

**LATE QUATERNARY FAULTING AND
EARTHQUAKE LIQUEFACTION FEATURES
IN SOUTHEAST MISSOURI:
THE IDENTIFICATION OF NEW EARTHQUAKE
HAZARDS**

Prepared for the

**43rd ANNUAL MEETING AND FIELD TRIP
OF THE ASSOCIATION of MISSOURI GEOLOGISTS**

in

**Cooperation with the Missouri Department of Natural Resources
Division of Geology and Land Survey**

**September 20 and 21, 1996
Cape Girardeau, Missouri**

FOREWORD

The earthquake features seen on this trip are geologic evidence that a number of large earthquakes have occurred during the recent prehistoric past in areas that today are not known for such activity. How will this geologic data be used to improve and change understanding of earthquake hazards in Missouri? Until recently, our understanding of where and how often major earthquakes occur in the middle Mississippi Valley was based mostly on historic and seismograph records. The historic record of earthquakes -- a mere 200 years -- is dominated by the extraordinary 1811-12 shocks which were centered in an area near and south of New Madrid, Missouri. This area, the New Madrid seismic zone (NMSZ), is the most seismically active region in the eastern United States. The second type of information has come from the seismograph recorded earthquakes operated by St. Louis University and the University of Memphis since the mid 1970s. Seismologists studying these modern seismograph records, together with the historic records, have estimated the size and repeat intervals for damaging earthquakes.

A third source of information, from geologic mapping, has more recently been expanded to improve our earthquake understanding. Previous geologic studies have focused in the area shaken by the strong 1811-12 quakes. For example, surface faulting is known at Reelfoot scarp where there is evidence for three surface faulting events, two of which occurred prior to 1811-12. Paleoliquefaction studies, the search for and study of older earthquake sandblows and dikes, have provided additional evidence of earthquakes prior to 1811-12, but mostly from the heart of the NMSZ, with the important exceptions of the Wabash Valley and the Western Lowlands. Together, the historic, seismological, and geologic data suggest an obvious conclusion: fault zones in the active area of the New Madrid region can produce large destructive earthquakes. Not as obvious is the earthquake risk posed by fault zones in areas which have not had historic damaging earthquakes.

Geologic mapping in the Western Lowlands and the Benton Hills has found evidence for multiple prehistoric earthquakes, most of which are not directly related to the faults believed to have produced the 1811-12 earthquakes. The prehistoric earthquake features at the Dudley Main Ditch site and elsewhere in the Western Lowlands represent three, probably four, prehistoric earthquake events during the past 25,000 years. The magnitude of these earthquakes probably equaled or exceeded the 6.5 surface wave magnitude quake of 1895 at Charleston, Missouri.

The Benton Hills, at the head of the Mississippi Embayment, has some of the largest and most complex faulting in Missouri. Of these faults, those at English Hill show evidence of five, possibly six, surface faulting events that have occurred since about 75,000 years ago to perhaps a few thousand years before present. The site is extraordinary -- no similar recent surface faulting has been found outside of major western state earthquake zones. Surface fault ruptures are generally associated with earthquakes of at least large magnitudes. The liquefaction features that should have been produced by earthquakes from the faulting at English Hill have not yet been found, nor have they been systematically searched for. It seems likely that a number of

additional moderate prehistoric earthquakes occurred in the Benton Hills that did not have surface ruptures. The moderate Benton Hills earthquakes recorded by modern seismographs are consistent with the types of faults seen at the English Hill site. These findings are very new, and our investigations are ongoing. Much work remains to be done to determine the level of risk associated with these faults and other faults in the region.

We anticipate that future geologic studies will determine that a number of fault zones outside of the New Madrid seismic zone have produced damaging earthquakes in the recent geologic past. The evaluation of which faults have had earthquakes is best determined by mapping the faults and nearby surficial materials for evidence of surface rupture and liquefaction; if they produced earthquakes in the recent prehistoric past, they remain capable of producing them in the future. Ultimately, only geologic mapping will provide clear information of where and how often damaging prehistoric earthquakes have occurred.

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and

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September 1996

ACKNOWLEDGMENTS

We are indebted to Leonard G. Weber and his family for graciously providing access to his property and assistance for this field trip. We also thank the Missouri Department of Conservation for permitting access to Dudley Main Ditch. Additional funding support for Vaughn, Palmer and Hoffman has been provided by United States Geological Survey-National Earthquake Hazard Reduction Program awards, and a United States Geological Survey-Nuclear Regulatory Commission contract. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U. S. Government.

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**FIELD TRIP ITINERARY
September 20 and 21, 1996**

Friday, September 20

11:00 am A. M. G. Executive Staff Meeting in Drury Lodge Lobby

12:00 noon Leave Drury Lodge for Dudley Main Ditch of Missouri
Department of Conservation's Otter Slough Wildlife Area,
southwest of Dexter, Missouri.

Stop 1. Dudley Main Ditch: Multiple late Quaternary earthquake induced
liquefaction events.

Stop 2. Dudley Ridge: Late Wisconsinan terrace or fault scarp?

Buses Return to Cape Girardeau

7:00 pm Banquet at Drury Lodge.
Business meeting and evening program:

**Late Quaternary Earthquake Deformation in Southeast Missouri
And The Earthquake Hazards Implications for the 21st Century**

by

DAVID HOFFMAN, JAMES VAUGHN, AND JAMES PALMER
MISSOURI DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGY AND LAND SURVEY
ROLLA, MISSOURI

and

RICHARD HARRISON
UNITED STATES GEOLOGICAL SURVEY
RESTON, VIRGINIA

Saturday, September 21

8:30 am Depart from Drury Lodge

Stop 1. The 327 Road Graben (?) and Escarpment of Benton Hills

Stop 2. Albrecht Creek Fault

LUNCH Benton American Legion Hall

Stop 3. English Hill Fault Zone

3:00 pm Stop 3 ends trip - buses will leave the site and return to the Drury Lodge

Friday, September 20

**STOP 1. Dudley Main Ditch:
Multiple late Quaternary earthquake induced liquefaction events**

James D. Vaughn, David Hoffman and James R. Palmer
Missouri Department of Natural Resources-Division of Geology and Land Survey
(MDNR-DGLS)

INTRODUCTION

Strong ground motion in saturated unconsolidated Late Wisconsinan sands, silts and clayey sediments produced a series of sand dikes, sandblows and complex deformed beds observed in the Dudley Main Ditch near its confluence with the St. Francis River in the Western Lowlands of southeast Missouri. This site (Figure 1) is about 40 miles west of the New Madrid seismic zone axis. The Late Wisconsinan deformed beds and sand dikes underlie relatively undeformed recent fluvial sediments and modern soils. In nearby late Wisconsinan terrace deposits, there are tens of northeast-trending prehistoric dikes, which are conspicuously absent from the younger Holocene deposits of the St. Francis River. Crosscutting relationships and stratigraphic positions of features along a 0.5 mile reach of Dudley Main ditch represent at least two paleoearthquakes. Other smaller liquefaction dikes are thought to be caused by the earthquakes of 1811-12. Radiocarbon dating of wood and bone at several locations and the crosscutting relations show that these prehistoric events occurred between 22,750 and 590 years before present (BP). Worldwide and regional data on earthquake magnitude necessary to cause seismic liquefaction suggest minimum body-wave magnitude of 5.5 to 6.0 for the ancient earthquakes.

In the Dudley Main Ditch area, the older liquefaction dikes are substantially larger than the features attributed to 1811-12 earthquakes. This would indicate two possible views of the causative earthquake source zone: 1) either ancient earthquakes sourced near the 1811-12 epicentral areas were stronger than those great historic earthquakes, or 2) additional seismogenic fault zones are present west of the New Madrid seismic zone (NMSZ). Two new studies, seismic reflection images at Dudley Ridge showing complex Quaternary faults (Friday Stop 2), and the recurrent Late Quaternary faulting in the Benton Hills (Saturday Stop 3), provide compelling evidence that fault zones outside of the NMSZ have produced major earthquakes. Additionally, Vaughn (1992 and 1994) and Fischer and Schumm (1995) have discussed geomorphic, pedologic, and sedimentologic evidence for possible neotectonic deformation in the Western Lowlands.

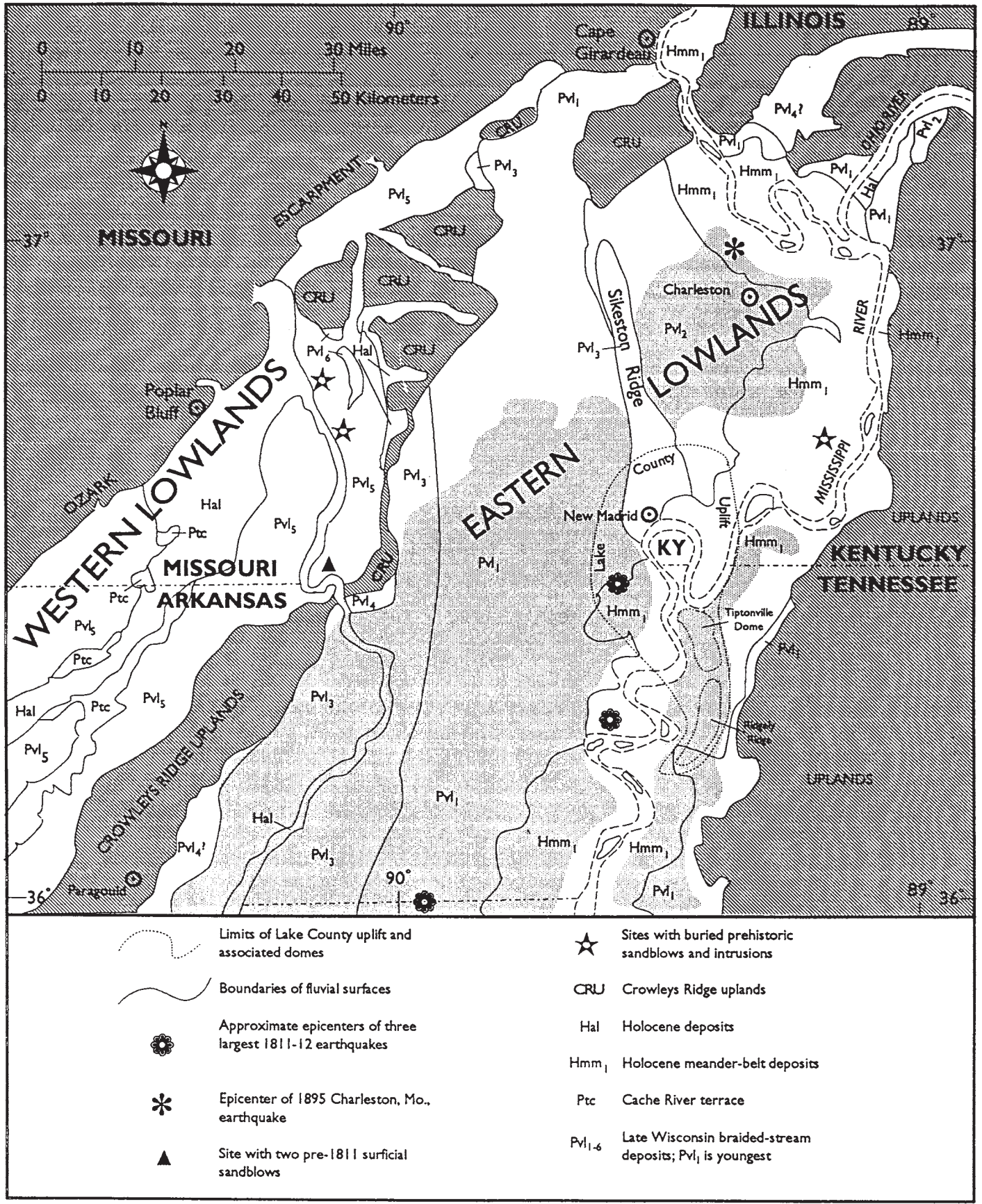
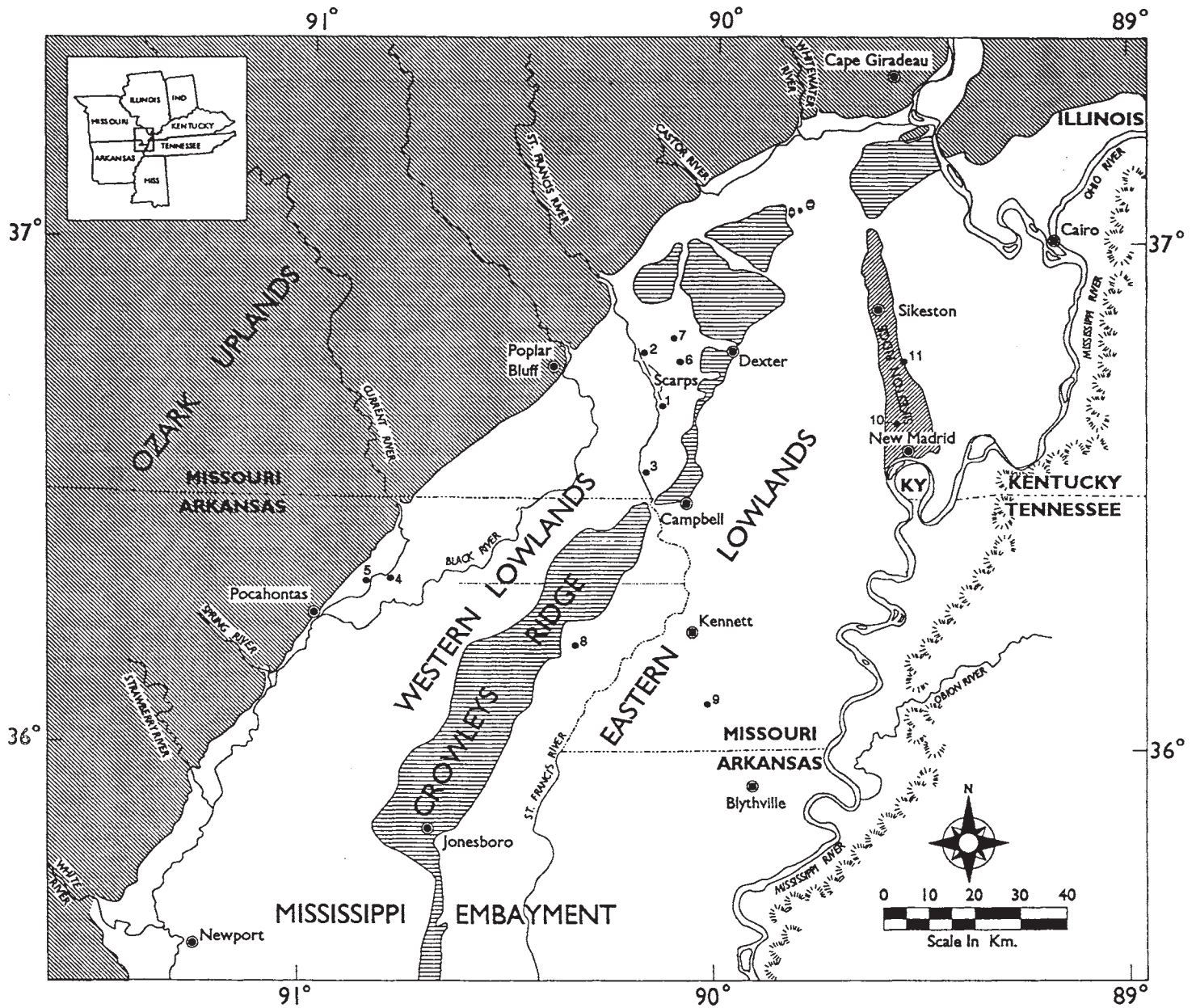


Figure 1. Map of the study area showing the major fluvial surfaces, major surficial sandblow deposits (stippled areas), uplands (hachured areas), and paleoearthquake sites. Adapted from Russ (1982); Obermeier (1989); Autin and others (1991, Plate 6); with modifications by the author.



