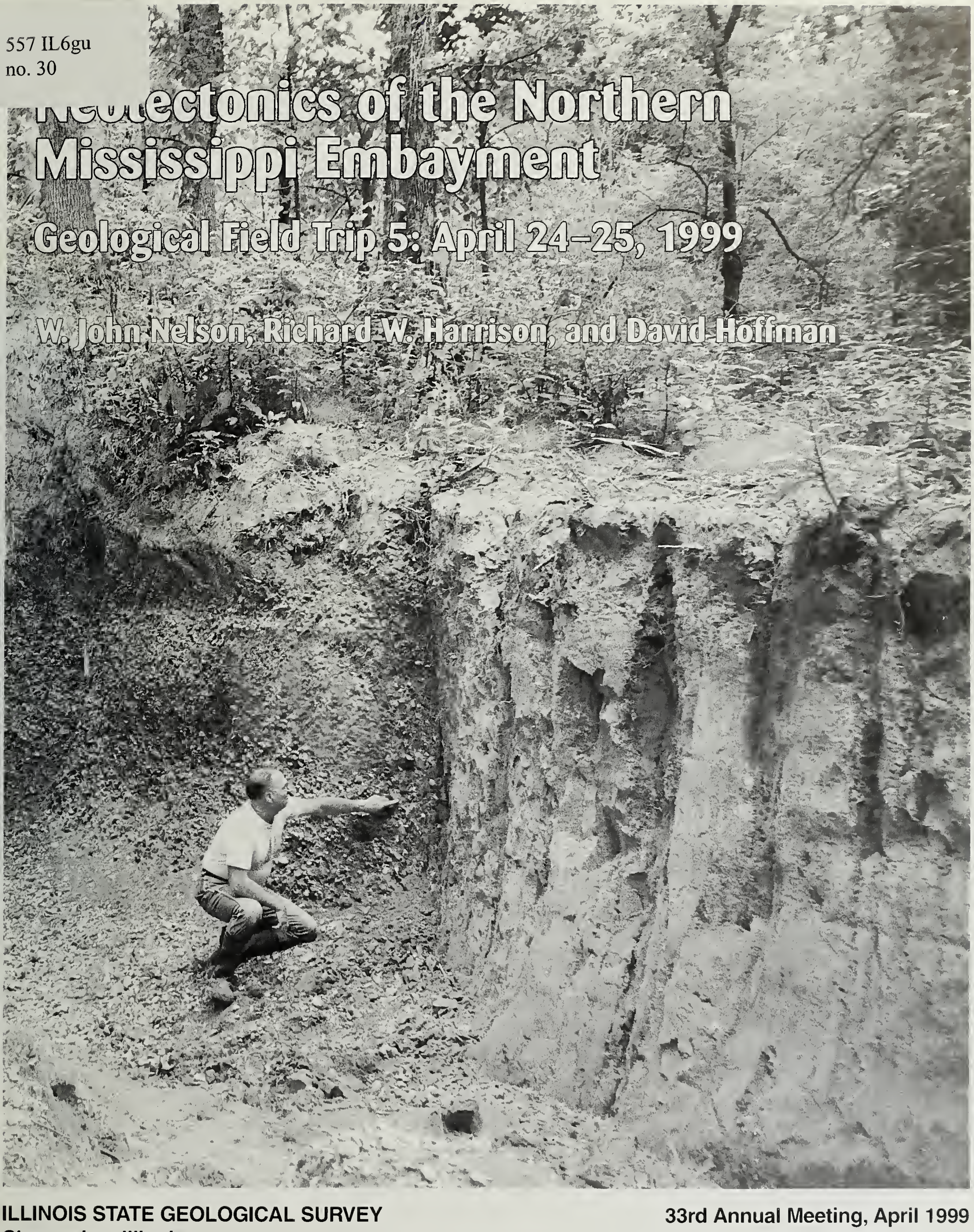
Neotectonics of the Northern Mississippi Embayment

Geological Field Trip 5: April 24–25, 1999

W. John Nelson, Richard W. Harrison, and David Hoffman



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Cover photo *The Old Quarry Trench at English Hill (Stop 4), showing a fault that juxtaposes the Peoria Silt 9,000–25.000 years old with the Mounds Gravel, Miocene to early Pleistocene (photo by Dave Hoffman).*

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INTRODUCTION

A series of cataclysmic earthquakes struck the central Mississippi River Valley during the winter of 1811–1812. The three largest events had estimated moment magnitudes of 8.1 to 8.3, based on published accounts. These earthquakes may have been the most powerful and felt across the greatest land area of any earthquakes for which reliable historical records exist (Johnson and Kanter, 1970).

Epicenters of the 1811–1812 earthquakes, as well as current seismicity phenomena in the Mississippi Valley, are concentrated in a narrow belt known as the New Madrid Seismic Zone (NMSZ; fig. 1). Geophysical studies indicate that seismic activity in the NMSZ takes place along two northeast-trending, right-lateral strike-slip faults connected by a short, northwest-trending reverse fault that represents a restraining step-over between the two northeast-trending segments (Andrews and Mooney, 1985; Sexton and Jones, 1986; Chiu et al., 1992; Pratt, 1994; VanArsdale et al., 1998). These faults are slipping under a stress field in which the principal compressive axis is oriented E-W to ENE-WSW (Zoback and Zoback, 1980 and 1991).

The NMSZ is a young feature (Pratt, 1994; Schweig and Ellis, 1994). The 1811–1812 events produced a fault scarp 3 to 5 m high, separating an uplift (Lake County uplift) from a sunken area (part of which became Reelfoot Lake). Had earth movements of similar magnitude occurred frequently prior to 1811, dramatic landforms should be evident upon the Mississippi alluvial plain. Such landforms are not evident. Displacements on near-surface faults in the New Madrid area, as shown by high-resolution seismic reflection profiles, are quite modest: 50 to 82 m on the base of the Cretaceous, less than that on younger units (Sexton and Jones, 1986 and 1988; Stephenson et al., 1995; Van Arsdale et al., 1998). Seemingly, ten to twenty events comparable to those of 1811–1812 could account for all of the observed deformation.

Recent studies document widespread Quaternary tectonic activity in the central Mississippi Valley outside the NMSZ. Seismic reflection surveys of Crowley's Ridge in northeastern Arkansas and southeastern Missouri (fig.1) reveal faults that displace Eocene units as much as 60 m and Pliocene sediments as much as 7.5 m (Van Arsdale et al., 1995; Stephenson et al., in press). Trenching, drilling, and high-resolution seismic surveys in the Benton Hills of southeast Missouri show intricate faulting of Quaternary sediments. One fault displaces Pleistocene deposits no less than 41 m, and Holocene displacements are evident in a number of places. (Harrison et al., 1997; Palmer et al., 1997a and 1997b). In southern Illinois, faults displace Pleistocene sediments at least 30 m and Pliocene sediments more than 90 m (Nelson et al., 1996; Nelson et al., in press). Published geologic maps in western Kentucky depict faulted Miocene/early Pleistocene gravel (Amos, 1967 and 1974; Amos and Wolfe, 1966). The lower Wabash River valley in Indiana and Illinois may have undergone earthquakes of moment magnitude 6.2 or greater during the Holocene, as shown by sand dikes and other paleoliquefaction structures (Obermeier et al., 1991, 1992, and 1993).

Thus a large area of the northern Mississippi Embayment has been subject to tectonic activity during the last 2 million years. The NMSZ is only the latest manifestation of this activity. Evidence for neotectonism is not easy to find; digging and other subsurface methods generally are needed. More neotectonic features probably await discovery beneath thick surficial sediments. Questions to consider are how many times has tectonic activity shifted among these sites, and will the next major earthquake take place in the NMSZ or in one of these neighboring areas?

This field trip features evidence for tectonic faulting during the Quaternary Period in the Bloomfield Hills and Benton Hills of Missouri, and in southernmost Illinois.

