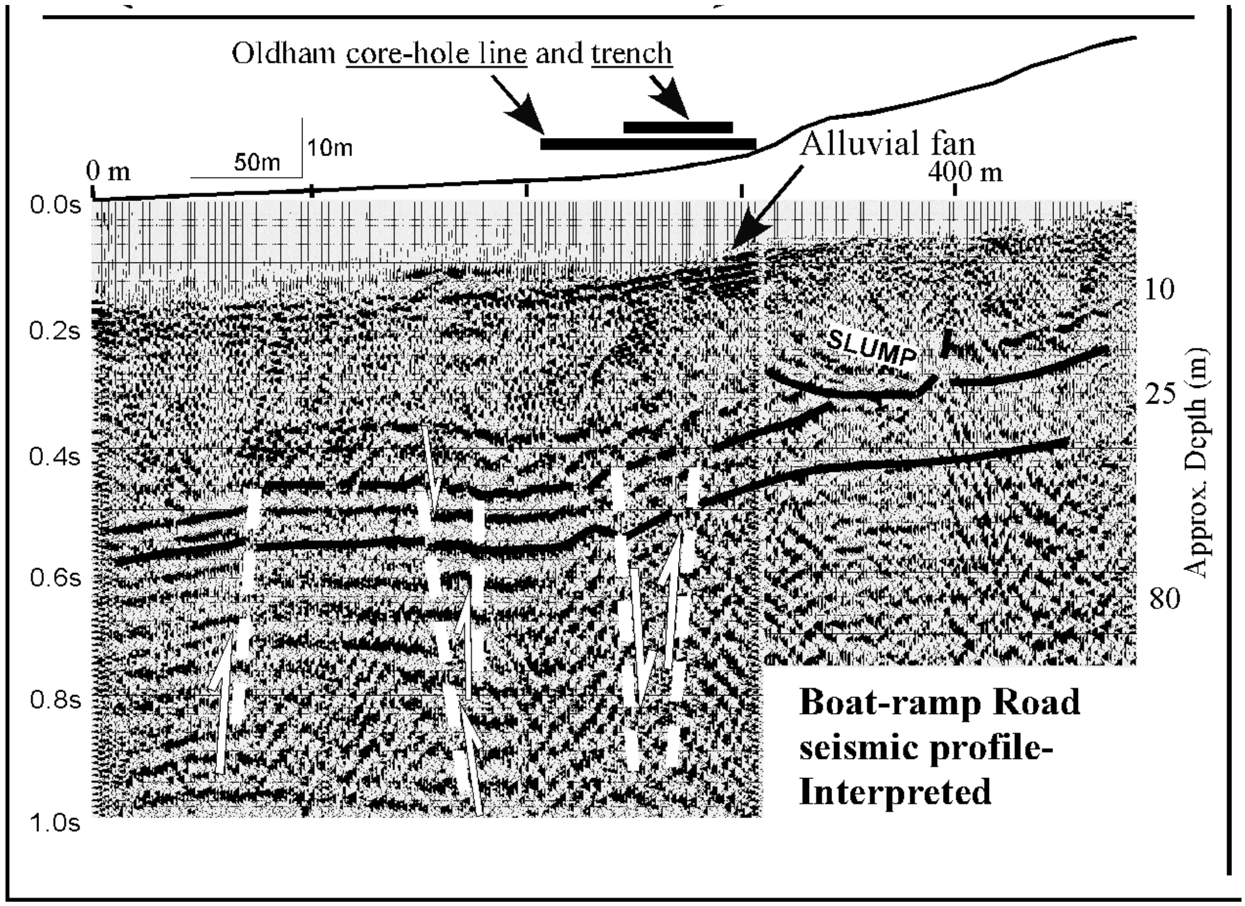

Figure 16. S-wave seismic profile (two contiguous lines combined) at Boat-ramp Road site (Cox et al., 2006) across southern segment of bluff-line lineament (see Fig. 15 for location). Prominent reflectors in these profiles (denoted by black lines on the lower profiles) are Jackson Group and upper Claiborne Group (middle Eocene) stratigraphic horizons and the interface between Quaternary alluvium and Eocene units, although surficial alluvial fan stratification c also be discerned. White dashed lines are interpreted faults. White half-arrows denote sense separation across faults. We interpret these faults as the top of a strike-slip flower structure related to the eastern margin of the Reelfoot Rift.