SETTING

The Dudley Main Ditch site is located in the Western Lowlands basin of southeastern Missouri, where there is scant geologic evidence of strong shaking from the great 1811-12 earthquakes (Figures 1 and 2). The Western Lowlands basin is a nearly level plain situated between the Ozark Plateau on the west and the uplands of Crowley's Ridge on the east. This basin includes sedimentary deposits of late Wisconsinan outwash of the ancestral Mississippi River, hummocky areas of late Wisconsinan sand dunes, and Holocene floodplain deposits of the St. Francis, Black, Castor and Whitewater rivers. In most areas there is up to about 6 feet of relief on the terraces and floodplain margins, but there is locally up to 21 feet of relief along some terrace risers, natural levees, and dunes.

The immediate area of the Dudley Main Ditch site has previously been described as a terrace of late Wisconsinan braided stream outwash. However, there has been incision and deposition during the Holocene and there are areas with thick meander-belt deposits. Much of the Late Wisconsinan deposits have a well developed Farmdale paleosol which serves as a time-stratigraphic marker. Just west of the Dudley Main site, exposures along the St. Francis River are dominated by these older and reddish loamy sediments. In general, the Quaternary sequence of the Western Lowlands consists of a lower sequence of 90 to 250 feet of sandy to gravelly outwash overlain by 15 to 60 feet of fine-grained and cohesive sediments. During the Holocene, until the earlier parts of this century, this area was dominated by marshes, swamps, oxbow lakes, and sluggish meandering streams. The Dudley Main Ditch is part of an extensive drainage ditch network constructed to drain the lowland areas of southeast Missouri. Of the many hundreds of miles of excavated drainage canal banks in the otherwise flat lowlands of southeastern Missouri, only a fraction have been examined for possible prehistoric earthquake features.

DESCRIPTION

Our original hand-dug excavations in the ditch banks were made between 1990 and 1993. All of our original excavations have long since been destroyed by erosion from flooding. The features seen in the ditch banks include a variety of soft-sediment features, deformed bedding, ball-and-pillow structures, sand dikes, small dewatering features, and, with a little digging luck, a buried sandblow.

Figure 3 is a log of the ditch bank which shows the general stratigraphy and a number of sand dikes. The sand in the dikes was extruded during earthquakes from saturated sand beds below the clayey and silty topstratum beds. Often, the force of the rising mixture of watery sand breaks pieces of the dike walls and deposits the clasts in the dikes and sandblows. The force of the erupting sand may form a crater where the dike comes to the surface and domes the beds on either side of the dike. Many such sandblows have variable stratigraphy on opposite sides of feeder dikes. In one of the original exposures, the surface sandblow had moustache-shaped laminations centered over a dike and crater, which indicate upward and lateral flow issuing from the dike. Figure 4 shows characteristics found in the ditch that are related to the earliest paleoearthquake event.

The second liquefaction event produced contorted bedding and dikes that cut across the event 1 features. Figure 5 shows the dikes interpreted as Event 1 cut by Event 2 dikes, which are cut in turn by a late-Holocene channel. Organic materials used to date the events at this spot yielded ages of $12,570 \pm 200$ BP. and 590 ± 80 BP.

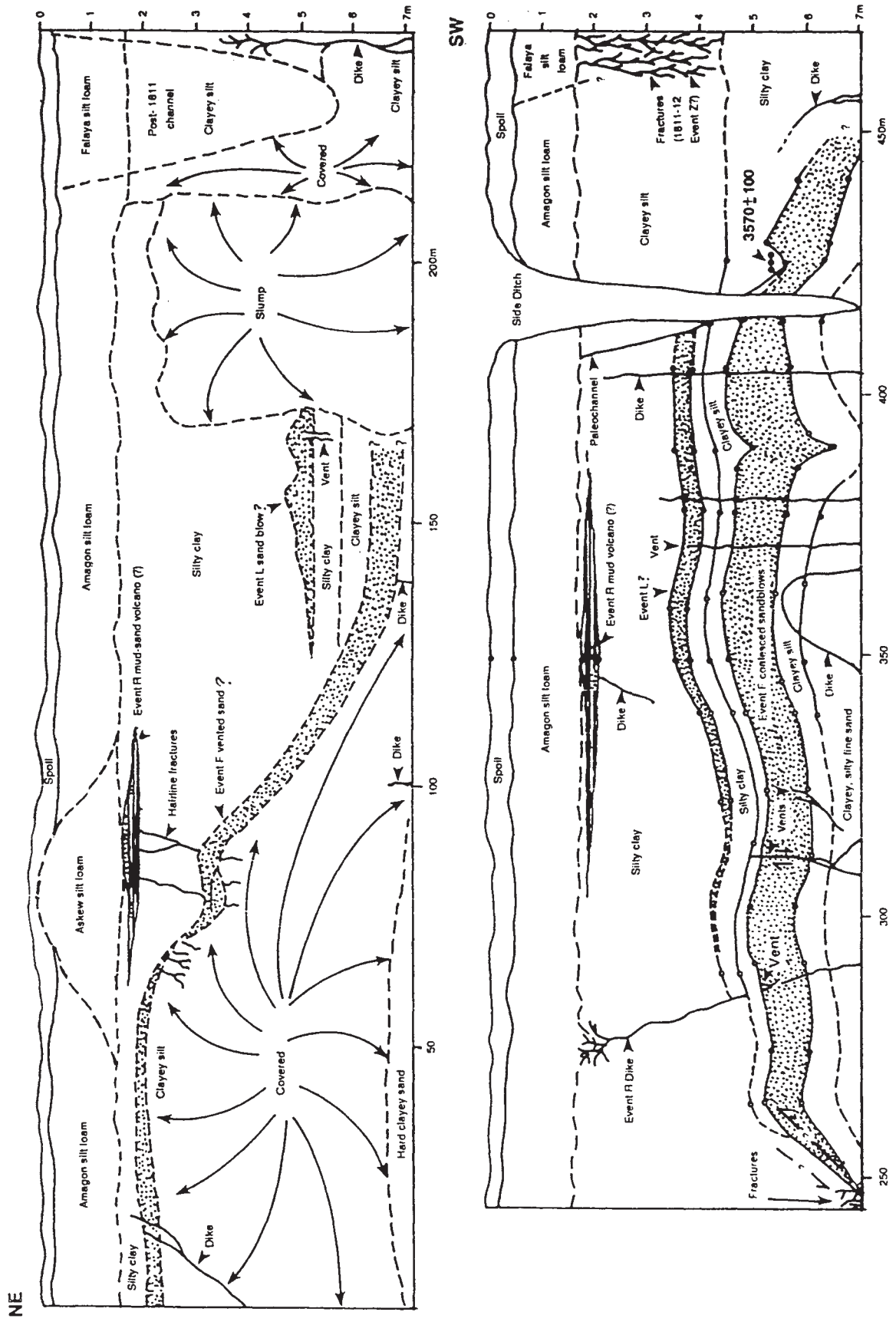


Figure 3. Graphical logs of Dudley Main Ditch 1 (DM1) depicting general stratigraphy and inferred earthquake features. Note apparent monoclinical displacements between 10 and 150 m, at 250 m, and possibly at 450 m. Gentle sinusoidal folding of both event F and L sand volcanoes, crosscutting dikes, and possible mud-sand volcanoes at base of modern soils imply an event R. Radiocarbon dating of wood at base of paleochannel near 425 m provides a minimum age of 3,570 ± 100 yr B.P. (Teledyne L-16,460) for all three events. Small open circles on contacts mark relative elevations determined by leveling; other contacts and horizontal distances are approximations. Horizontal and vertical scales in meters. Vertical exaggeration X10.

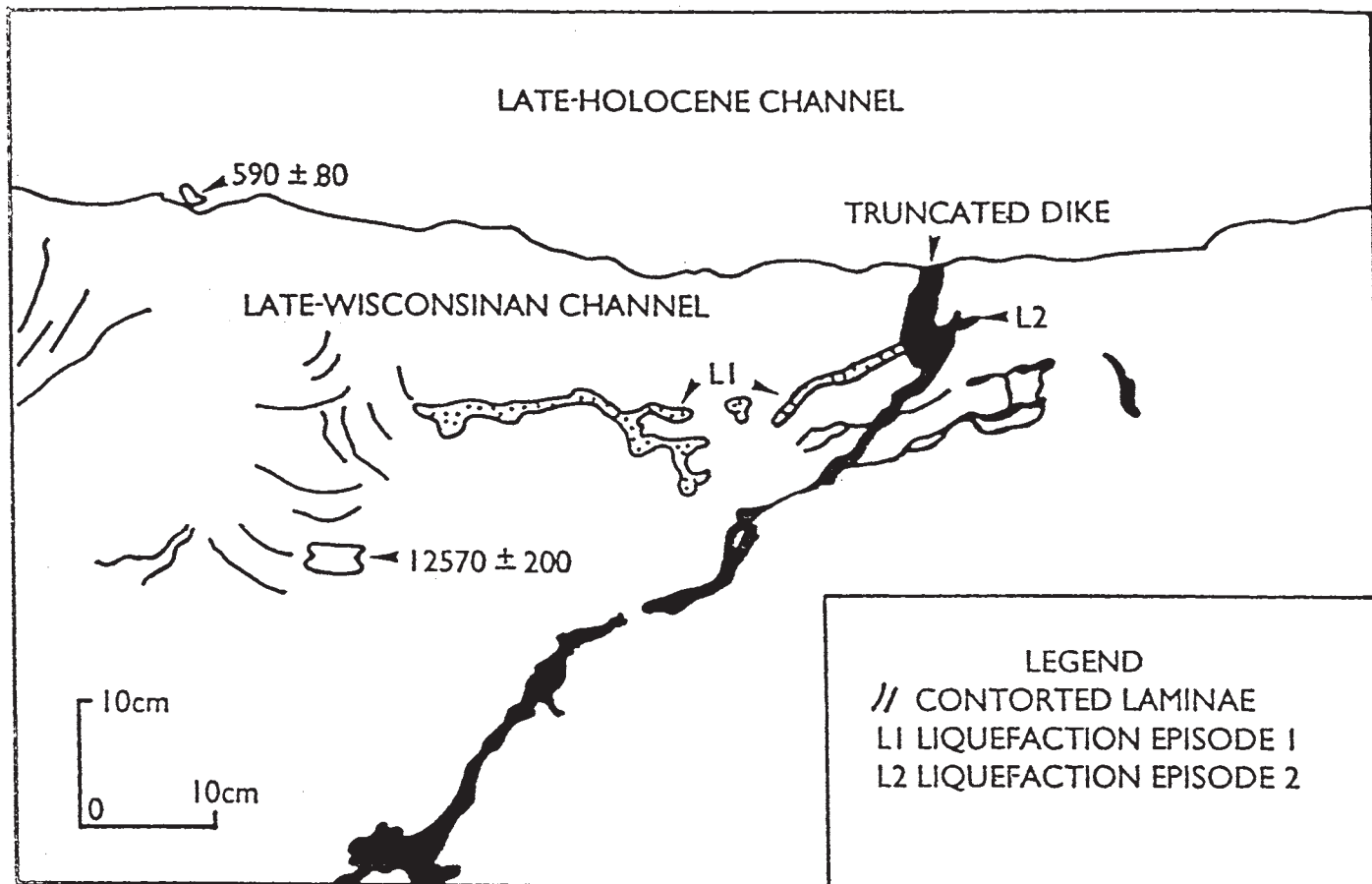


FIGURE 4 Schematic showing older clastic intrusion (L1) beheaded by younger intrusion (L2), which was truncated by late-Holocene paleochannel at Site 1. Scale in lower left.