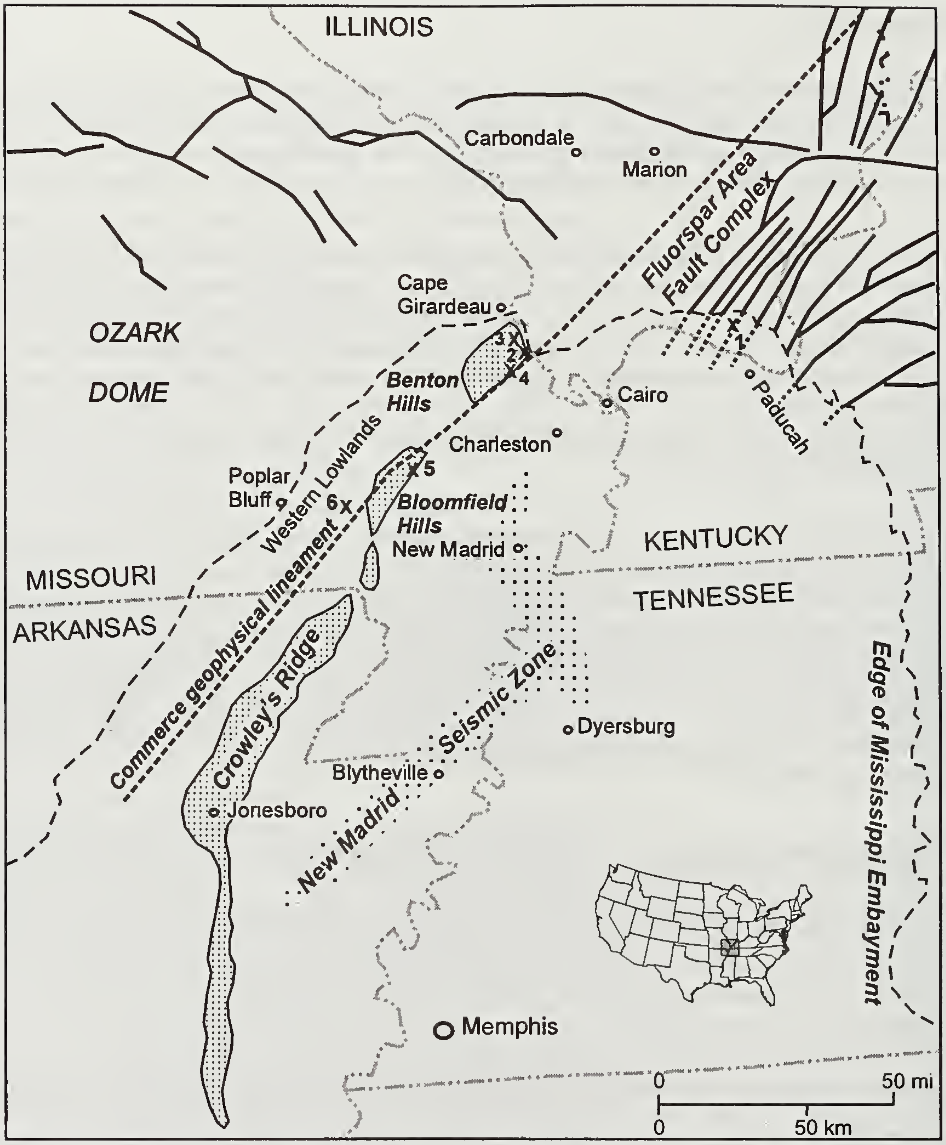


Figure 1 Mississippi Embayment: map shows field trip stops in relation to major tectonic and physiographic features. Stops: 1. Barnes Creek, 2. Happy Hollow and Sassafras Canyon 3. Albrecht Creek, 4. English Hill, 5. Holly Ridge, and 6. Dudley Main Ditch.

Physiographic Setting

The field trip area is in the northern part of the Mississippi Embayment, which is a northward salient of the Gulf Coastal Plain (fig.1). The Embayment is a level to gently rolling plain that is underlain by weakly lithified to unlithified Upper Cretaceous, Tertiary, and Quaternary sediments. The Ozark Plateau on the northwest, and the Interior Low Plateaus on the north and northeast, border the northern Mississippi Embayment. The plateaus are moderately to strongly rolling uplands of Paleozoic bedrock mantled with variable thicknesses of Pleistocene windblown silt (loess). The northern edge of the Embayment is about 25 km south of the southernmost limit of Pleistocene continental glaciation.

The most prominent upland feature of the Embayment in the field trip area is Crowley's Ridge, which extends northward in a broad arc through northeastern Arkansas and southeastern Missouri (fig. 1). The ridge is composed primarily of loess-covered Tertiary strata. Previously interpreted as a remnant of Pleistocene erosion, Crowley's Ridge now is recognized as partially a product of tectonic uplift

(Van Arsdale et al., 1995). The Benton Hills near Cape Girardeau and the Bloomfield Hills near Dexter, Missouri, are segments of Crowley's Ridge.

Stratigraphy

Ordovician through Mississippian bedrock, chiefly limestone, dolomite, sandstone, and shale, lies at shallow depths of 30 to 90 m under most of the field trip area. Unlithified to weakly lithified sand, silt, clay, and minor lignite and ironstone assigned to several Cretaceous, Paleocene, and Eocene formations overlap Paleozoic bedrock within the Mississippi Embayment (fig. 2).

The Mounds Gravel (fig. 2) is widespread in the northern Embayment, where it is chiefly found capping hills. The red to brown, sandy gravel is composed mainly of chert pebbles that have a characteristic bronze patina. The Mounds Gravel was deposited by large braided rivers and overlies at least four distinct erosion surfaces in western Kentucky. The age of the Mounds Gravel, based on two pollen samples and regional inference, is probably late Miocene to early Pleistocene (Willman and Frye, 1970; Olive, 1980).

A Quaternary fluvial deposit of strongly mottled and burrowed pebbly sand and silt has been named the Metropolis Formation (Nelson et al., in press). The Metropolis overlies the Mounds Gravel on its lowest, youngest erosion surface near the Ohio River. Gravel in the Metropolis consists of chert pebbles reworked from the Mounds; most pebbles are worn, bleached, and have lost their patina. The Metropolis Formation is overlain by the Loveland Silt (Illinoian) and has the Sangamon Geosol developed at the top (fig. 2). The Sangamon Geosol developed during the interglacial Sangamonian Stage, approximately 75,000 to 130,000 years ago. The Metropolis therefore is inferred to be of Illinoian and pre-Illinoian, Pleistocene age.

Younger Quaternary sediments in the field-trip area include the Wisconsinan Roxana and Peoria Silts (loesses) and various alluvial, lacustrine, and colluvial deposits, most of which are unnamed. The Peoria Silt is dated at 10 to 25 ka old (Blum et al., 1995).

Structural Geology

The northern Mississippi Embayment is underlain by the Reelfoot Rift, a failed intracratonic rift of late Proterozoic to Cambrian age (Kolata and Nelson, 1997). Normal faults that developed during rifting trend mostly northeast and have been reactivated repeatedly. Northeast-trending elements of the NMSZ are inherited from the Reelfoot Rift, as are most of the other faults that show Quaternary activity in the region.

A swarm of northeast-trending, mineralized fractures in southern Illinois and western Kentucky is known as the Fluorspar Area Fault Complex (FAFC) (fig. 1). Major faults in the FAFC represent rift-derived normal faults that were reactivated in late Paleozoic and younger time (Potter et al., 1995; Kolata and Nelson, 1997). Most are high-angle normal faults that outline long, narrow horsts and grabens. Reverse faults also are present, as are right- and left-lateral oblique-slip faults. Permian ultramafic dikes, sills, and diatremes also are present in the FAFC.

Portions of the FAFC displace Cretaceous, Tertiary, and Pleistocene units at the head of the Mississippi Embayment in Massac, Pope, and Pulaski counties, Illinois. Every major fault zone of the FAFC in Illinois disturbs Quaternary sediments (Nelson et al., 1996). Most neotectonic structures are grabens that are less than 300 m wide. The majority strike N25°E to N45°E, but some strike N-S to N20°W. The boundary faults are mostly high-angle normal faults, but high-angle reverse faults also are present. Typically strata outside a graben show little or no displacement across the structure, although the bedding along both margins dips steeply inward. Such a geometry suggests that these are strike-slip pull-apart grabens (a combination of strike-slip and extensional stress being involved). As yet no direct indication has been found of either the direction or amount of strike-slip.

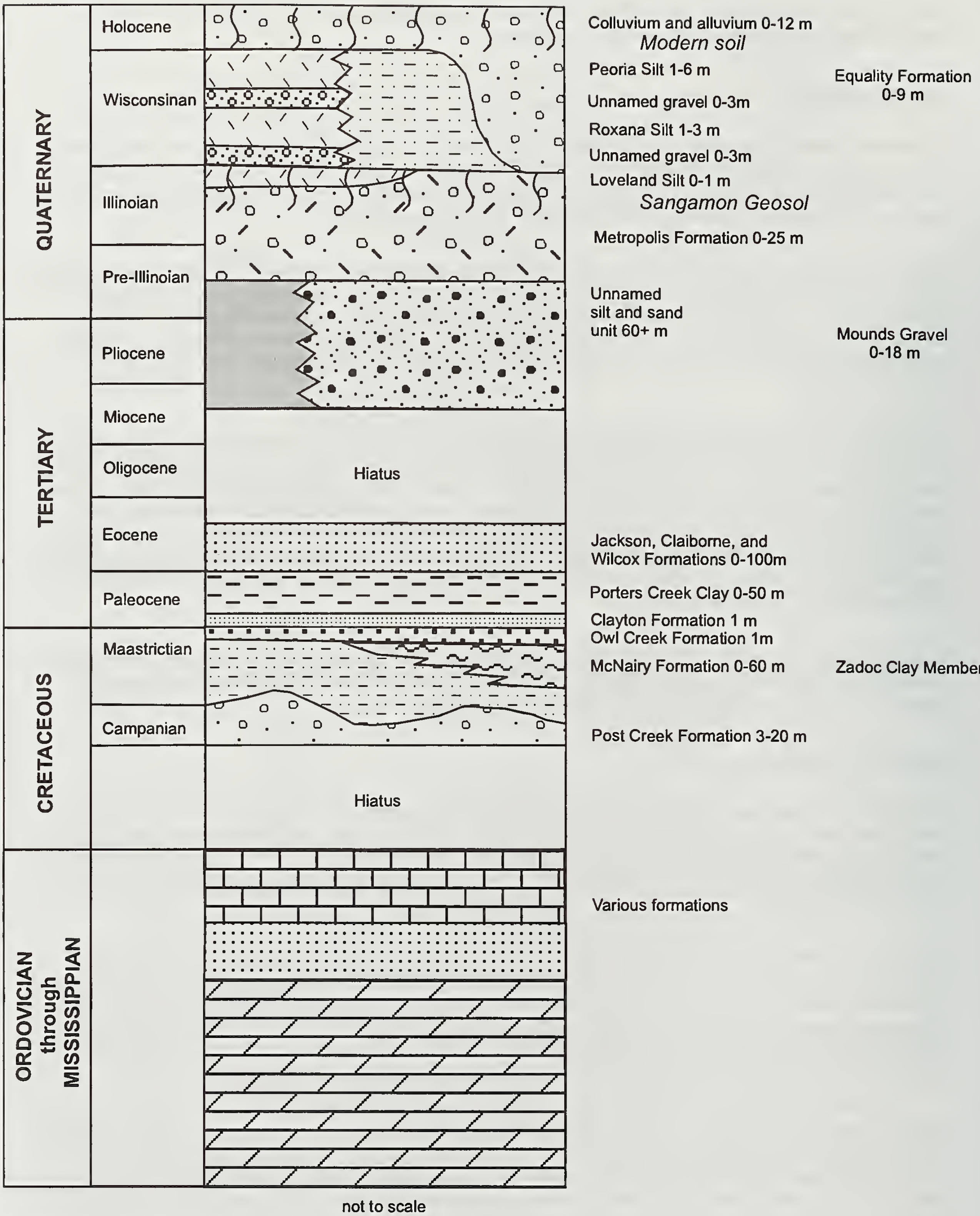


Figure 2 Generalized stratigraphic column for the field trip area.