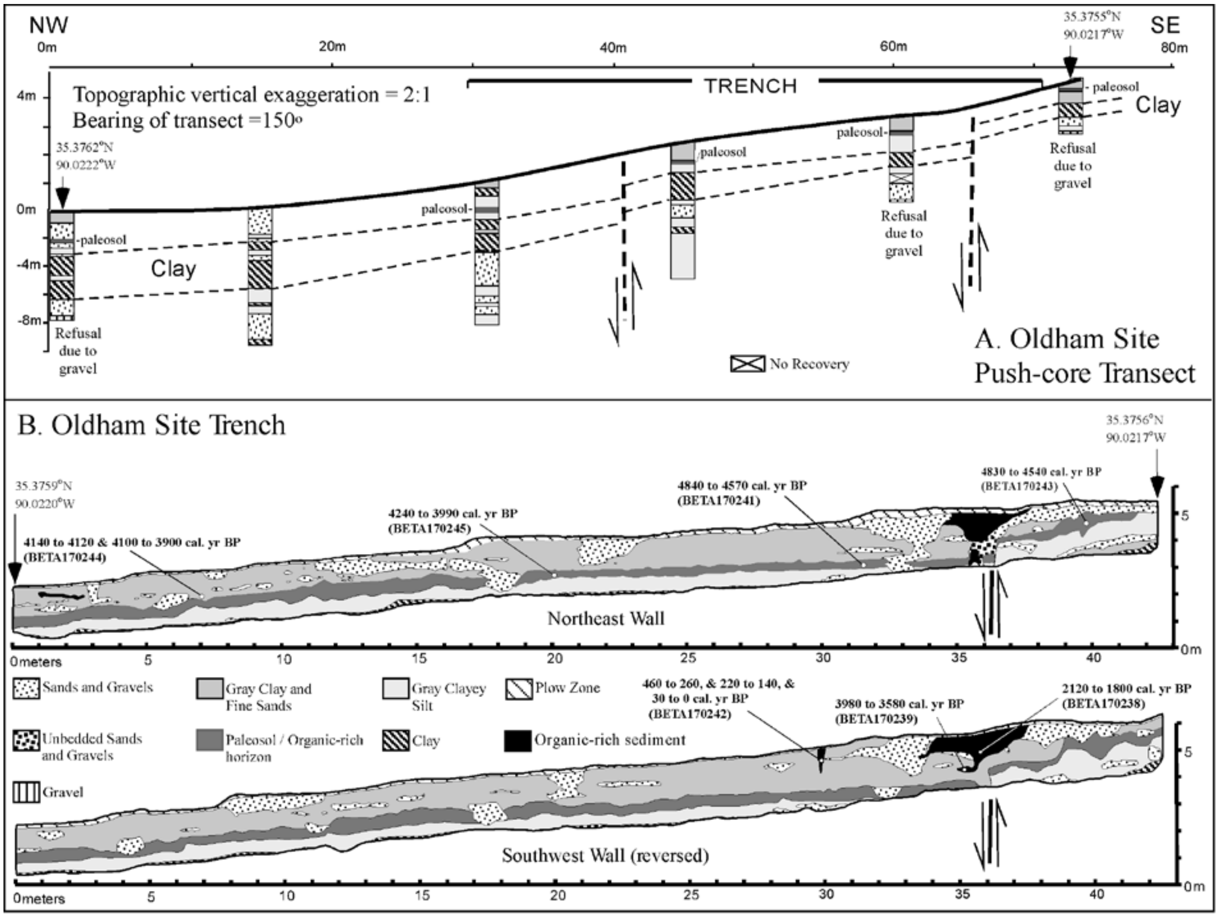

Figure 17. Oldham site on an alluvial fan at the base of the bluff-line lineament near the Boat-ramp Road seismic profile (see Figs. 15 and 16 for location). A) Interpretation of push-core transect (see B for stratigraphic legend). Heavy dashed lines are interpreted faults. Thin dashed lines denote a clay marker bed. B) Logs of trench walls. Open circles = 14C samples. Heavy line below log denotes a fault seen in trench walls and floor. Half-arrows denote sense of separation across fault. From Cox et al. (2006).

References Cited

The complete reference list for this field guide is available by request to H. DeShon.