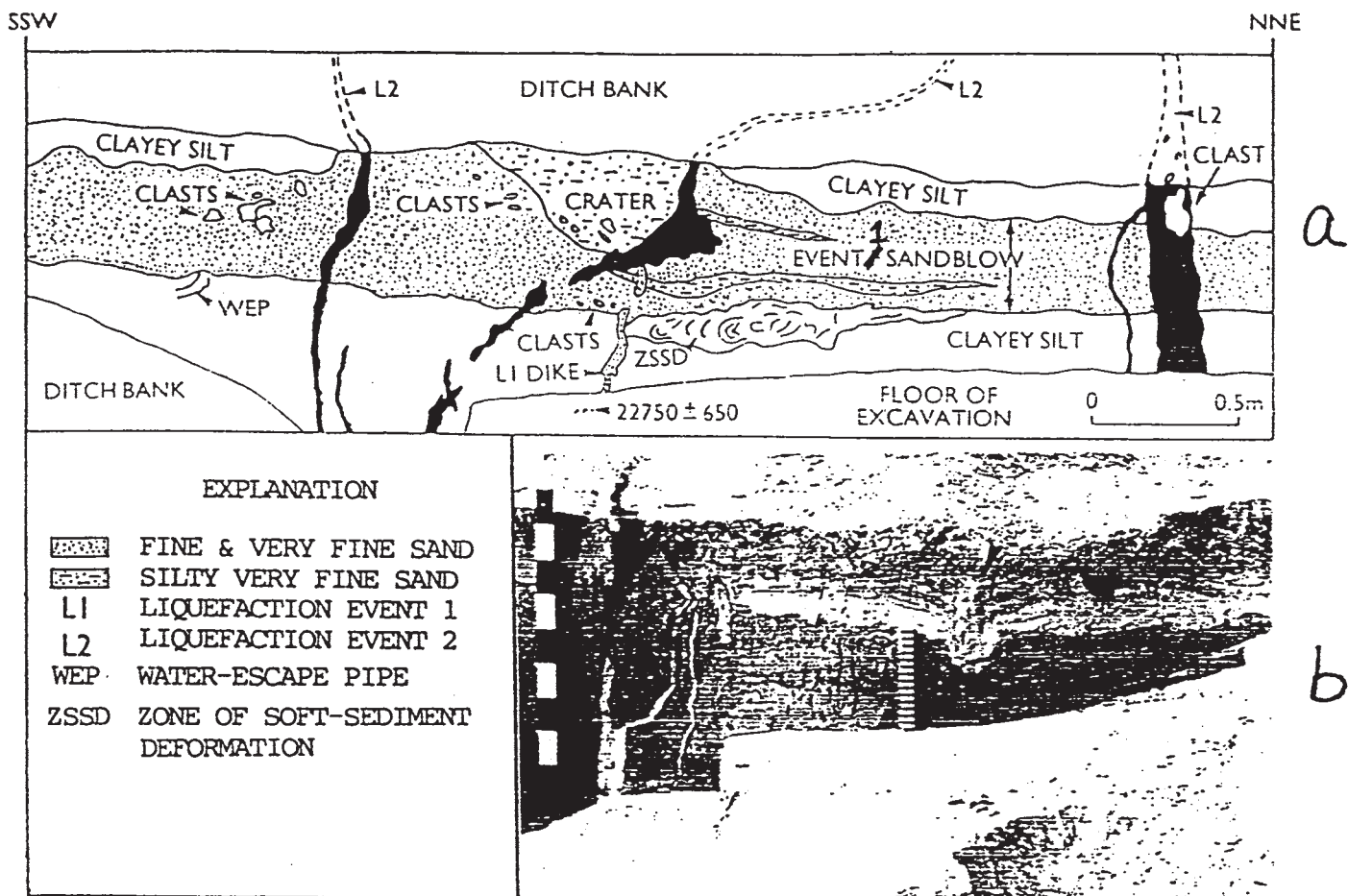


FIGURE 5 Event-1 sandblows buried at a depth of 5-7 m at Site 1. a, sketch from field notes and traced photograph showing sandblow, dikes of two ages, and zones of soft-sediment deformation. Fining-upward sequences to right of crater indicate at least three episodes of venting attributable to multiple shocks or hydrostatic flux following a major shock. Crosscutting of older dike, crater, and adjacent portions of sandblow by younger dikes, which penetrate up section another $2.0 \pm$ m, shows that another large event occurred much later. Scale in lower left. b, small secondary sandblow with eruptive vent (at arrow) identified in an initial exposure ca. 0.75 m in front of crater and L1 dike shown in 2a. Small scale below sandblow is 30 cm long.

SIGNIFICANCE OF THE DUDLEY MAIN DITCH SITE

The liquefaction features at this site and other sites in the Western Lowlands represent evidence of four damaging prehistoric earthquakes. Current estimates of earthquake recurrence are based on data from the New Madrid seismic zone, where evidence for four to five pre-1811 earthquakes have been found and do not address the possibility that such large earthquakes might occur in the Western Lowlands. The presence of paleoearthquake features in the Western Lowlands implies that earthquakes can and have occurred outside of the main New Madrid zone.

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Stop 2. Dudley Ridge: Late Wisconsinan Terrace of Fault Scarp?

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University of Missouri -Rolla
and

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INTRODUCTION

Seismic reflection, landforms, and geologic data indicate that faulting beneath Dudley ridge has occurred during the Wisconsinan Stage, and possibly during the Late Wisconsinan. Dudley Ridge is west of Dexter, Missouri, in the Western Lowlands, and is an area where there have been historic moderate earthquakes. The faults imaged in the seismic reflection surveys, referred to as the Dudley Ridge fault zone (Shoemaker, 1996), show reactivation of older structures which clearly pierce Paleozoic bedrock. Many faults penetrate upwards into the alluvium and locally into the uppermost part of the imaged Late Quaternary sequence. Shallow seismic reflection data at this site provides evidence of a complex tectonic history at Dudley Ridge (Shoemaker, 1996). Some faulting within the upper portion of the Late Quaternary sequence may have been surface ruptures. These faults may have been an earthquake source for nearby paleoliquefaction features at the Dudley Main Ditch site (Stop 1) and elsewhere in the Western Lowlands of southeast Missouri.

SETTING

Dudley Ridge is located within the Western Lowlands Basin of southeast Missouri. This nearly level alluvial plain is situated between the Ozark Plateau on the west and Crowleys Ridge on the east (Figure 1). Geomorphic surfaces of the basin in southeast Missouri include late Wisconsinan outwash terraces of the ancestral Mississippi River, Holocene flood plains of local streams, and sand dunes (Saucier, 1974). In most places, there is about 0-2m of relief on the Wisconsin terraces and Holocene flood plains, but there is locally up to 7m of relief along some terrace risers, natural levees, and dunes.

Most of the terraces in the lowlands are probably erosional. However, few have been systematically studied to determine their origin. Fuller (1912) speculated that Dudley Ridge might be partly attributable to uplift. In a classic monograph, Fisk (1944) believed that angular drainage and escarpment patterns throughout the central and lower Mississippi Valley, including the Western Lowlands region, were strongly indicative of fault control. Vaughn (1992 and 1994) discussed several lines of evidence which imply that active tectonics may have caused tilting, upwarping and downwarping of significant areas in the Western Lowlands during the late Quaternary. Some of this evidence included laterally shifted streams, thickening of silty and clayey top stratum deposits, anomalous soil patterns, and dramatically thicker or thinner Quaternary

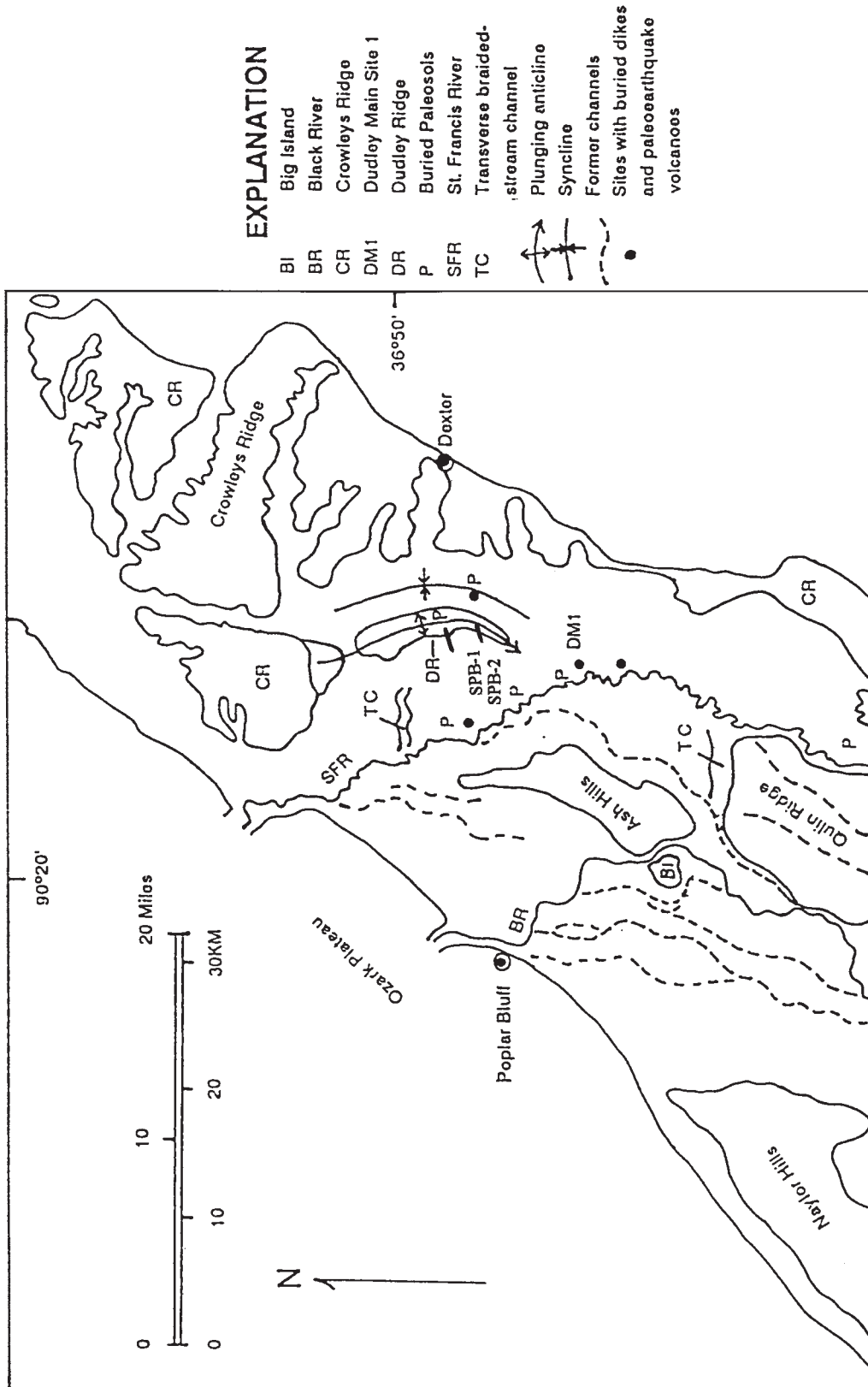


Figure 1 . Location map of the Western Lowlands of southeast Missouri, situated between Crowleys Ridge and the Ozark Plateau. Traces of former channels of Black River (BR) and St. Francis River (SFR) indicate eastward migration possibly attributable to subsidence. Relict transverse braided-stream channels (TC) may also indicate tectonic deformation. Dudley Ridge (DR) is tentatively interpreted to be a south-plunging asymmetrical anticline.

sequences in specific areas. These investigations presented geomorphic, pedologic and limited drill hole data indicative of tectonic deformation. However, this data alone is equivocal. Limited drill hole information for Dudley Ridge suggests that the stratigraphic section above Paleozoic bedrock includes some Cretaceous strata and about 90 meters of Late Quaternary sediments. This study confirms shallow faulting beneath Dudley Ridge.

DESCRIPTION

The surface seismic reflection technique involves the recording of surface-generated acoustic energy that has been reflected back to the surface geophones or receivers and recorded by a seismograph. Reflected events are generated at acoustic impedance boundaries. The boundaries are the interface between two rock types or layers which have dissimilar densities. The energy source for generating the down-going waves from the surface may include chemical explosions, sledgehammer blows, or an elastic assisted weight drop. For this survey, the sources were 12-gauge blank shotgun shells and a manually-operated 12 pound sledgehammer. The returning signals from these acoustic boundaries arrive at different times, are recorded by the seismograph, and, once processed and printed by computer, display the subsurface structure.

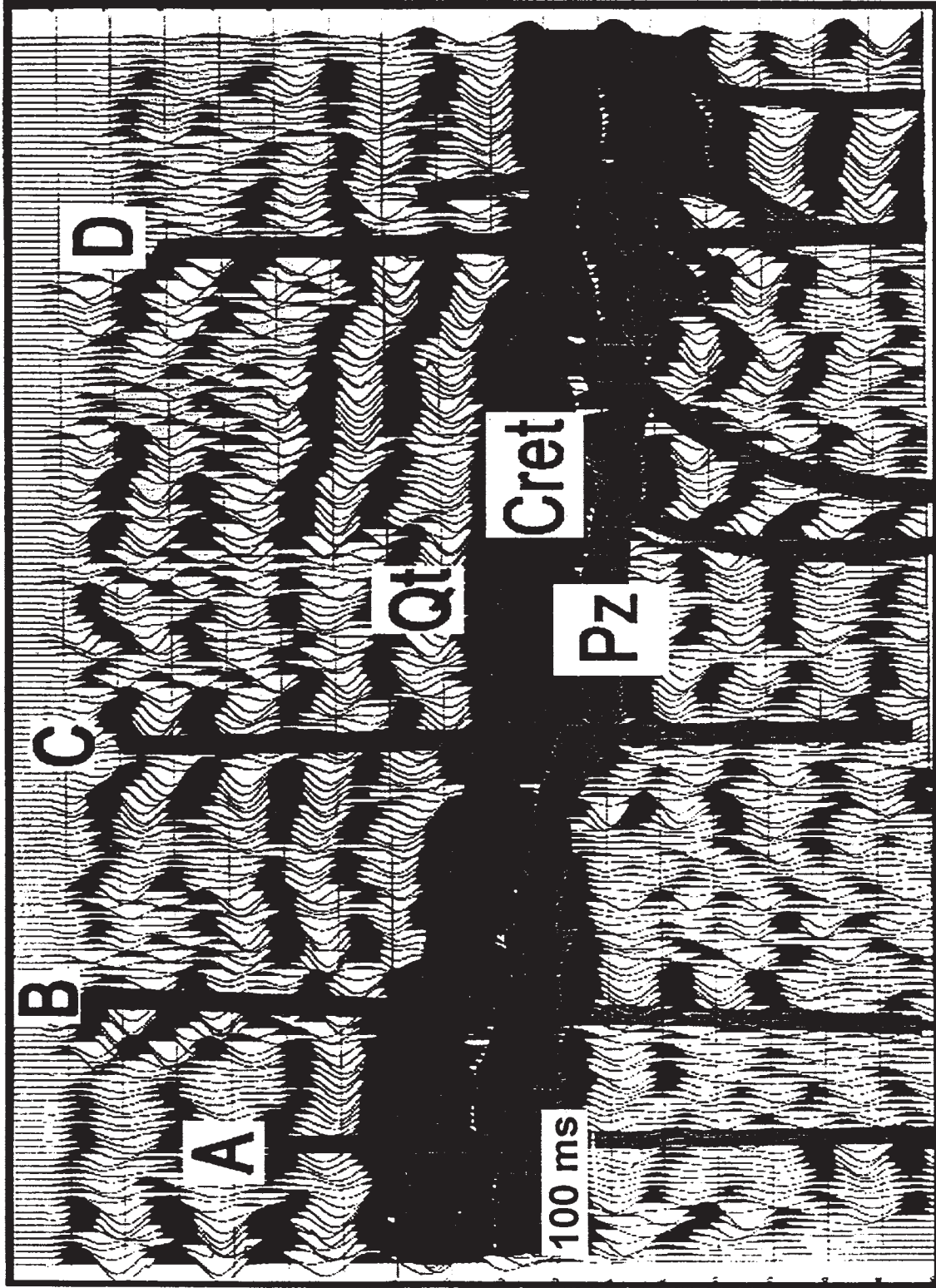
Two high resolution shallow seismic profiles, SPB-1 and SPB-2, were acquired east of Popular Bluff, Missouri, across the western boundary of Dudley Ridge (Figure 1). Seismic line SPB-1 was acquired almost entirely on the ridge in an area where the subsurface is extensively faulted. SPB-2 traverses southwest of line SPB-1, away from the ridge, in an area with less faulting.