The **Commerce geophysical lineament** (fig. 1) is a northeast-trending magnetic and gravity feature that extends from northeast Arkansas to southern Illinois. Modeling indicates that the source of the lineament is probably a mafic dike swarm (Langenheim and Hildenbrand, 1997), which presumably was intruded along a northeast-trending fracture zone. The Commerce feature coincides with the steep southeast-facing escarpments of the Bloomfield and Benton hills and is associated with Neogene tectonic faulting in both areas. Possible current activity is suggested by 12 earthquake epicenters that lie on or very close to the lineament (Harrison and Schultz, 1994). Four of the six stops on this field trip feature deformation along the Commerce geophysical lineament.

Crowley's Ridge (fig. 1) is a striking feature of the broad Mississippi floodplain. Previously, Crowley's Ridge was interpreted as erosional remnants left by repeated channel shifts of the Mississippi River during the Quaternary Period (Guccione et al., 1986). New findings indicate, however, that the ridge is at least partly a product of tectonic uplift. Fifteen high-resolution seismic profiles across Crowley's Ridge in northeastern Arkansas show many high-angle normal faults and several high-angle reverse faults underlying the ridge (Van Arsdale et al., 1995). These faults produce vertical offsets as great as 60 m in Eocene strata and 7.5 m in Pliocene sediments. Seismic-reflection surveys in the Bloomfield Hills, Missouri, indicate faults displacing units as young as Quaternary (Stephenson et al., in press). Still other seismic profiles from the Benton Hills depict extensive faulting of units as young as Quaternary (Palmer et al., 1997a and 1997b).

Trenching studies in the Bloomfield and Benton hills confirm the seismic evidence for widespread faulting of Quaternary sediments. Several of these trenches will be featured on this field trip.

Geomorphic evidence also strongly implies that the Bloomfield and Benton hills were tectonically uplifted and tilted toward the northwest during the late Pleistocene, if not the Holocene. The southeast margins of both sets of hills are sharply linear and coincide with both the Commerce geophysical lineament (fig. 1) and with Quaternary faults revealed by trenching and seismic profiles. Drainage patterns in both areas are highly asymmetrical. The drainage divides are nearly linear and less than 1 kilometer (a few thousand feet) from the southeast margin of the hills. The southeast-facing slope is steep and cut by many shallow ravines. The broad northwest-facing slopes are gentle and incised by large, well-integrated drainages.

FIELD TRIP STOPS

Stop 1: Barnes Creek

Location Approximately 5 miles (8 km) northeast of Metropolis, Illinois: mainly in the SE¼ of Section 9, T15S, R5E, Massac County, Metropolis 7.5-minute quadrangle (fig. 3). UTM coordinates 4,120,930 N, 351,900 E (west end of exposures) to 4,120,800 N, 352,900 E (east end of exposures), grid zone 16.

Site Description Barnes Creek is a small west-flowing tributary of Massac Creek, which flows south to the Ohio River. Local farmers straightened Barnes Creek to improve drainage, and have periodically removed gravel from the stream bed. These activities accelerated downcutting by the stream, revealing faulted sediments underlying Holocene alluvium.

Faulted Pleistocene sediment was first noted along Barnes Creek in 1994 in the course of routine geologic mapping. Follow-up studies included repeated examination of natural exposures (which change after every heavy rain), backhoe excavations, shallow core-drilling along both sides of the creek, and a seismic reflection profile 1.9 km long that parallels the north bank of the creek. These investigations defined four large graben or half-graben structures, along with many smaller faults and fractures, that displace Pleistocene strata (Nelson et al., 1996 and in press).

The field trip group will observe faults in the bed and banks of Barnes Creek, beginning about 180 m west of Barnes Creek Road and proceeding 910 m east (fig. 3). Rubber boots are recommended.

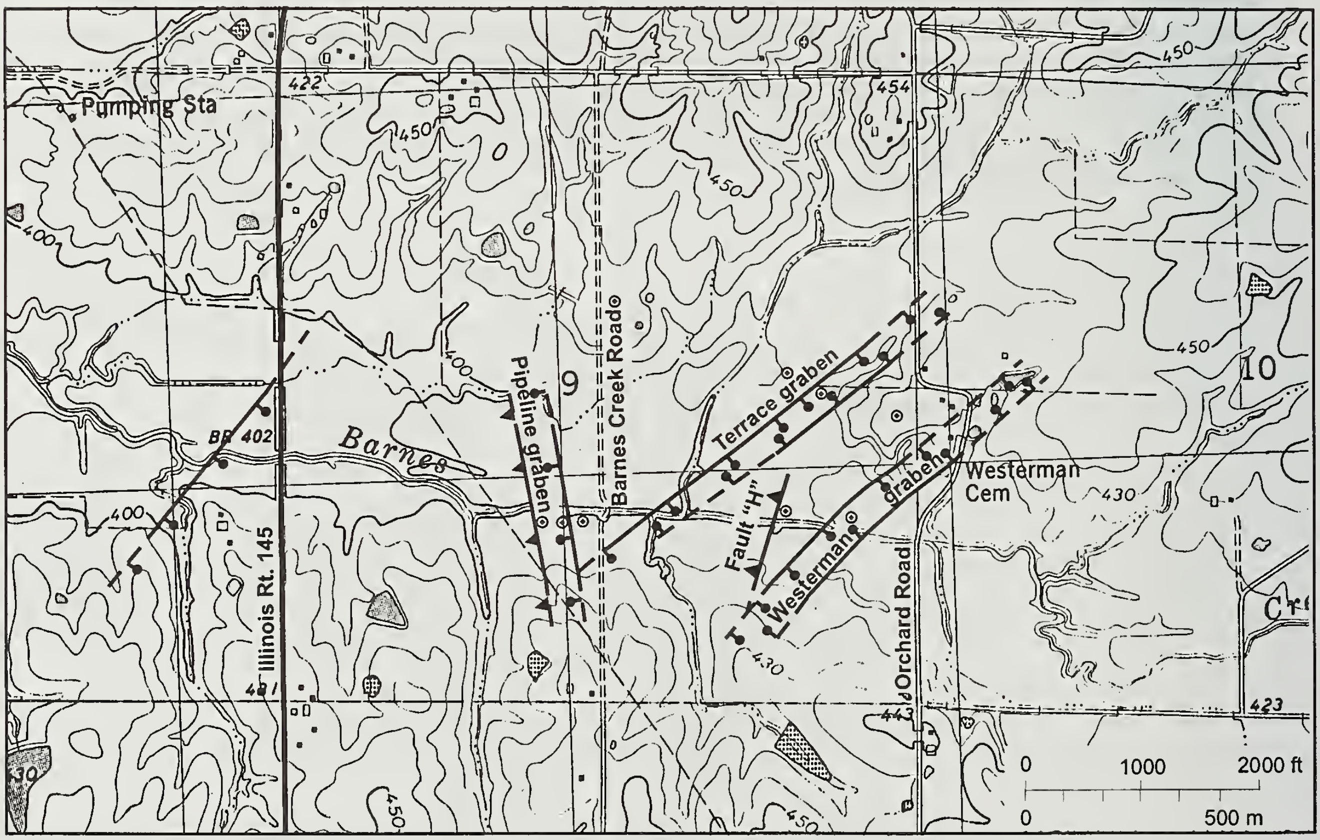


Figure 3 Stop 1, Barnes Creek Fault Zone along Barnes Creek in Massac County, Illinois.

normal fault; ball and bar on downthrown side
reverse fault; sawteeth on upthrown side
ISGS test boring

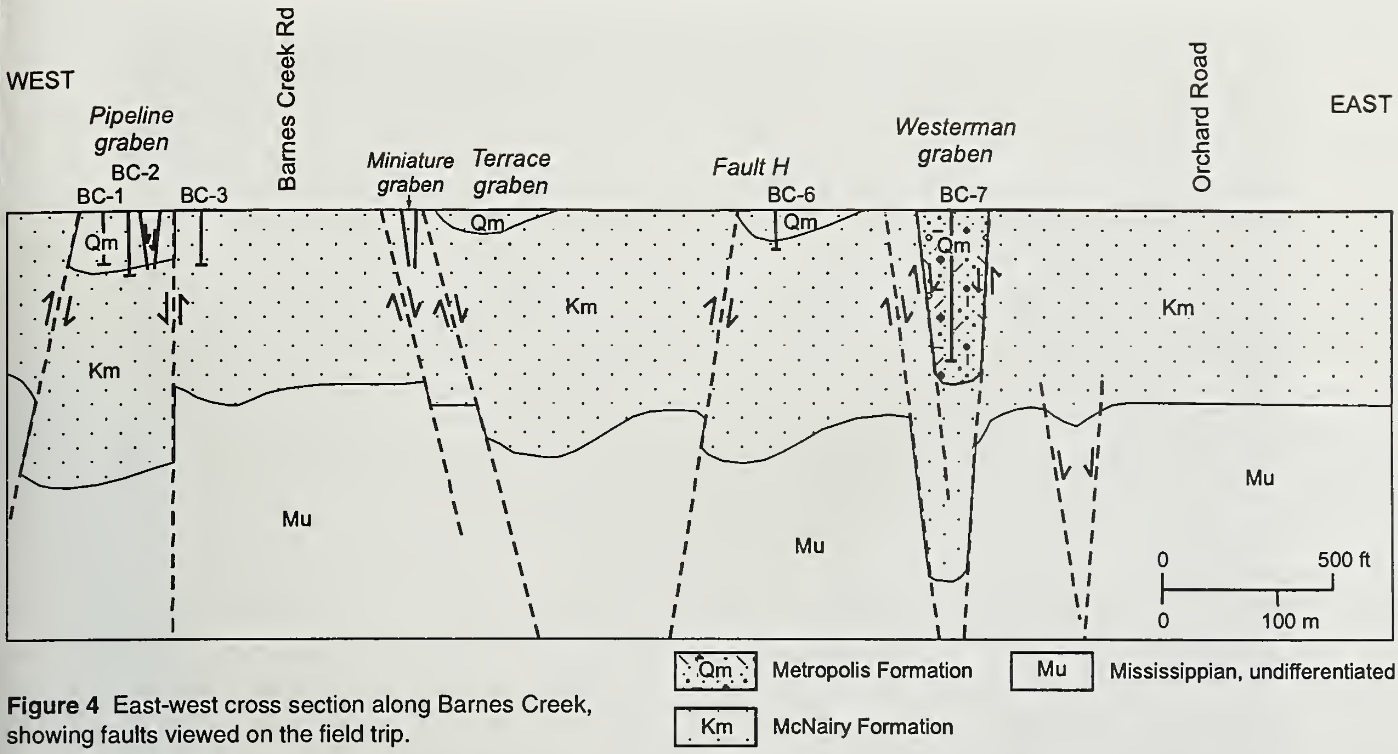


Figure 4 East-west cross section along Barnes Creek, showing faults viewed on the field trip.