Line SPB-1 is of good data quality (Figure 2). The data of line SPB-1 imaged geologic structure at greater depths than line SPB-2. This was due to a larger source-to-closest receiver offset of 12 meters for SPB-1, as opposed to 6 meters for line SPB-2. The shallowest reflector on line SPB-1 is between 35 milliseconds (ms) to the west and 50 ms to the east, which corresponds to depths of 16 and 23 meters, respectively, based on the normal moveout (NMO) velocity. This reflector and those that generally occur before 100 ms, are dated to the middle part of the Late Quaternary sequence.

In some locations, the reflective energy within the Quaternary sediments shows varying amplitudes and discontinuous reflections. This can be related to a variety of causes: 1) low reflection coefficients in the unconsolidated silts and sands, 2) varying bed thicknesses, and, 3) localized deformation. Poor reflections below the Quaternary/Cretaceous contact at approximately 120 ms are attributed to energy attenuation. The exceptional data quality of seismic line SPB-1 resulted in a subsurface image illustrating a complex subsurface geology.

west

east



100 ft

Fig 2. Seismic line SPB-1

Line Spb-1

Fault A - This reverse fault at location common depth point (CDP) 35, shows relative displacement within the Cretaceous and Paleozoic reflections, but not within Quaternary sediments. This suggests that vertical displacement occurred before the deposition of Quaternary sequence. Normal and reverse drag can be inferred from reflection energy to suggest that the fault is strike-slip in nature. Across the fault the Cretaceous reflector is offset approximately 3 ms between CDP 20 and 50.

Fault B - This west dipping fault shows relative displacement within the Paleozoic, Cretaceous and Quaternary. The structure exhibits offsets of 3-5 ms of vertical displacement within the Quaternary and Cretaceous reflections with less offsets in the Paleozoic. With shallow Quaternary displacement imaged at depths of 15-20 m, it is possible that this structure was a surface rupture that could be confirmed by trenching.

Fault C - This eastward dipping fault at CDP location 100 has high amplitude reflections on both sides of the structure, with clear evidence of normal displacement at shallow and deep depths. Offsets in lower Quaternary reflections range from 1-2 ms of displacement at 50 ms to 5-6 in upper Quaternary sediments. The Quaternary-Cretaceous contact reflector shows a relative displacement of 8 ms, approximately 6m, down to the east. Total displacement of the Cretaceous, from CDP location 20, 240 m east to CDP location 100, suggests a total offset of 15m. The Cretaceous-Paleozoic reflector displays similar amounts of offset. Cretaceous reflections clearly show normal drag, which also suggests normal faulting. Because of shallow displacement in Quaternary sediments, this apparent normal fault may have had a surface rupture.

Branch structure D - A complex branching fault zone, between CDP locations 160 and 195, shows two separate forms of displacement. At CDP station 168 a thrust fault is clearly evident with maximum displacement occurring at 125 ms. An east -dipping apparent normal fault intersects the thrust fault at CDP station 173. This normal fault has displaced Quaternary reflections on the order of 3-5 ms with similar displacement within the Cretaceous and Paleozoic reflectors. The normal fault also cuts an interpreted paleochannel at 70 ms or 32 m below the surface.

Line SPB-2

Although line SPB-2 is also of good data (Figure 3), the reflections show much simpler structure than line SPB-1. However, line SPB-2 possesses a clearer image of the shallow subsurface between depths of 16-43 m because a smaller source-to-closest receiver offset of 6m was used in acquiring the data, as opposed to 12m for line SPB-1, which was intended to image deeper reflections. Smaller offsets resulted in high amplitudes and coherent reflections within the Quaternary sequence.

Fault A - This prominent fault on SPB-2, between CDP locations 90 and 120, is an apparent down-to-the-east normal fault with 3-5 ms relief. This displacement coincides with the terrace margin and is a tantalizing suggestion that the scarp is faulted. The reflections within the entire Quaternary sequence are higher to east onto the Dudley Ridge. Additional study is warranted at this site.

east

west

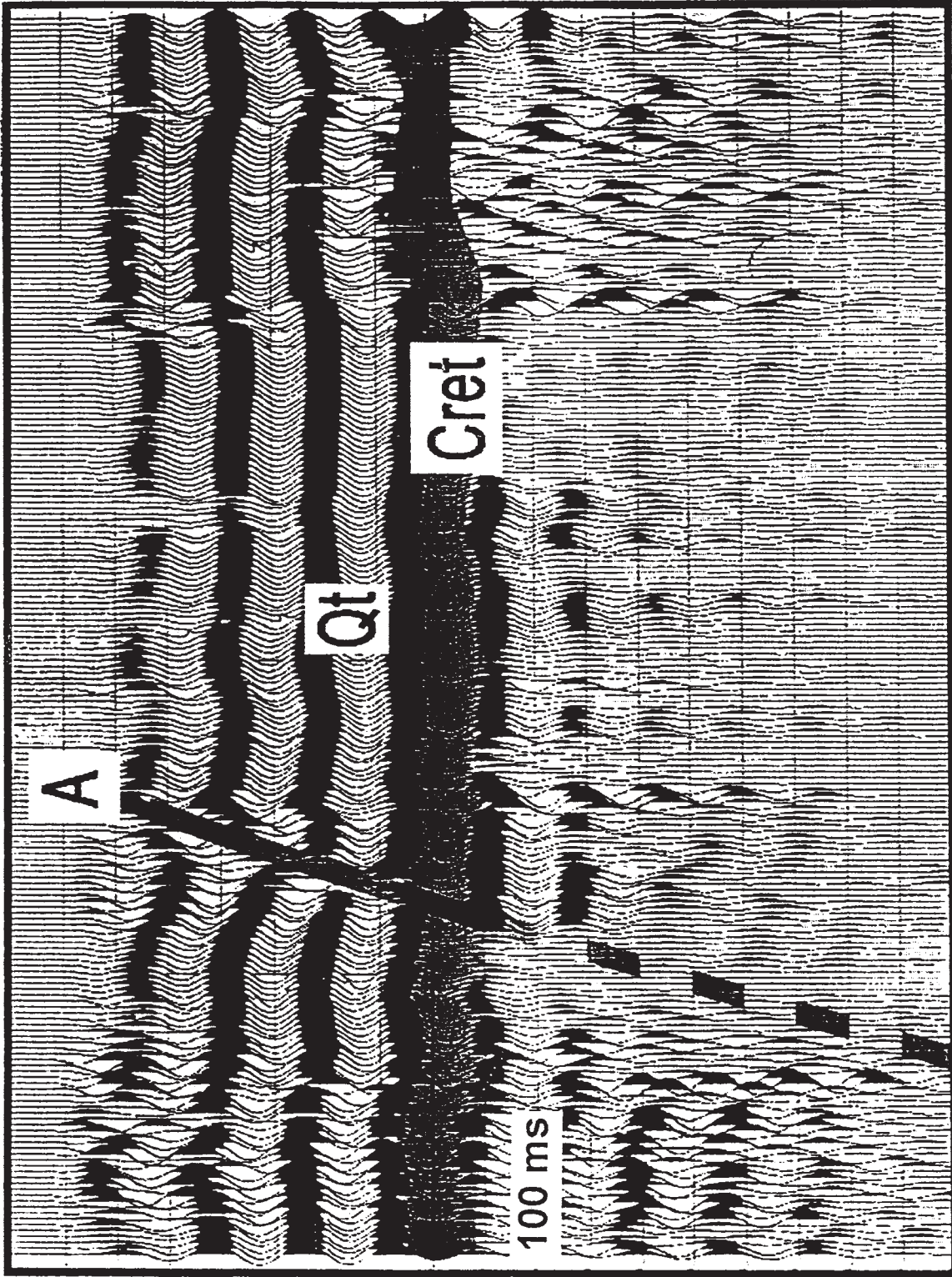


Fig 3. Seismic line SPB-2

100 ft

SIGNIFICANCE

Shallow high resolution seismic reflection has provided a view of the complex structure in the subsurface beneath Dudley Ridge, an area which has long been speculated as being faulted. Both seismic lines show evidence that extensive faulting has occurred within shallow Quaternary sediments at Dudley Ridge in the Western Lowlands (Shoemaker, 1996; Hoffman and others, 1996). Fault reactivation, with both normal and thrust displacement, suggest this area has undergone strike-slip deformation. This is not too surprising, considering the faulting in the Benton Hills (Saturday Stops 2 and 3), and the possible relationship of Dudley Ridge fault zone to the Commerce Geophysical Lineament (Vaughn, 1992).

The Western Lowlands is an area that has had moderate earthquakes, but lacks a record of damaging quakes. However, paleoliquefaction and geomorphic evidence (Vaughn, 1992 and 1994) in the Western Lowlands suggests a prehistoric record that includes large earthquakes. The seismic reflection data described above points to a possible source zone for such quakes.

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Saturday, September 21

**STOP 1. County Road 327 Graben
and the Escarpment of the Benton Hills**

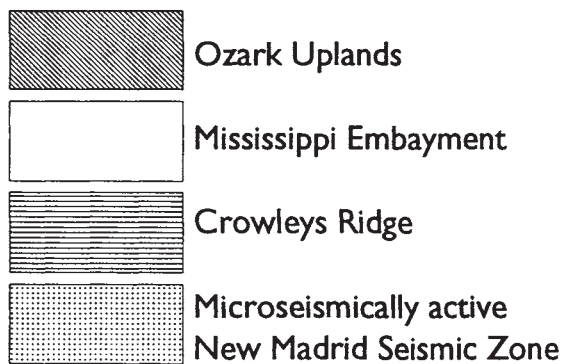
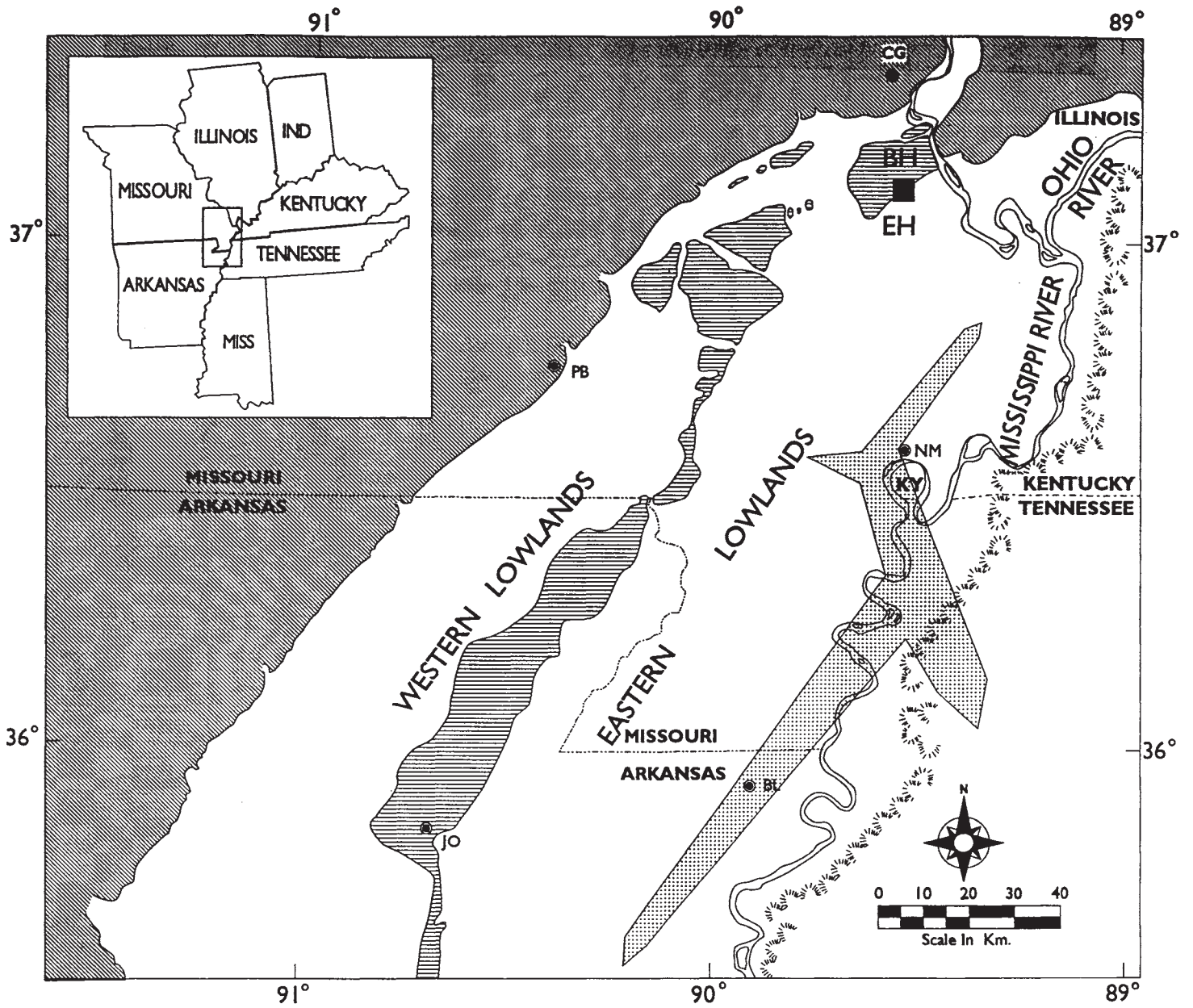
James R. Palmer (MDNR-DGLS), David Hoffman (MDNR-DGLS), Richard Harrison (USGS), and James D. Vaughn (MDNR-DGLS)

INTRODUCTION

The southern escarpment of the Benton Hills is broken into a series of North 50°- 55° East oriented right-stepping en echelon linear segments which have shorter northeast terminations that curve to North 35-40° East. These orientations are identical to the two dominant fault trends in the Benton Hills, and, given the scale of faulting at English Hill (STOP 3), suggest a relationship between faulting and landforms similar to those seen in other parts of Crowleys Ridge (Cox, 1988). The linear segments have steep, youthful slopes, of highly erodible Cretaceous and Tertiary sediments. The step-over areas between the linear segments have small youthful, southward draining basins of 1-2 mi². These small south-facing basins in the escarpment are more youthful than the large, +25 mi², north-draining dendritic basins of the uplands. The older upland drainages are beheaded at three locations along the escarpment and have areas that have been captured by the youthful south-facing basins. In right lateral strike-slip fault settings with sufficient lateral displacement, the area between right-stepping en echelon faults can become a structural basin. A surface landform response to such deformation could include the formation of a fault bounded lake, sag pond, or drainage basin. Erosion following the tectonic deformation should produce colluvial aprons and alluvial fans at the margin of the escarpment. County Road 327 runs through a drainage basin in a step-over area onto an alluvial fan; hence the similarity to tectonically active alluvial basin margins.

SETTING

The Benton Hills portion of Crowley's Ridge is an isolated upland of Paleozoic, Cretaceous, Tertiary rocks and sediments at the head of the Mississippi Embayment (Figure 1). The Paleozoic rocks in the upland dip a few degrees towards the Illinois basin and strike northwesterly. The overlying Cretaceous and Tertiary (K-T) sequences strike mostly easterly, and, in general, dip at very low angles toward the south into the Mississippi Embayment. Around many faults, Paleozoic and K-T strata are extremely deformed and dip vertically. The lowland areas to the north, west, and south have thick Quaternary alluvium of the ancestral Mississippi and Ohio Rivers. The subsurface stratigraphy of these Quaternary sediments and the underlying bedrock is known only through a handful of widely scattered drillholes. The east side of the Benton Hills, along with the corresponding upland in southern Illinois, bound the narrow Thebes Gap of the modern Mississippi River.



BH = Benton Hills
 BL = Blytheville
 CG = Cape Girardeau
 EH = English Hill
 JO = Jonesboro
 NM = New Madrid
 PB = Poplar Bluff

Figure 1.

The uplands have locally thick Quaternary surficial materials. The Quaternary stratigraphic units are: Sangamon geosol, Roxana Silt and Farmdale geosol and the Peoria Loess. Gravel-, and sand-rich colluvium and alluvium are also interbedded with these pre-Holocene silt-dominated units. Differentiating the pre-Holocene from the Holocene stratigraphy can be complicated by local erosion and redeposition of the older Quaternary strata into modern alluvium and colluvium.

As observed at STOPS 2 and 3, the structures in the Benton Hills, in part, owe their complexity to multiple periods of activity through the Phanerozoic (Stewart and McManamy, 1944; Stewart, 1942; Harrison and Schultz, 1994), including at least 5 periods which post-date the Sangamon geosol (Harrison and others, 1995; Hoffman and others, 1996). It is very appealing to consider that the surface landforms along the edge of the escarpment owe their origin to co-seismic tectonism. The dominant structure in this region controlling the subsequent development of the exposed faults may be the North 55° East Commerce Geophysical Lineament (CGL; Figure 2), a magnetic basement lineament which extends from Arkansas through Missouri into Illinois, and maybe Indiana. The CGL may either be a border fault zone of the early Paleozoic Reelfoot Rift, and, or a synrift mafic dike swarm (Langenheim and Hildebrand, 1996). The relationship of the CGL to exposed faults is not yet clear. However, the surface mapped Commerce fault zone directly overlies the CGL.

DESCRIPTION

Modern landforms of the lowlands bordering the escarpment are dominated by three roughly north-south terrace belts, which are oldest to the west at Morley and youngest to the east at Commerce (Figure 3). The western most terrace at Morley is presumed to be a Wisconsinan remnant of Sikeston Ridge. Between the terrace remnant at Morley and the Holocene floodway of the Mississippi River, the alluvial plain surface is dominated by braided stream sandy outwash of the latest Wisconsinan. Alluvial fans and aprons of colluvium have prograded from the drainages along the southern escarpment of the Benton Hills and onto these Wisconsinan and Holocene terraces. The fans and wedges of colluvium from similar sized drainage basins are about the same size from west to east, regardless of which of the older terraces they overlie, suggesting that their appearance was related to rejuvenation of the entire escarpment.

Two large, north-draining upland drainage basins, Caney Creek and Ramsey Creek, have abrupt, beheaded terminations at the escarpment with severely underfit transverse profiles and longitudinal profiles, suggesting that there was another mile of upland stream to a divide. Compared to drainages in the Shawnee Hills on the Illinois side of Thebes Gap (Figure 4) the north versus south drainages are highly asymmetrical. At English Hill, the stratigraphic evidence in the valley floor of Ramsey Creek suggests these headwater areas had large, gravelly bedload streams. The headwater area at English Hill was truncated during the Late Wisconsinan after deposition of Roxana silt and prior to the Peoria Loess.

Within the small drainage basin at County Road 327, the stratigraphic contact between Paleozoic rocks and the Cretaceous is up to 100 feet lower than in the uplands to the

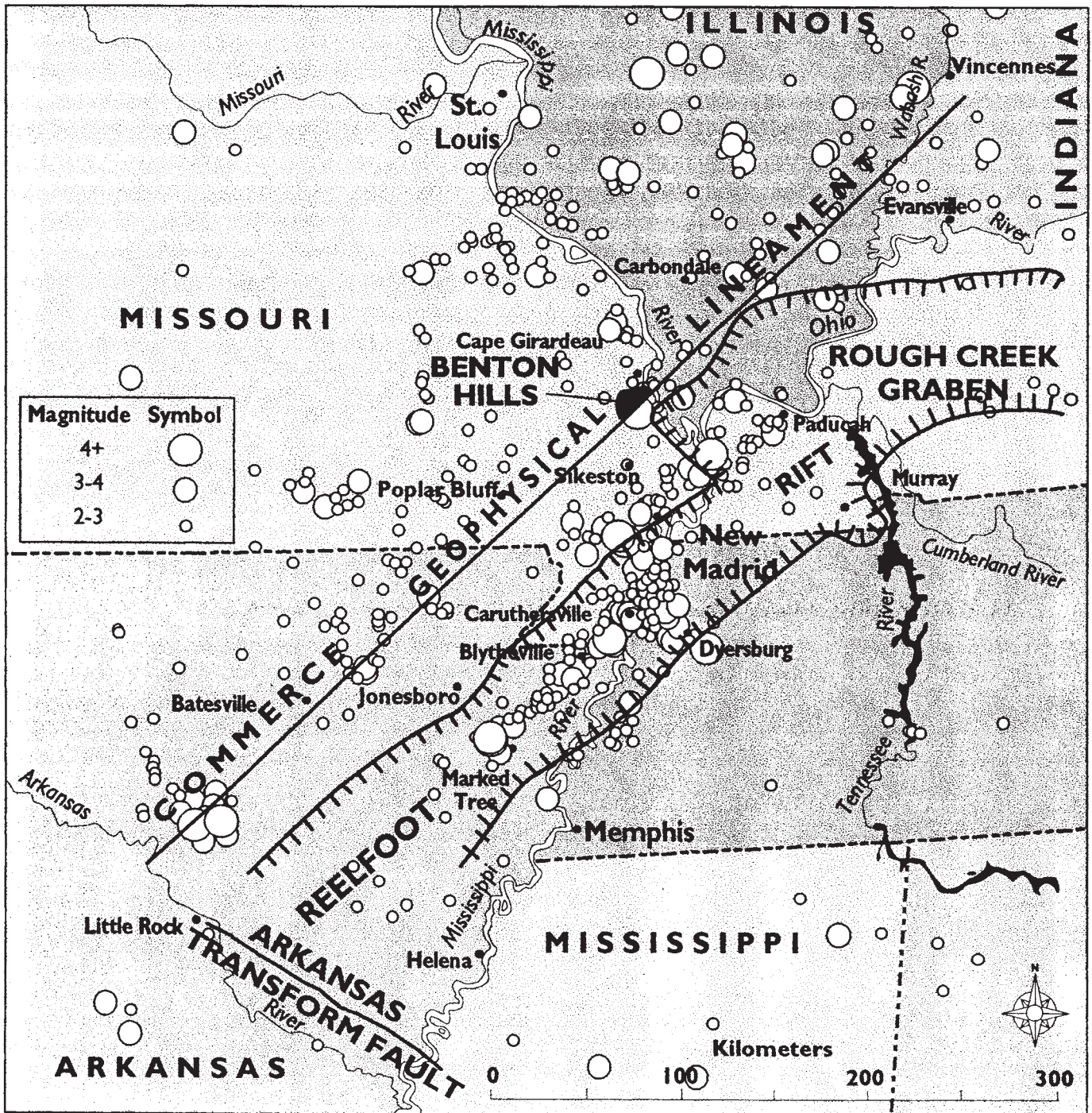


Figure 2. Location of the Benton Hills, 1974 to 1990 earthquake epicenters, the Commerce Geophysical Lineament and the Reelfoot Rift.

east, west and north. Stratigraphic contacts between Quaternary materials also suggest structural deformation. Cores taken along the west side of the basin, near an area with steeply dipping Cretaceous beds, show the upper and lower contacts of Peoria Loess- Roxana Silt and Roxana Silt-Sangamon geosol parallel modern slopes and slope breaks. Given the amount of faulting at the English Hill site, this is too great a coincidence, and suggests post-Peoria Loess tectonic downwarping of the valley floor.

SIGNIFICANCE

We see little reason to believe that erosion by the ancestral Ohio and Mississippi Rivers flowing along the edge of the escarpment are solely responsible for the linear escarpments which, coincidentally, parallel the major fault trends in the southern Benton Hills. Faulting in the Commerce area and at English Hill both point to extensive late Quaternary seismotectonic deformation in the northern Embayment. To us, it would seem more extraordinary to explain that erosion produced these linear escarpment segments which bend from North 55° East to North 35° East northeast along their length. The apparent structural deformation of Paleozoic and Cretaceous contacts and Late Quaternary contacts in the County Road 327 basin, suggest that downwarping of the basin has occurred between overlapping strike-slip fault zones at the margin of the escarpment. The areas where these faults overlap are likely targets for additional study and mapping.

Tectonic deformation can influence sedimentary sequences and patterns. If seismotectonic deformation accounts for some of the observed erosion and depositional features along the margin of the Benton Hills, then careful stratigraphic analyses of Quaternary sediments would provide invaluable insight to the nature of the faulting. Beyond the Benton Hills, such stratigraphic analyses of Quaternary sequences in the subsurface could also provide additional clues of seismotectonic deformation and improve our understanding of earthquake risk in areas which also lack a historic record of earthquake activity.