Structural Setting The faults along Barnes Creek are part of the Barnes Creek Fault Zone (BCFZ), which in turn is part of the Fluorspar Area Fault Complex (fig.1). The BCFZ strikes northeast and extends about 40 km northeast of Barnes Creek into Hardin County, Illinois. Its extent southwest of Barnes Creek is not known.

Similar to other faults in the Fluorspar Area, the BCFZ is composed mainly of high-angle normal faults. In Paleozoic bedrock northeast of Barnes Creek, the BCFZ is mapped as either a single fault, or two faults outlining grabens less than 500 m wide. Vein deposits of fluorspar were once mined underground along the northeast end of the fault zone. Fault surfaces in the mines bear prominent obliquely-plunging mullions and striations. Vertical displacements along the BCFZ are in the range of 15 to 60 m.

The fault pattern at Barnes Creek is considerably more complex than that seen to the northeast. The fault zone here is at least 1.2 km wide and composed of many faults that outline horsts and grabens. A seismic reflection profile (Sexton et al., 1996) indicated both normal and high-angle reverse faults, some of which bifurcate upward to form positive and negative "flower structures." Most faults strike northeast, parallel to the BCFZ as a whole, but several faults and many joints trend N-S to NNW, crossing the regional grain.

Pipeline graben The westernmost structure to be viewed on the field trip is a graben adjacent to a natural-gas pipeline (figs. 3, 4). The pipeline graben is about 90 m wide, and its boundary faults trend N-S to N10°W. The Metropolis Formation is downthrown against McNairy Formation along both boundary faults. The western fault is a reverse fault that dips 75° west and shows drag in laminated McNairy on the hanging wall. The eastern fault is nearly vertical. An asymmetrical syncline that borders the east side of the graben is not explainable as a simple drag-fold.

Three cored test holes were drilled on the south bank of Barnes Creek, two within the graben and one just east of it. Drilling shows that the Metropolis Formation is downthrown at least 10 m relative to the McNairy outside of the structure.

Near the east edge of the pipeline graben are two parallel faults that strike N40°W and are about 1 m apart. These faults displace not only the Metropolis Formation, but the basal gravelly layers of overlying alluvium. Vertical separation on the alluvium is less than 1 m. Younger layers of alluvial gravel and silt are not disturbed.

The reverse fault on the west side and discordant fold on the east side suggest that the pipeline graben is bordered by strike-slip faults. Major displacements were Illinoian and older; however, small post-Illinoian movements also took place.

Miniature graben A small graben is exposed in the south bank of Barnes Creek about 115 m east of Barnes Creek Road (fig. 5). This structure is about 0.9 m wide at the top, narrows downward, and strikes northeast (parallel to most faults in the BCFZ). Gravel and silt are downdropped against the McNairy Formation. The downdropped gravel and silt may be Metropolis Formation or younger alluvium. They bear features typical of the Sangamon Geosol, whereas the McNairy outside of the graben lacks Sangamon features. The top of the little graben is truncated by horizontal, undeformed Holocene alluvium. Hence, the graben is likely to be of Wisconsinan age.

Outside of the graben, crossbedded sand of the McNairy dips gently west on both sides of the graben. There is very little drag, and layers in the McNairy appear to match up across the graben with no offset. This is a miniature example of larger Neogene and Quaternary grabens in southernmost Illinois.

Terrace graben A half-graben feature is exposed in the south stream bank about 15 m east of the miniature graben. The western margin of the half-graben is a normal fault that strikes N30°E and dips 65° southeast (fig. 4). East of this fault, the McNairy and Metropolis Formations are folded into a northeast-trending syncline that is about 60 m across. Dip of bedding gradually decreases from 30-35° on the outer flanks to horizontal along the broad trough of the fold. If the east flank is faulted, the faults are concealed.

We call this structure the terrace graben because it offsets a Pleistocene terrace north of Barnes Creek. A northeast-trending, marshy swale separates two terrace segments that stand at different elevations (figs. 3, 4). Core drilling revealed that the swale is underlain by a graben, in which the Metropolis Formation is downthrown 18 m.

Fault H A feature we call fault H can be seen on the north bank of Barnes Creek 400 m east of Barnes Creek Road (figs. 3, 4). This fault strikes N15°E and dips steeply west. The McNairy Formation west of fault H is nearly horizontal. East of Fault H the McNairy dips steeply eastward, and is overlain by gray, faintly bedded silt that has gravel layers at the base. The McNairy and the gray silt are folded into a broad syncline (fig. 4), the top of which is truncated by horizontal Holocene alluvium.

The identity of the gray silt unit is unknown. It is unlike the strongly mottled sandy, gravelly silts of the Metropolis Formation. Black-stained layers in the silt proved to be manganese oxide, barren of carbon or microfossils. Silt of similar character from cores in the Massac Creek graben (about 2 miles north of this site) yielded late Miocene to early Pleistocene pollen.

Fault H is interpreted as a high-angle reverse fault having a drag-fold in the footwall. The major movements were Illinoian or older; however, a small amount of younger movement took place. This is evident by a few cm of normal displacement in the lower layers of horizontal alluvium. The fault surface is lined with a film of clay. Also, alluvial gravel moved downward along the fault plane, between McNairy Formation on either side.

Westerman graben The largest Quaternary graben along Barnes Creek is the Westerman graben, which is about 150 m east of fault H, or 210 m west of the bridge on Orchard Road (figs. 3, 4).

Figure 5 Miniature graben in bank of Barnes Creek. Quaternary gravel is downthrown between nearly horizontal McNairy Formation (Cretaceous) on either side.

The Westerman graben is 75 m wide and outlined by faults that strike N25°E. The outer part of the graben is filled with McNairy Formation that dips steeply inward. The inner part is filled with Metropolis Formation. Many near-vertical, clay-lined fractures in the Metropolis trend perpendicular to the walls of the graben.

A cored test hole drilled into the center of the graben penetrated 4 m of alluvium overlying 28 m of Metropolis Formation to the bottom of the hole. The Metropolis therefore is downdropped a minimum of 28 m. The core showed several intervals of steeply inclined layering, and near-vertical bedding at the bottom of the hole. Fossil pollen from the Metropolis Formation in the core indicated an interglacial Pleistocene flora (Norman Frederiksen, U.S. Geological Survey, personal communication,1997). Post-Sangamonian alluvium that overlies the Westerman graben is horizontal and unbroken.

Stop 2: Happy Hollow and Sassafras Canyon

Location Approximately 0.3 km north of Commerce, Missouri, in the SE¼ of Section 24, T29N, R14E, Scott County, Thebes 7.5-minute quadrangle (fig. 6). UTM coordinates are 282,460 E, 4,114,440 N (west end of exposures) to 282,180 E, 4,115,525 N (east end of exposures), grid zone 16.

Site Description Happy Hollow is the local name for a northeast-trending ravine that cuts across the Benton Hills to the Mississippi River just north of Commerce, Missouri (fig. 6). The exposure consists of an artificial excavation into a hillside along the southeast side of Happy Hollow. Sassafras Canyon is our name for a small southeast-trending ravine that joins Happy Hollow. A trench was excavated along Sassafras Canyon in 1997 to expose geologic structures. Structures that are characteristic of neotectonism in the Thebes Gap-Benton Hills area of southeast Missouri will be examined at this stop: high-angle reverse and thrust faults exposed in the Happy Hollow trench, and complex flower structures produced by strike-slip faulting exposed in Sassafras Canyon.

Figure 6 Location map of Albrecht Creek, Happy Hollow, and Sassafras Canyon sites on Thebes 7.5-minute quadrangle.

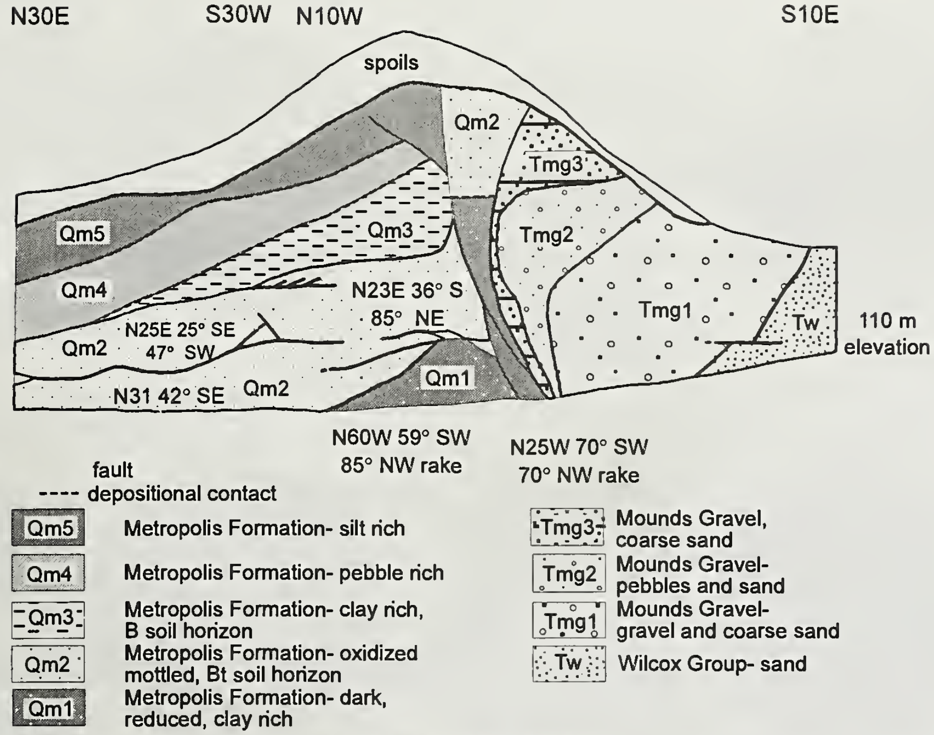


Figure 7 Section of fault zone at Stop 2, Happy Hollow.