ESCARPMENT SEGMENTS & FAULTS

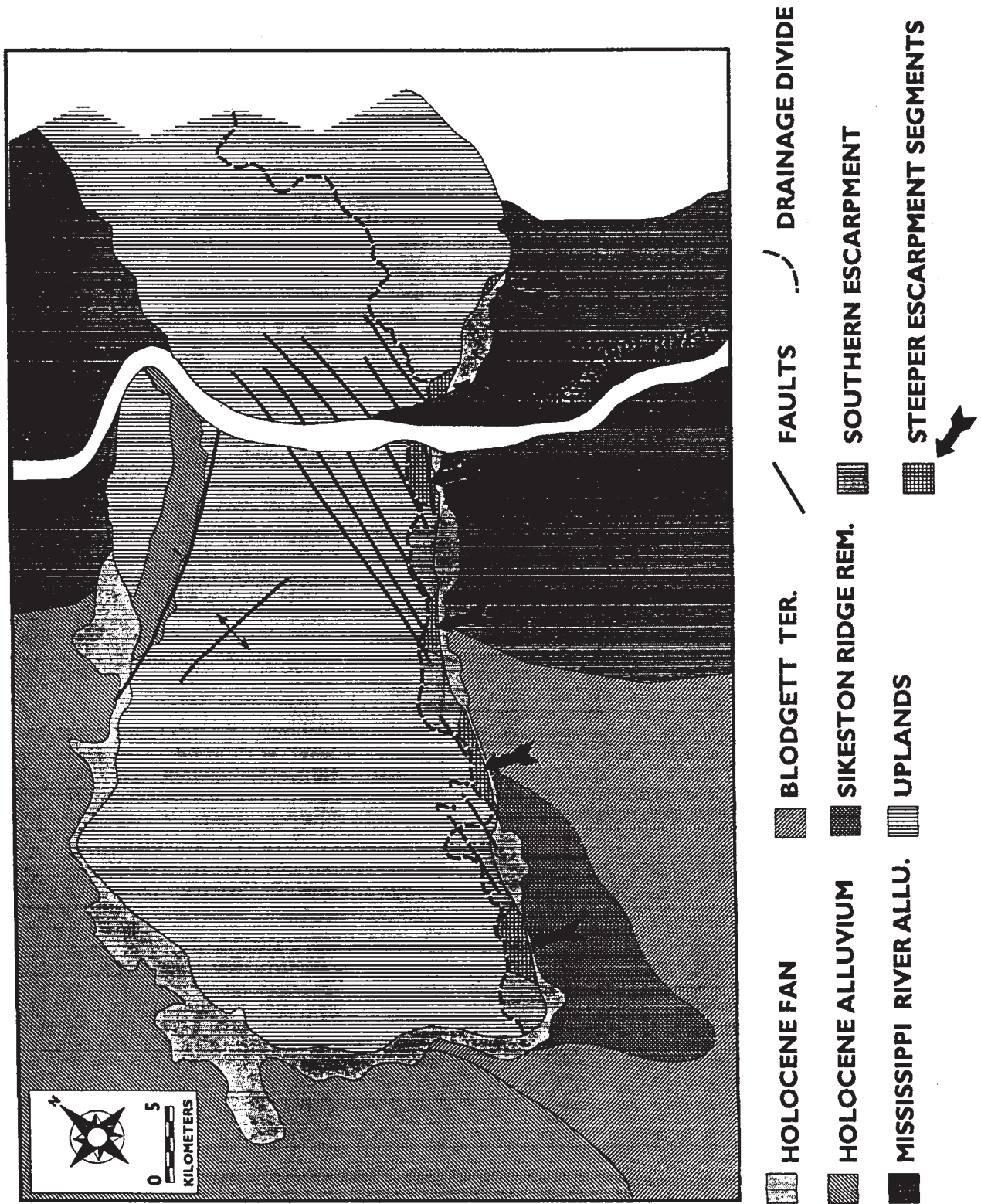


Figure 3. Surficial geology along the margin of the Benton Hills.

DRAINAGE PATTERNS IN THE BENTON HILLS AND SHAWNEE HILLS

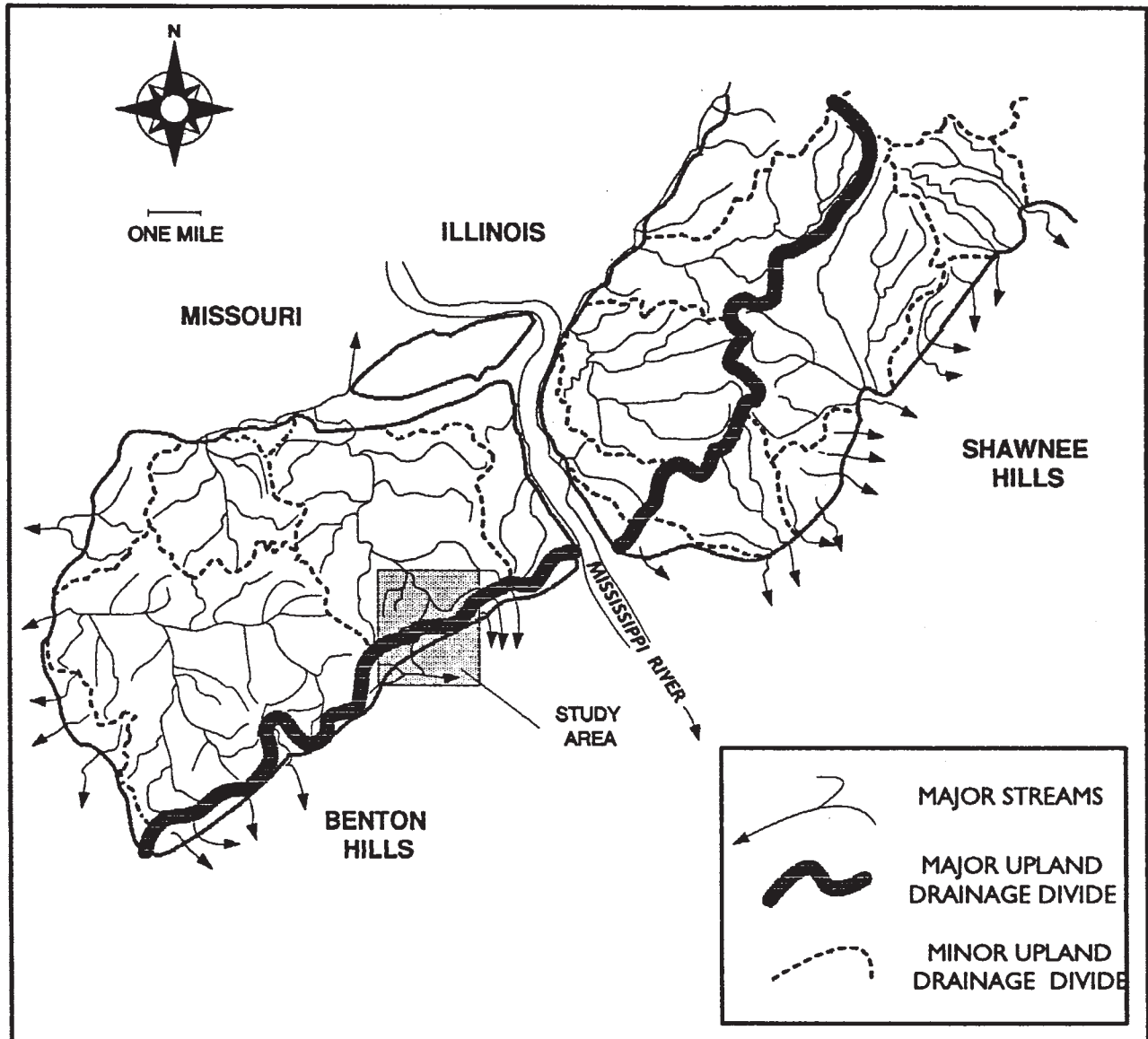


Figure 4. Drainages and drainage asymmetry in the Benton Hills.

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STOP 2. Albrecht Creek Fault

James R. Palmer (MDNR-DGLS), Richard Harrison (U. S. G. S), David Hoffman (MDNR-DGLS) and James D. Vaughn, (MDNR-DGLS)

INTRODUCTION

The Albrecht Creek Fault is one of several in the eastern part of the Benton Hills which show recurrent periods of faulting. Many of these faults have been well known for decades. Stewart (1942), using extensive drilling and mapping data from the Benton Hills, described a number of complex faults, including those at English Hill. Stewart and McManamy (1944) were able to identify four periods of deformation: (1) post-Devonian pre-Cretaceous, (2) post-Cretaceous and pre-Eocene, (3) post-Tertiary and pre-Quaternary, and (4) a period of post-loess faulting at English Hill and other locales. However, recent geologic mapping and fault and fold geometry studies find that many northeast trending faults have had recurrent right-lateral strike slip movement (Harrison and Schultz, 1994; Harrison, 1996).

Exposed in a cutbank of Albrecht Creek north of Commerce, this fault crosses the valley floor in a north-northeast direction. The natural cutbank exposure has Cretaceous and Tertiary sediments in reverse faulted contact with a Quaternary colluvium that we correlate with the Sangamon Geosol. While these younger strata are involved in the fault at this site, northward the fault has splays along which Ordovician, Silurian and Devonian rocks are wildly contorted (Stewart and McManamy, 1944). Strike-slip and reverse periods of motion are indicated by striations in the fault planes. At other locations in the Benton Hills, reverse faulted sequences have been noted in drill hole logs (Grohskopf, 1955). These structures illustrate that faulting at STOP 3, the English Hill site, 3.5 miles to the southwest, is not an isolated anomalous zone of Quaternary fault deformation. Such young strike-slip faulting in an area that only has records of small earthquakes points to the problem of evaluating the hazards represented by individual faults. The Albrecht Creek fault surely produced a large Late Quaternary earthquake, and could do so today.

SETTING

Several high-angle faults that cut Cretaceous through Quaternary deposits are exposed in cutbanks along Albrecht Creek, approximately 3.5 miles northeast of the English Hill site (Stop 3). Dominant strikes are north-northeast and northeast, similar to fault strikes at English Hill. Kinematic indicators developed along Albrecht Creek faults suggest both strike-slip and reverse motions. Drill-hole data recently acquired in the area indicate the existence of extraordinary pull-apart grabens of Quaternary age. At all exposures along Albrecht Creek, faulted deposits are overlain with angular

unconformity by unfaulted Holocene terrace deposits that have a preliminary (radiocarbon) age of approximately 1,880 years B.P.

The high-angle reverse fault at this stop juxtaposes Cretaceous and early Tertiary deposits (McNairy Formation and Wilcox Group) against Quaternary colluvial material deposited in a pull-apart graben. The reverse fault strikes North 10° - 25° East and dips 64° - 80° to Northwest. Two sets of slickenside striations have been observed raking 80° Southwest and 75° - 80° Northeast, suggesting at least two periods of faulting. The fault is filled with 4-6 inches of red clay derived from the Wilcox Group.

Bedding of Wilcox Group and McNairy Formation in the hanging wall adjacent to the fault strike North 15° East and dip 64° Southeast. Bedding of Quaternary colluvial material in the footwall adjacent to the fault strikes North 15° - 20° East and dips 35° - 80° Southeast. These attitudes are interpreted to represent drag along the fault. Several subsidiary faults striking from North 75° East to North 45° West cut the colluvial material. Many of these structures have subhorizontal slickenside striations and several are filled with dikes of dominantly clay with lesser sand and pebbles believed to have been injected from below. One of the dikes yielded very sparse pollen grains including *Pinus sylvestria*, the predominant modern form of pine pollen (N. Frederiksen, written commun., 1996). The colluvial material consists of poorly to very poorly sorted, poorly bedded clay, silt, sand, and gravel. Clasts vary from rounded to angular and are dominantly cherts and quartz. Lithologies derived from the early Tertiary Wilcox Group and Plio-Pleistocene Mounds Gravel are incorporated in the colluvium. A moderate soil profile has developed in the colluvium that is tentatively identified as Sangamon Geosol. No soil development exists in the hanging wall deposits. At the south end of the cutbank, a prominent red clay bed occurs that is interpreted as a slack-water deposit from the ancestral Mississippi River. Recent core drilling indicates that this colluvial material is at least 168 feet thick, extending far below surrounding outcrops of Cretaceous and Paleozoic units and more than 70 feet below Quaternary fill in the Mississippi River in nearby Thebes Gap. Our interpretation is that this colluvium represents syntectonic deposition in a subsiding pull-apart graben active in the Quaternary. A Quaternary age is indicated by 1) the presence of clasts derived from Mounds Gravel, 2) modern pollen in the dikes, and 3) development of the Sangamon Geosol. Some carbon material was recovered from the recently drilled core, but age dates are pending.

The faulted strata has an angular, unconformable contact with the overlying Holocene point-bar sequence which consists of coarse sandy gravel capped by silt and clay. One sample of charcoal in this overlying unfaulted Holocene sequence of coarse gravel yielded a C14 age of 1880 ± 70 y.b.p. The ages for four additional samples are pending.

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Stop 3. English Hill Fault

James R. Palmer, David Hoffman, James D. Vaughn (MDNR-DGLS)
and
Richard Harrison (U. S. G. S.)

INTRODUCTION

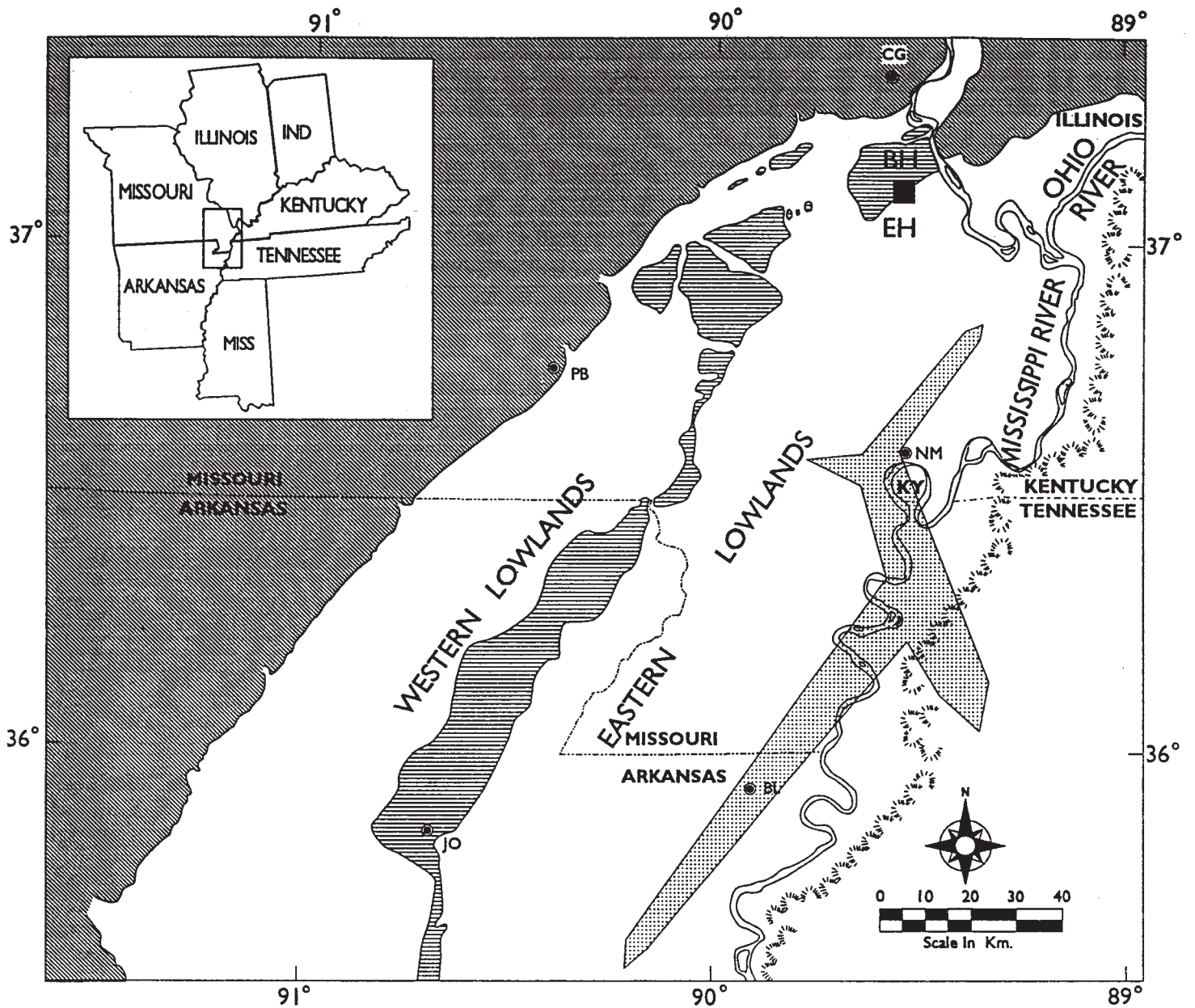
The faults which deform Late Quaternary strata in the English Hill fault zone (EHFZ) are spectacular. This fault zone is located at the head of the Mississippi Embayment (Figure 1) in the Benton Hills southern escarpment. The cross-cutting relationships between faults and stratigraphy in various fault blocks demonstrate that surface faulting has occurred along the dominantly northeast striking faults (Figure 2) at least five, probably six, times during the last 75,000 years (Harrison and others; Hoffman and others in prep.). Three faulting events post-date deposition of Peoria Loess and could have occurred within the last 10,000 years. Our mapping demonstrates that the structures are reactivated faults which were deformed during the Tertiary. Seismic reflection surveys completed at the site demonstrate that the surface mapped faults correspond with faulting imaged at the Paleozoic-Cretaceous contact. Geologic mapping and drillhole data (Harrison, 1994; Harrison and Schultz, 1994; Harrison and others, 1995) and seismic reflection data (Palmer and Hoffman, 1994; Palmer and others, in prep; Anderson and others, 1996; Shoemaker, 1996) present consistent evidence that surface faulting represents wide areas of strike-slip deformation characteristic of active seismic zones. Such complex faulting has not been seen outside of major active strike-slip fault zones. This site is 20 miles north of the northernmost part of the active microseismicity of the New Madrid seismic zone. We consider this area a separate earthquake source zone which needs to be evaluated.

SETTING

The English Hill site is located in the edge of the escarpment (Figure 1) between Commerce and Benton, Missouri. The site is on one of the more youthful linear escarpment segments and has a narrow belt of colluvium extending south onto the Blodgett Terrace. As noted at STOPS 1 and 2, Dan Stewart and Lyle McManamy (1944) mapped faulting at several locations along the escarpment, including a pair of graben bounding faults at English Hill. Stewart's (1942) description of the faulting is as follows:

"English Hill Fault: (SW, SW, NW, of Section 34, T. 29 N., R. 14 E.) Scott County. This fault is exposed about half way up the hillside of the English Hill road. At this locality the loess is down faulted against the Holly Springs (Wilcox) sand in the form of a graben which strikes N. 30 E. The throw is probably not greater than 30 feet."

LOCATION OF ENGLISH HILL





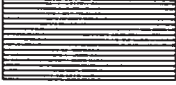
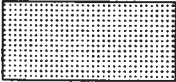
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|-------------------------------------------------------------------------------------|----------------------------------------------------|---------------------|
|  | Ozark Uplands | BH = Benton Hills |
|  | Mississippi Embayment | BL = Blytheville |
|  | Crowleys Ridge | CG = Cape Girardeau |
|  | Microseismically active
New Madrid Seismic Zone | EH = English Hill |
| | | JO = Jonesboro |
| | | NM = New Madrid |
| | | PB = Poplar Bluff |

Figure 1.

GEOLOGIC MAP OF ENGLISH HILL AREA

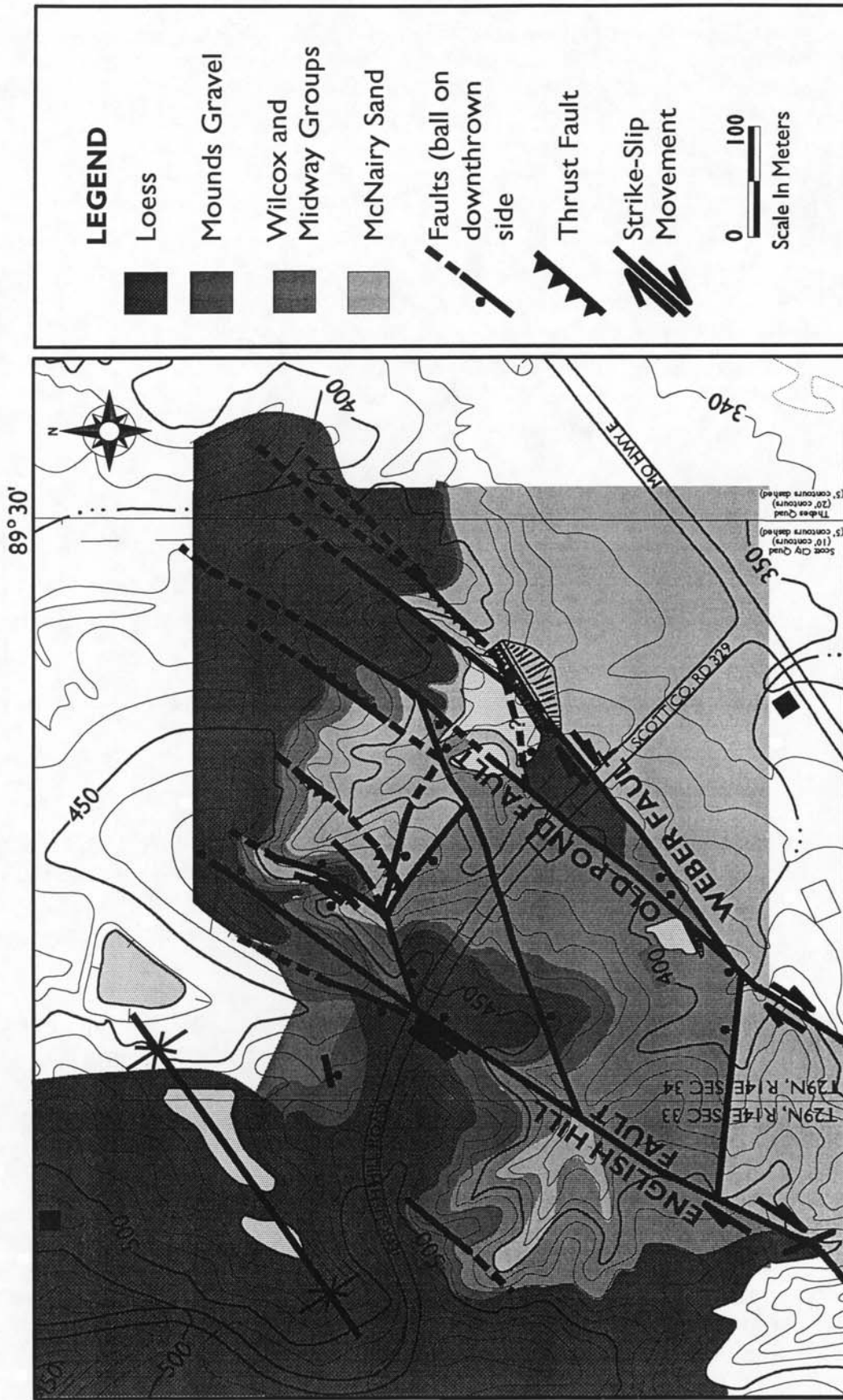


Figure 2.

FAULT EXPLORATION TRENCHES IN THE ENGLISH HILL AREA

89° 30'

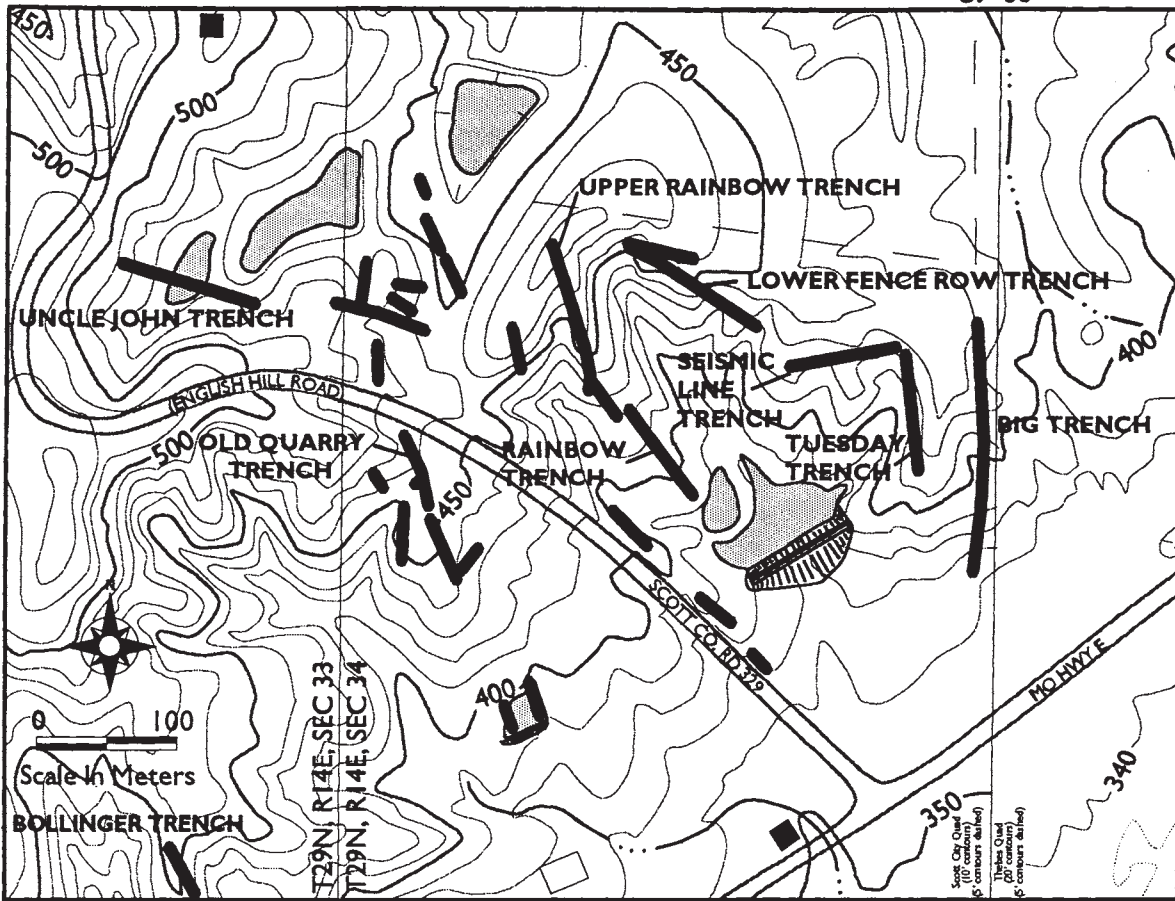


Figure 3.

This description is an understatement based on the exposures available at the time. A look around the site shows what may be observed without trenches -- jungliferous tangles of brush and poison ivy covering already poor natural exposures. Today, a cursory examination of the trenches reveals multiple periods of pre-Quaternary and Late Quaternary deformation.

Major stratigraphic units at the site include the Cretaceous McNairy Formation, the Paleocene Clayton and Porters Creek clays, the Eocene Wilcox group, and the Neogene Mounds gravel. Unconformities between these units and variable thicknesses across short distances make working here an adventure in correlation. The Quaternary stratigraphy is dominated by clay-rich silts with intervening sands and gravels. We recognize the following Quaternary units, from oldest to youngest: 1) Sangamon geosol, clay-rich pedogenically modified silts and local gravelly and sandy beds; 2) The Roxana silt and Farmdale paleosol, pinkish clay-rich silts, with local gravel beds; 3) Peoria Loess, ped-modified silts with variable clay; and 4) local thin gravel-rich horizons. Recent gravel- and sand-rich colluvium covers much of the Cretaceous, Tertiary and Quaternary sediments. This colluvium is not amenable to correlation beyond any given trench .

DESCRIPTION

Four trenches available today are arranged from straightforward to complex. Their locations are shown on Figure 3.

Old Quarry Trench-

The stratigraphy in this trench (Figure 4, scale in meters) is from oldest to youngest: Mounds Gravel, Sangamon geosol, Roxana Silt and Peoria Loess. Four prominent faults cut all units, and extend upward into the surface pedogenic zones where they become difficult to resolve. The fault planes have minor pedogenic development restricted to iron-manganese coatings and stainings with little or no pedogenic clay. The faults form a horst-graben complex. The southern-most main fault strikes North 35° East and has at least 12 feet of vertical displacement. This fault can be traced off the site to the west and can be seen in two other trenches to the east. We suspect that the faulting followed deposition of the Peoria Loess and is younger than about 12.5 thousand years.