Happy Hollow Two episodes of faulting are exposed at the Happy Hollow trench. An older set of low-angle thrust faults in the Metropolis Formation is truncated by younger high-angle reverse faults (fig. 7). Rakes of striations on fault surfaces indicate that the thrust faults were generated by northeast-southwest compression (fig. 8b). Multiple splays of the reverse faults strike from N25°W to N60°W, dip steeply to the southwest, and have steeply dipping deposits of Mounds Gravel dragged along the fault in the hanging wall. Fault surfaces bear slickenside striations that rake steeply to the northwest, which indicate a northwest-southeast-directed horizontal compression (fig. 8b). Drilling indicates a minimum of about 30 m of vertical displacement across the reverse faults.

The time of movement on both sets of faults is constrained only as post-Metropolis Formation; that is, Illinoian or younger. However, a thick soil profile is well developed in the Metropolis Formation and is absent from the Mounds Gravel. If this paleosol is the Sangamon Geosol, as we interpret it, then the latest faulting probably occurred less than 55,000 years ago.

Sassafras Canyon Trench exposures (fig. 9) along the walls of Sassafras Canyon, located about 200 m northwest of the Happy Hollow excavation, reveal two zones of transpressional, strike-slip faulting separated by a broad syncline. The southern zone cuts deposits ranging in age from the Cretaceous McNairy Formation through the Neogene Mounds Gravel. Bedding within this zone is steeply dipping to overturned and broken by many faults. The major fault strands strike N50°E to N75°E and are steeply dipping. Both high-angle reverse faults and strike-slip faults containing sub-horizontal slickenside striations and mullions are present. Kinematic indicators such as scallop- and carrot-shaped depressions on fault surfaces suggest right-lateral strike-slip motion on some of the major faults. Alluvial valley fill, which overlies all faulted units, provides a minimum age constraint. A charcoal sample from this alluvium yielded a ^{14}C age of 1,410 $\pm$ 40 yrs.

The northern fault zone is structurally complex. Two major, near-vertical faults that occur in this zone, SC-1 and SC-2, strike N65°W and N80°W, respectively. Bedding of the 10-m-thick section of the Wilcox Group between these two faults is vertical. Several southwest-dipping, oblique-slip faults also occur in this northern zone. One of these faults, SC-3, strikes N86°W and has a concave-downward dip

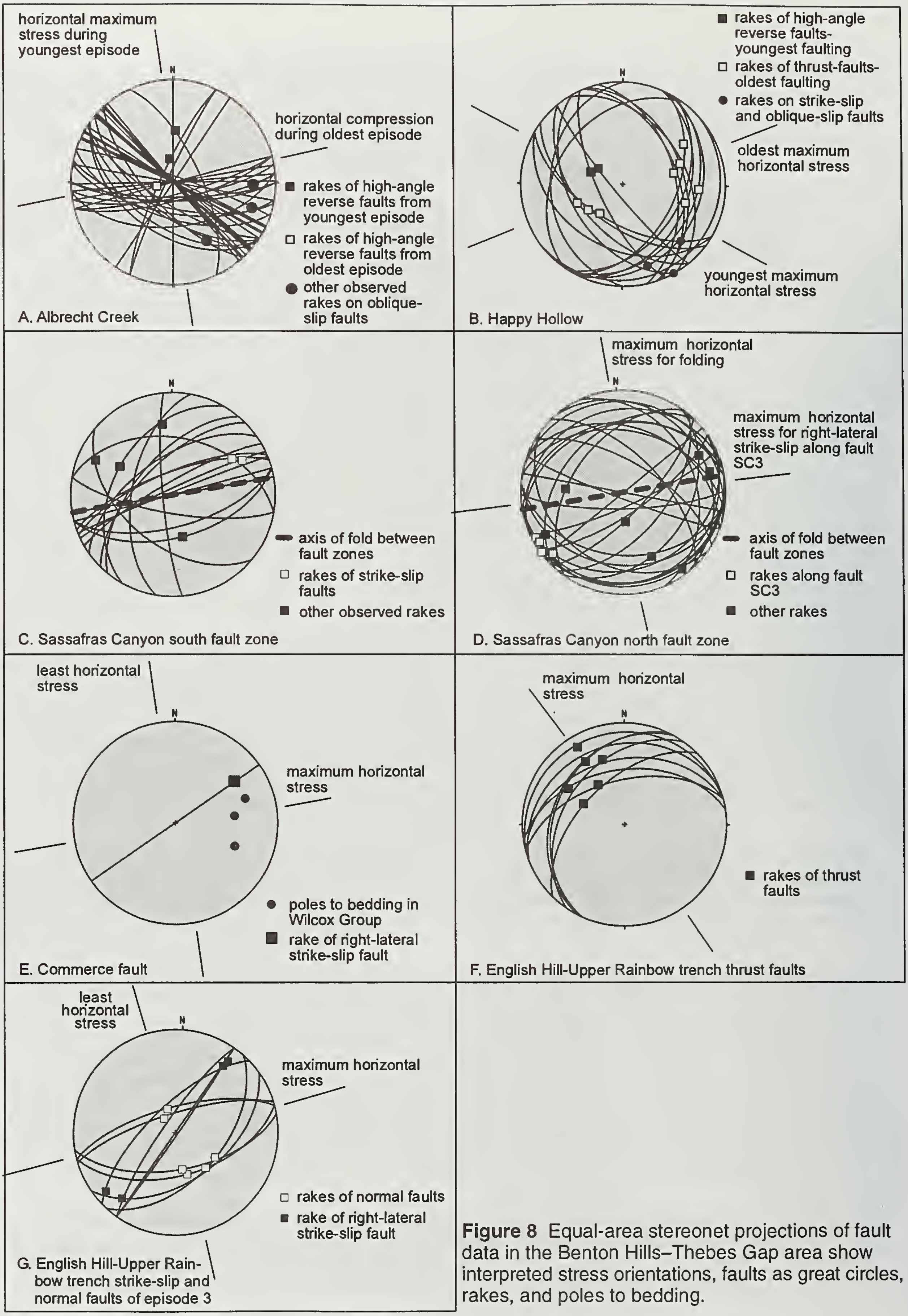
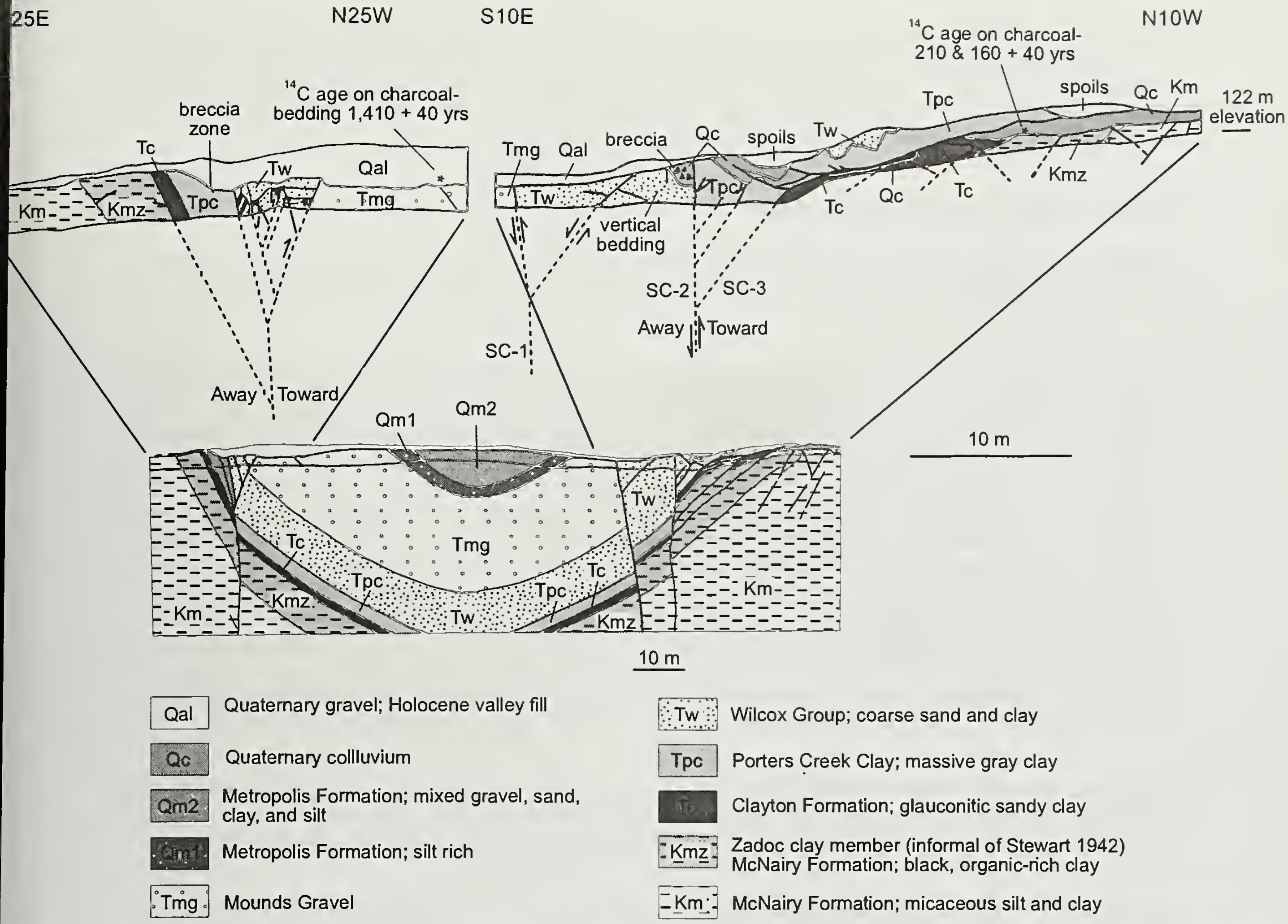