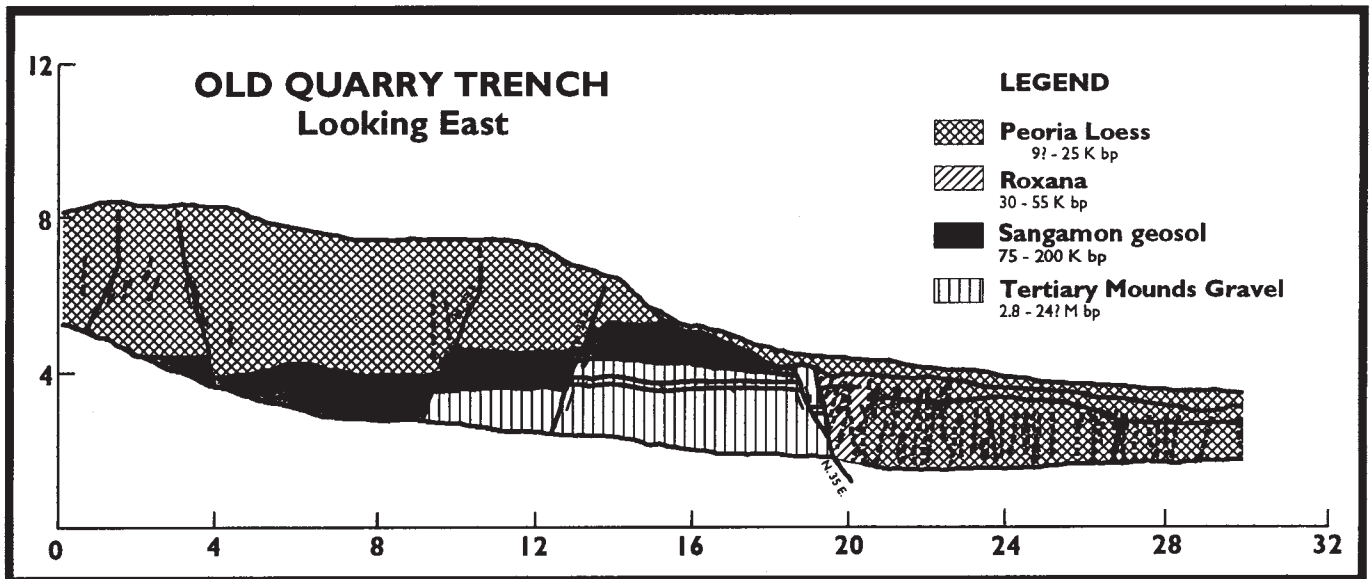


Figure 4

Upper Rainbow Trench-

The pre-Quaternary strata in this trench are, from oldest to youngest, McNairy formation, Clayton clay, and Wilcox group sand and clay. The late Quaternary strata, from oldest to youngest, include: pre-Roxana colluvial gravel, the Roxana silt, Peoria Loess, and two post-Peoria silty colluvial units. The Porters Creek clay and the Sangamon geosol are both absent in this trench. However, the Porters Creek is over 30 feet thick in a drill hole just a few hundred feet to the west and exposed to the east and west. The Sangamon geosol is also present in adjacent trenches. The absence of

UPPER RAINBOW TRENCH

Looking East

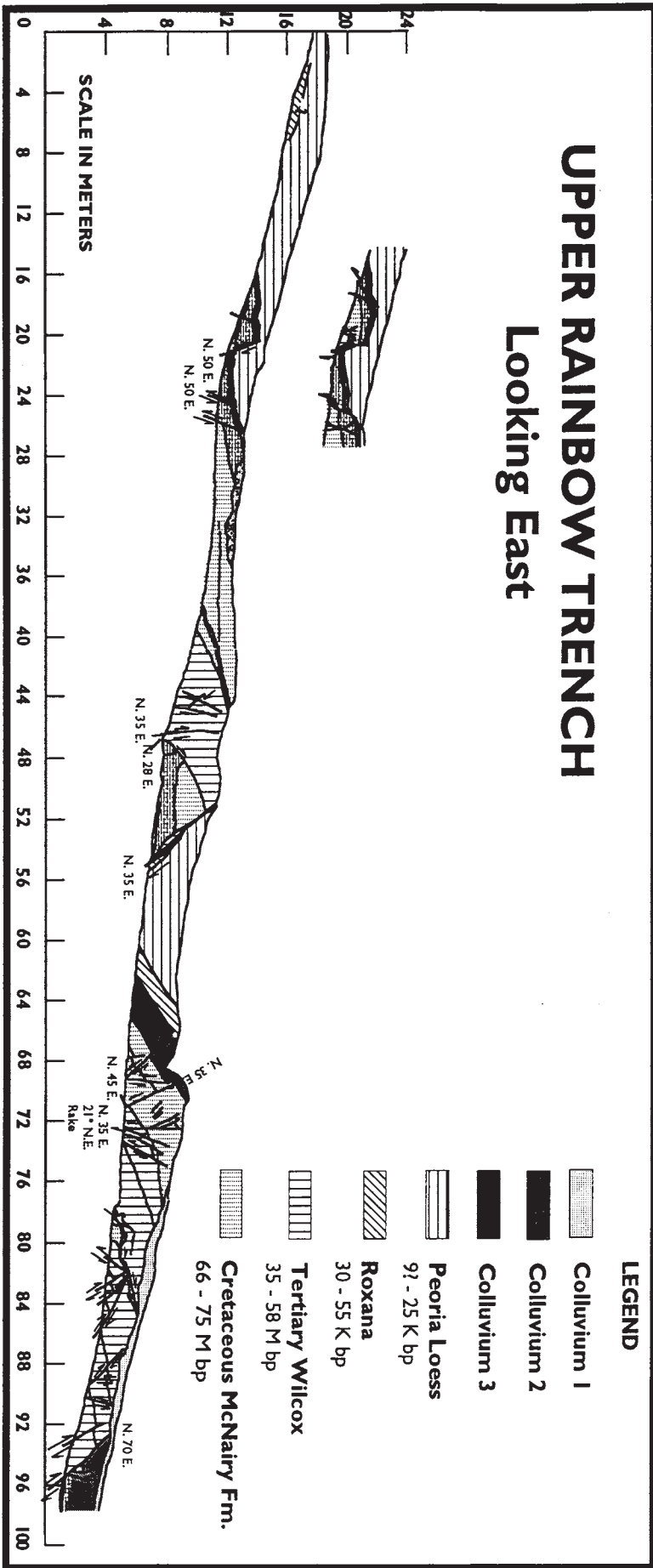


Figure 5

Porters Creek and the Sangamon in the Rainbow Trench suggest uplift and subsequent erosion following Tertiary and Late Quaternary faulting.

There are more than 30 faults in this trench (Figure 5). The rotated beds and normal faults in McNairy and Wilcox strata exposed in the trench demonstrate a complex structural history prior to late Quaternary faulting. We interpret the cross-cutting fault and stratigraphic relationships to represent at least five periods of late Quaternary faulting. The most complex zone of deformation is towards the center of the trench where a series of low and high angle faults cut most stratigraphy. The earliest of these is a thrust fault which juxtaposes McNairy over Wilcox and Clayton strata. While not exposed in this trench, this fault also displaces Tertiary strata over the Sangamon geosol along strike to the northeast. These relations indicate the thrust is post-Sangamon. The thrust fault is cut by a large low angle fault which brings late Quaternary strata down more than 40 feet. On the downhill and uphill sides of the low angle fault, two significant but unimposing narrow vertical and branching fault zones cut the strata and truncate the two older faults. Both strike North 35° East. They have low angle mullion surfaces which are interpreted to show strike-slip motion and post-date the Peoria Loess.

The south end of the trench has silty colluvium along a fault which strikes North 70° West. The colluvium consists of mostly sand and silt, presumably mixtures of McNairy Formation and Peoria Loess, with only minor gravel. The colluvium overlies Wilcox clay and sand. The stratigraphic separation on this low angle fault may exceed 50 feet.

Seismic Line Trench-

This trench dug just this August (figure not available as of this writing) is located east of both preceding trenches. Pre-Quaternary strata include the McNairy Formation, Clayton, Wilcox, and Mounds gravel. Quaternary strata include the Sangamon geosol, Roxana silt, and Peoria Loess. There are at least three faults on the western end of this trench which offset the pre-Quaternary strata, including a McNairy over Clayton thrust. Towards the middle of the trench, Sangamon geosol is in faulted contact with Wilcox silty clays. This fault appears to be a deformed or rotated fault plane and block. East of this block, a pair of small faults displace the Quaternary sequence, which completely lacks gravelly colluvium. The Quaternary strata, including the B soil horizon developed in the Peoria Loess, dip nearly 30° easterly! This strong easterly rotation is probably towards the main north-south oriented fault located in the Tuesday trench, downhill and east of this trench. Significantly, deformation followed extensive pedogenesis in the Peoria Loess -- which strongly suggests a Holocene period of deformation!

Tuesday Trench-

This north-south oriented trench has the most complex deformation at the site (attached sheet). From south to north, the main features are: complex, horizontal motion in (North 40-45° East) reverse faulted Cretaceous-Clayton strata; north-dipping

McNairy beds with complex horizontal faults, cut by upward branching faults; Clayton, Porters Creek, Wilcox, Mounds Gravel, and Quaternary beds all in faulted contact and subsequently rotated; the main northeast-trending fault with Tertiary beds against Sangamon and Roxana; and, small high angle northwest faults in Roxana silt and Peoria Loess with low angle slickenside striations.

The complicated multiple periods of deformation, rotation of earlier faulted beds and fault blocks, and low angle to horizontal slickensides in many fault planes is startling evidence of recurrent strike-slip faulting. The most recent period of deformation may be in the middle of the trench on faults in the shallowest silty and gravelly colluvium. This period may represent the same youngest event in the Seismic Line Trench, which is probably Holocene.

SIGNIFICANCE

It is likely that the strike-slip faulting at English Hill was accompanied by many large, and perhaps great, magnitude earthquakes. We are not aware of similar young and complex fault zones that are outside major earthquake zones. Thus, we consider the English Hill site faults and the faults allied with the ~350 mile long Commerce Geophysical Lineament to be a new and significant seismic zone (Hoffman and others, 1996). These areas need much additional geologic mapping evaluation.

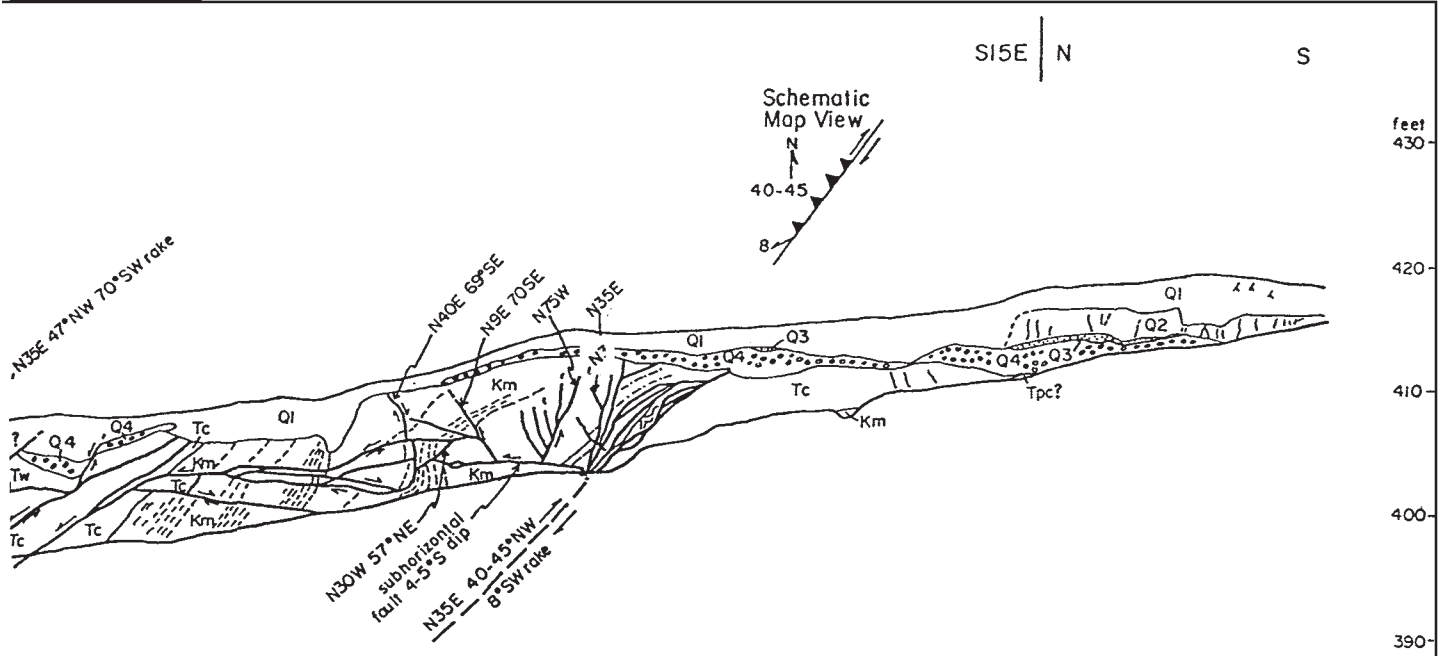
This potential seismic source zone is closer to most urban centers in Missouri than the New Madrid seismic zone. The faults associated with the Commerce Geophysical Lineament have the potential to affect significant portions of four states. In time, these data will be incorporated into the seismic risk assessment for the midcontinent. Today, probabilistic earthquake risk assessment is based on historic, geologic, and seismological evidence gained from studies in the heart of the New Madrid seismic zone. It is, therefore, extremely important to recognize that large earthquakes have occurred on fault zones outside of the microseismically active area of the New Madrid seismic zone.

Our geologic mapping at this site demonstrates that a significant earthquake risk exists in an area where historic and seismograph records lack evidence of significant damaging earthquakes. We owe a large debt to Dan Stewart and Lyle McManamy, whose geological mapping over 50 years ago has guided us to sites here in the Benton Hills. However, prior to trenching, no one would have guessed that there were at least five periods of Late Quaternary faulting here.

Around the region, there are other tectonic-looking landforms (Cox, 1988; Vanarsdale, 1995) in areas which have had small to moderate historic earthquakes. We would not be surprised if the fault zones outside of the Mississippi Embayment have produced significant prehistoric earthquakes. Only careful geologic mapping can determine if these areas have had Late Quaternary fault activity. This geologic information is necessary to formulate sound and reasonable public safety policy.

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locene Stage(?)
 a Loess
 nd alluvium

Eocene (?)
 Tw - Wilcox group

Paleocene
 Tpc - Porters Creek clay
 Tc - Clayton clay

Late Cretaceous
 Km - McNairy Formation

Tuesday Trench

0 10 20 feet

ped. modified clayey