Figure 8 Equal-area stereonet projections of fault data in the Benton Hills–Thebes Gap area show interpreted stress orientations, faults as great circles, rakes, and poles to bedding.



igure 9 Profile of Sassafras Canyon has simplified trench logs above and interpretive cross section below. Two zones of transpres-ional strike-slip faulting are separated by a syncline that trends ENE. Multiple episodes of deformation are evident, the youngest of which robably accompanied the great New Madrid earthquakes of 1811–1812, either as a co-seismic event or secondary slumping.

of 25° to 45° to the southwest. Slickenside striations and mullions raking 10° to 20° to the southwest occur on the surface of fault SC-3; numerous fault splays, striking N70°–80°E and dipping from 20° to 40° to the northwest, occur in the hanging wall of fault SC-3 and show thrust motion. Fault SC-3 is significant because it places Tertiary deposits over Holocene colluvium. Charcoal collected from the colluvium has yielded ^{14}C ages of 210 and 160 ± 40 yrs before present. These ages are just prior to the great 1811–1812 New Madrid earthquakes, suggesting three possibilities.

1. Our preferred interpretation is that in response to strong ground shaking generated by these great earthquakes, shallow gravity-driven sliding occurred that in part utilized the pre-existing slip surface along fault SC-3. The northwest-dipping thrusts in the hanging wall support this possibility.

2. Movement was tectonic and co-seismic, triggered by the New Madrid earthquakes. Colluvium, similar in appearance to that dated, in the south wall of fault SC-2 is possible evidence supporting tectonic movement, as this fault is vertical and clearly not of slump origin. However, it cannot be demonstrated that the two colluviums are correlative. Slickenside striations on fault SC-3 can be interpreted as supporting either of the above two possibilities as they rake virtually along strike of the fault (fig. 8c) and are consistent with right-lateral strike-slip movement produced by east-northeast compression, but they are also in a downhill direction.

3. Although considered unlikely, it is possible that this fault zone was one of several seismic sources active during the winter of 1811–1812.

Between the southern and northern fault zones at Sassafras Canyon is a broad syncline (fig. 9) that has an approximate east-northeast-trending trough line. The youngest known folded unit is the Metropolis Formation. North-northwest-oriented compressional stress (fig. 8d) is one possible interpretation for the origin of this folding. An alternative explanation is that the syncline formed between compressive positive flower structures that rose on both sides.

Stop 3: Albrecht Creek Cutbank

Location Approximately 2.5 km north of Commerce, Missouri in the SW¼ of Section 13, T29N, R14 E, Scott County, Thebes 7.5-minute quadrangle (fig. 6). UTM coordinates are 281,165 E, 4,117,260 N in grid zone 16.

Site Description A cutbank of Albrecht Creek exposes several high-angle reverse faults, strike-slip faults, and clay-filled fractures (fig. 10). High-angle reverse faults ACA, ACB, ACC, and ACD at the northern end of the cutbank offset strata of late Cretaceous through Quaternary (pre-late Illinoian) age. Vertical displacements are: approximately 10 m on fault ACA, 2 to10 m on fault ACB, 10-20 m on fault ACC, and at least 40 m on fault ACD. Displacement across ACD is constrained by drill hole BH-6, which penetrated the Mounds-Metropolis contact at a depth of 41 m. Because the Metropolis Formation is eroded from the upthrown (northwest) side of fault ACD, this fault underwent at least 41 m of late Pleistocene vertical displacement. Bedding between faults ACB and ACC is rotated to N15E, 64° SE; bedding between faults ACC and ACD is rotated to N15-20E, 20° to 90° SE. This is interpreted as drag related to development of these structures. Two sets of slickenside striations, raking 80° SW and 75° to 80°NE, occur on fault ACC. This suggests at least two episodes of faulting. Fault ACE, near the south end of the cutbank, contains subhorizontal mullions, suggesting a component of strike-slip motion; vertical displacement is approximately 1 m. The strike of bedding south of this fault is N-S, nearly perpendicular to fault strike, and dips range from 20° to 43° E.

Numerous fractures, some of which show subhorizontal slickenside striations, occur in the Metropolis Formation. Several of these are filled with clay that yielded fossil pollen, including *Pinus sylvestria*, the predominant modern form of pine pollen (N. Frederiksen, personal communication, 1996).

Overlying all units and faults is an unfaulted Holocene point-bar sequence consisting of coarse gravel and sand overlain by silt and clay. Four ^{14}C ages from charcoal in the lower deposits range from 2,070 to 1,540 $\pm$ 70 yrs before present, suggesting that the faulting at Albrecht Creek has not been active in the past 1,350 calendar years. An oldest constraint on faulting is provided by the pre-late Illinoian age of the Metropolis Formation. If the thick soil profile that has developed on the Metropolis Formation is the Sangamon Geosol as interpreted, then faulting probably is younger than approximately 55 ka, as there is no soil development in the faulted Cretaceous deposits at the north end of the Albrecht Creek cutbank. If faulting were older, the Sangamon Geosol should be developed in the Cretaceous deposits.

From fault and fracture data (fig. 8a) at the Albrecht Creek cutbank, two episodes of faulting are evident. The older is interpreted as the result of east-northeast horizontal compression that produced the west-southwest-oriented striations on fault ACC and most of the fractures either as left-lateral strike-slip or extensional surfaces. Dilation occurred along those that are clay filled. A second compressional episode, at nearly a right angle to the first, produced the northerly oriented striations on faults ACA and ACC.

Structures at Albrecht Creek are interpreted as part of a pull-apart graben that formed from left-stepping displacement along pre-existing, north-northeast-striking structures during the first episode of faulting. This interpretation is supported by a seismic reflection profile acquired along Albrecht Creek (fig. 11) that shows the Quaternary graben bounded by Cretaceous and Paleozoic units. This profile also suggests faulting of pre-Cretaceous age units, as well as complex post-Cretaceous deformation. Reversals in motion along several faults are indicated, including those that bound the Quaternary

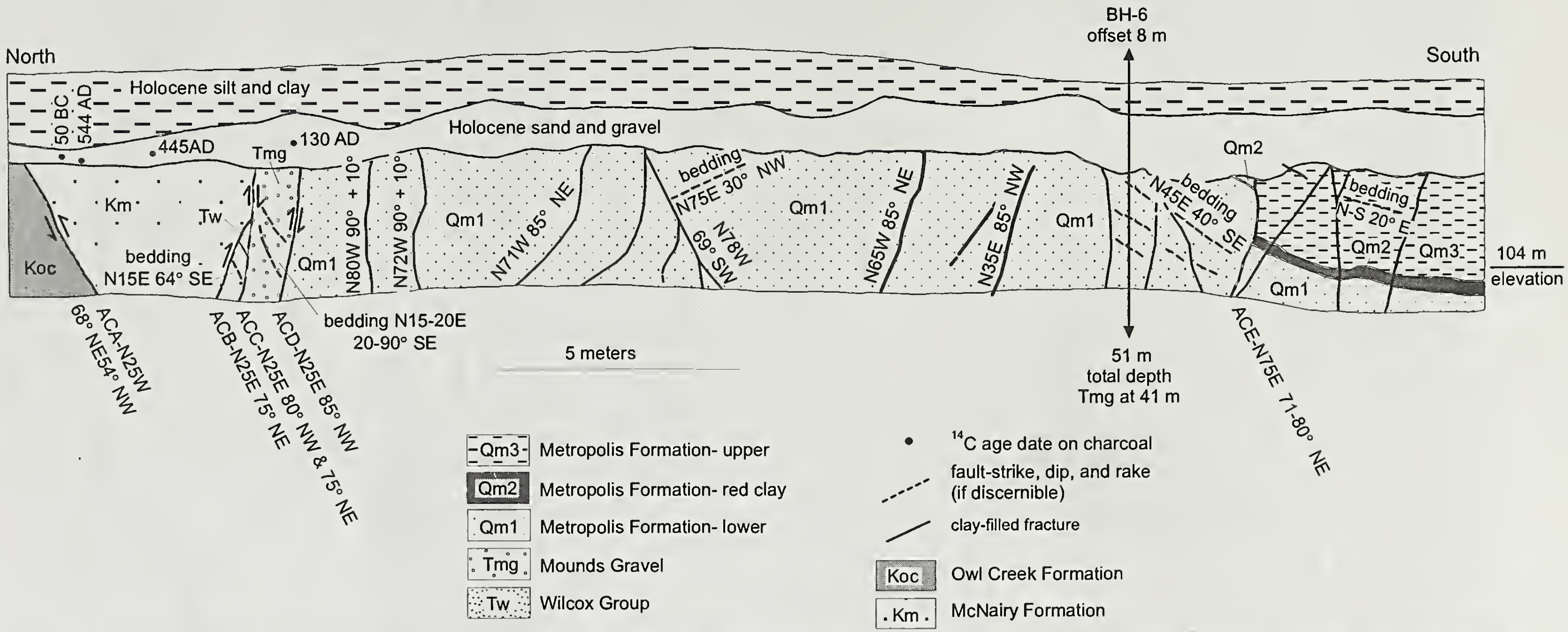


Figure 10 Section of cutbank along Albrecht Creek, shows a fault zone that displaces the Metropolis Formation and older units, but does not disturb Holocene alluvium.

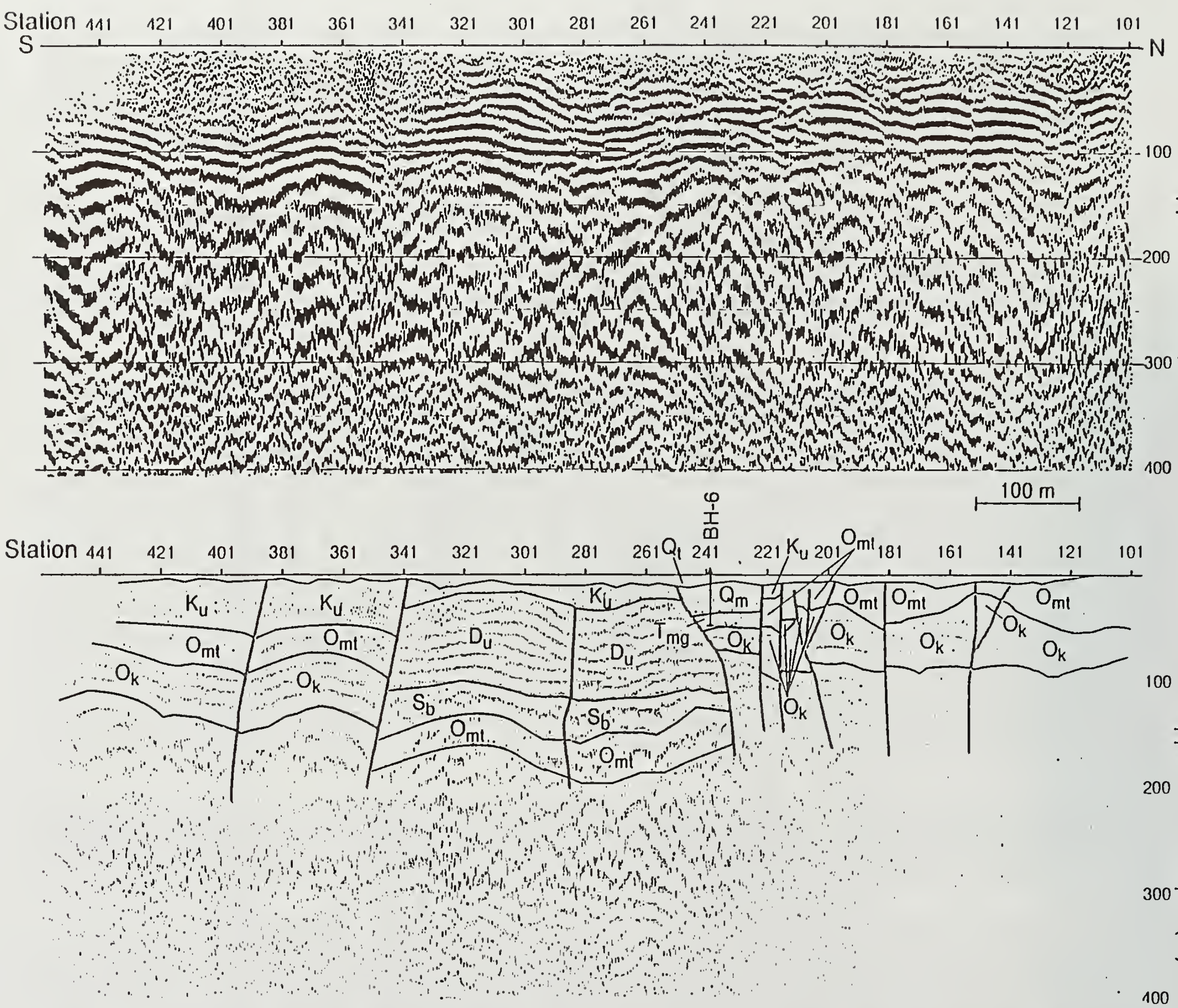


Figure 11 Seismic reflection profile along Albrecht Creek (see fig. 6 for location). Data were acquired using a shotgun source at 3 m spacing. Explanation of symbols on interpreted profile: Qt = Holocene point-bar sequence. Qm = Metropolis Fm., Tmg = Mounds Gravel, Ku = undifferentiated Cretaceous units, Du = undifferentiated Devonian units, Sb = Bainbridge Group, Omt = Thebes Sandstone Member of Maquoketa Gp., Ok = Kimmswick Limestone.

graben. Exposures in bluffs along the Mississippi River, approximately 500 m to the east, show similar patterns of faulting (see fig. 6b of Harrison and Schultz, 1994).

Stop 4: English Hill

Location Approximately 5.2 km west of Commerce, Missouri, in the eastern third of Section 33 and western third of Section 34, T29N, R14E, Scott County, Scott City 7.5-minute quadrangle (fig. 12). Area is bounded by UTM coordinates 277,320 to 277,920 E, 4,112,540 to 4,113,000 N, grid zone 16.

Site Description English Hill is situated along the steep southeast-facing slope of the Benton Hills. The most comprehensive studies of neotectonism in the Benton Hills have been conducted here. Trenching reveals complex faulting that displaces Pleistocene and Holocene deposits (Harrison et al., 1997). Seismic reflection profiles acquired at English Hill (Palmer et al., 1997a, 1997b) indicate that this faulting extends into the Paleozoic bedrock as near-vertical flower structures and shows both normal and reverse displacement. It also demonstrates that the deformation is tectonic and not merely the result of landsliding or other surficial, non-tectonic processes.

Old Quarry Trench The Old Quarry trench (fig. 13) was excavated at approximately mid-hill elevation along the eastern margin of a long-abandoned gravel quarry immediately south of English Hill Road (Scott County route 329) (figs. 13 and 14). The trench revealed several high-angle normal faults, all of which cut Mounds Gravel and a well-defined Quaternary sequence of Sangamon Geosol (developed in Loveland Silt), Roxana Silt, and Peoria Silt. Thermoluminescence (TL) dating (table 1) confirms the field identification of Roxana and Peoria Silts and establishes a maximum age of faulting in this trench of 21.9 $\pm$ 3.3 ka. Colluvial material caps the stratigraphic sequence and

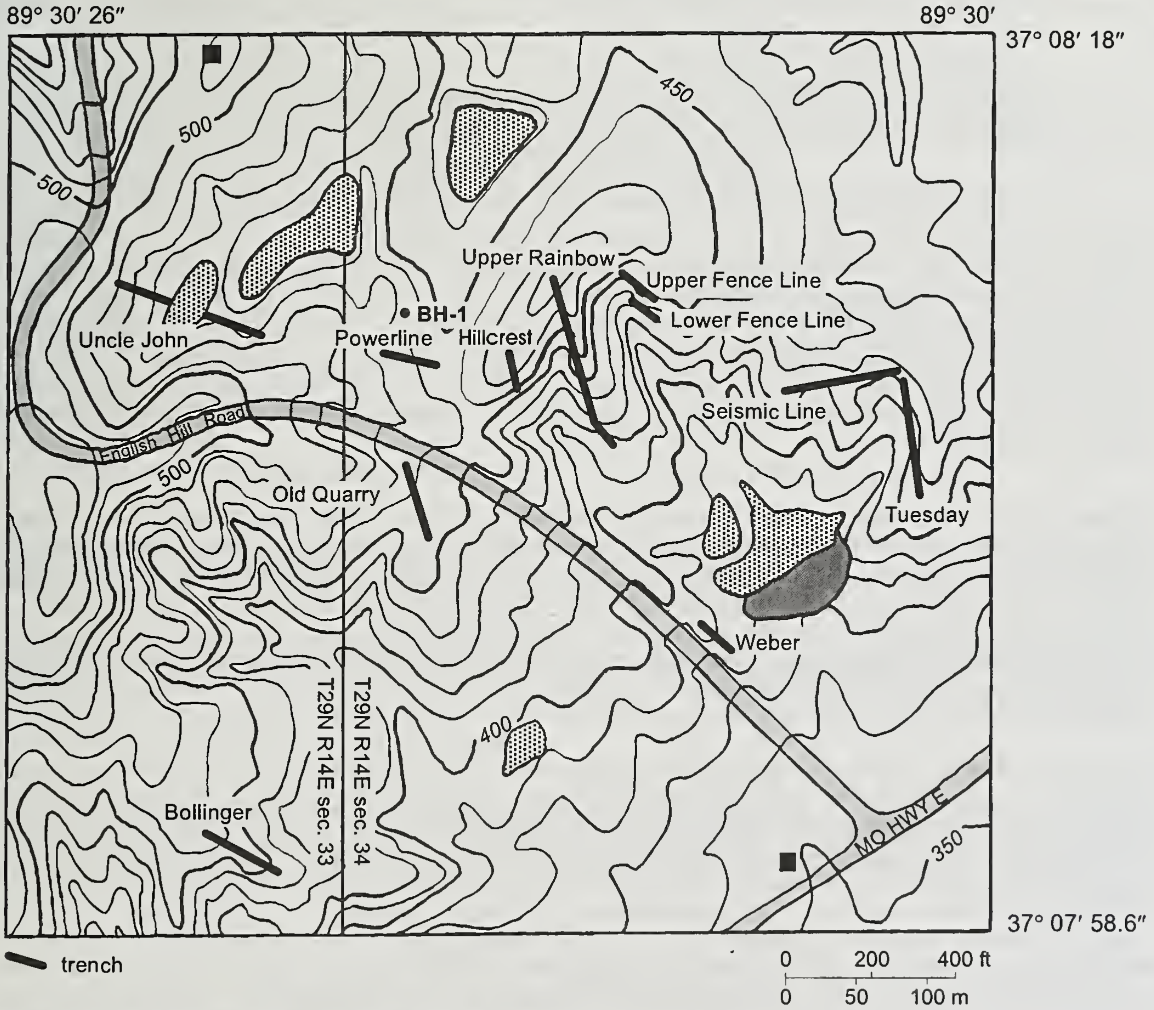


Figure 12 Trench location map for English Hill. Elevation contours in feet.

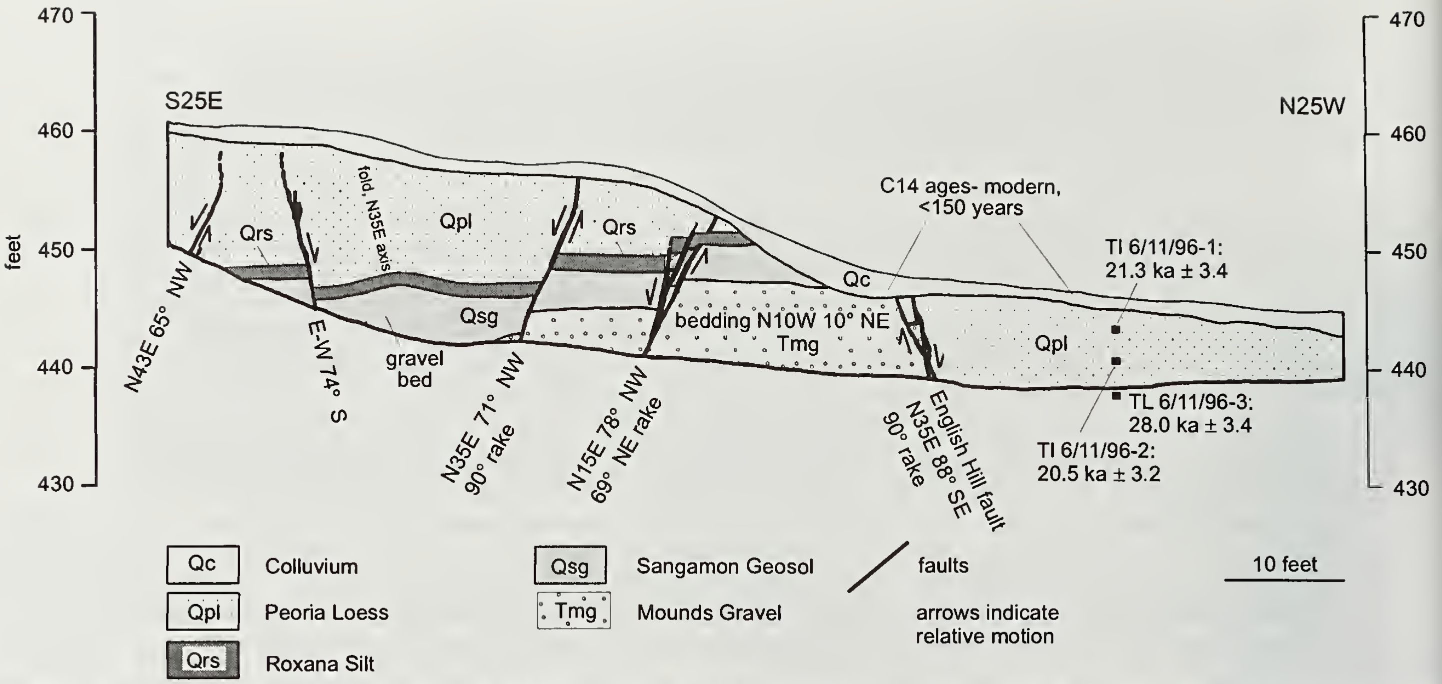


Figure 13 Section of the northeast wall of the Old Quarry trench (see fig. 11 for location). Normal faults that outline grabens and horsts displace Peoria Loess and older units.

truncates all faults. A horizon at the base of the colluvium contained several pieces of leaves, twigs, and nuts, four of which yielded modern (<150 years) ^{14}C age dates.

The major fault exposed in the trench is called the English Hill fault because it is believed to be the structure so named by Stewart (1942). This fault juxtaposes Peoria Silt in the hanging wall against Mounds Gravel in the footwall, and consists of several braided strands that strike N35°E and dip 88°SE. Slickenside striations along the fault surfaces rake 90°. Fault-bound slivers of Roxana Silt occur along the fault. Gouge-like, sandy clay and numerous pebbles derived from the Mounds also occur along fault surfaces. Shallow holes dug in the floor of the trench in the hanging wall of the English Hill fault encountered Roxana Silt just below trench-floor level, thus indicating approximately 4.5 m of dip-slip on the structure. A TL age of 28.3 $\pm$ 3.4 ka confirms the field interpretation of this material as Roxana Silt.

Progressing to the northwest in the footwall of the English Hill fault, three antithetic faults and one synthetic fault form a horst-and-graben sequence. Respective attitudes and rakes determined from slickenside striations (when observed) on these faults are N15E/ 78°NW with 69°NE rake; N35°E/ 71°NW with 90°rake; E-W/ 74°S, and N43°E/65°NW. Stratigraphic separation on the three south-eastern faults ranges from 0.3 to 1.2 m. Throw of the northwesternmost fault is unknown, because the trench was not deep enough to show an offset contact. A small N35°E-trending anticline was observed near the center of the graben.

Kinematic indicators provided by slickenside striation data on these larger faults exposed by the Old Quarry trench suggest overall northwest-southeast extension. A seismic reflection profile acquired along the trench (Palmer et al., 1997b) shows that the English Hill fault remains nearly vertical to depths of at least 67 m and that it offsets the Cretaceous-Paleozoic contact. Such a fault cannot be attributed to landsliding.

Several minor fractures, showing normal displacements of a few cm at the most, occur in the Mounds Gravel in the footwall of the English Hill fault. Attitudes vary considerably, both in strike and dip.

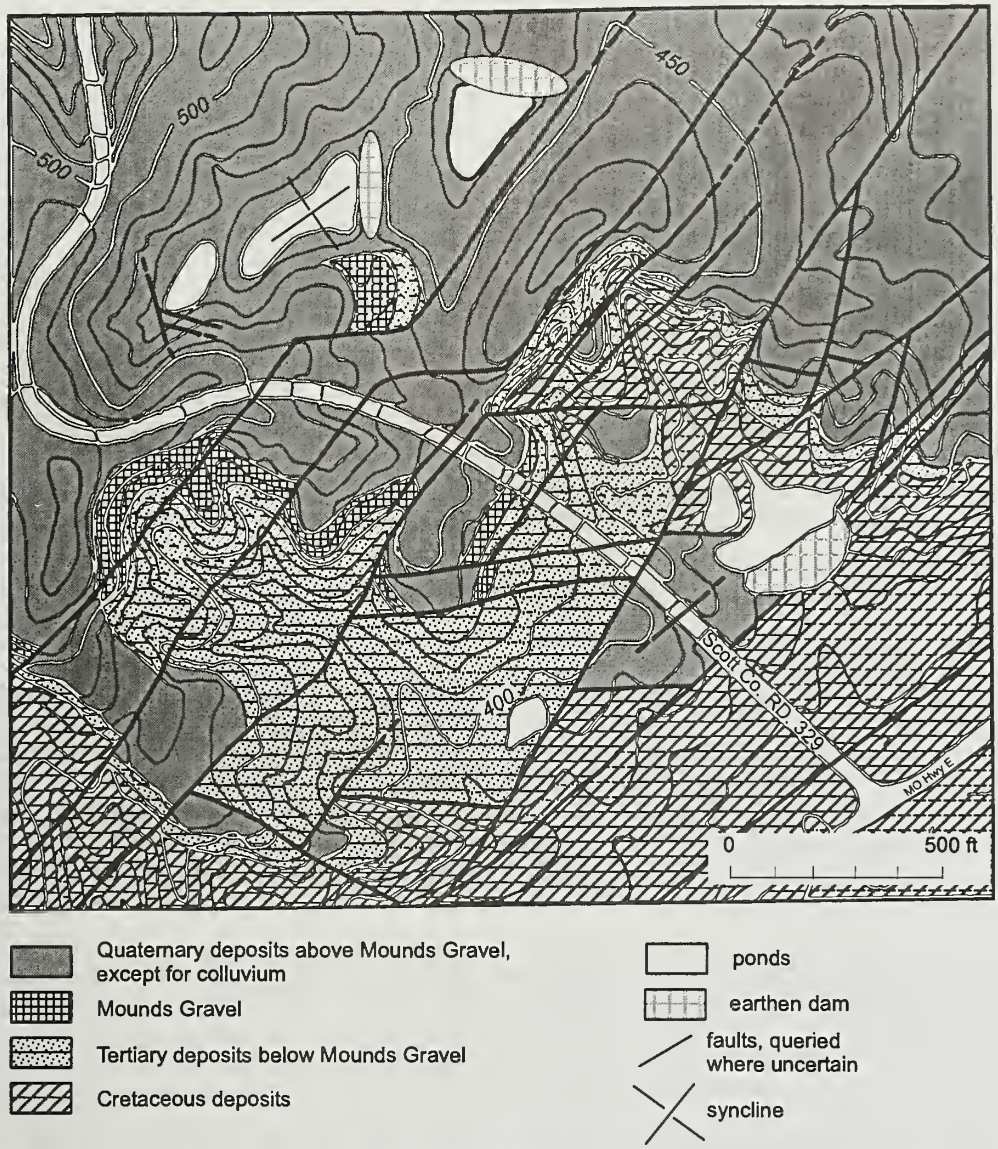


Figure 14 Generalized geologic map of the English Hill area showing faults and folds.

Faint striations that plunge 15°SE on a N17°W-striking fracture suggest a component of left-lateral shear; if real, this is inconsistent with overall northwest-southeast extension.

Several minor fractures also occur in the Sangamon Geosol that are untraceable into overlying or underlying units and except for one fracture showed no discernible displacement. That exception had striations indicating left-lateral, normal oblique slip on a N63°W-striking fracture. This is consistent with overall northwest-southeast extension.

Numerous vertical or near-vertical fractures showing no discernible displacement were observed in the Peoria Silt, particularly in the hanging wall of the English Hill fault. Although fractures in unfaulted loess are common, the density of fractures in the hanging wall of the English Hill fault is at least three times the density in the footwall, suggesting a tectonic origin. A comparison between fracture orientations in the Peoria Silt in the hanging wall versus the footwall (fig. 15) shows an overall polygonal pattern, but the hanging wall contains a much greater concentration of northwest-southeast-trending fractures, further suggesting a tectonic origin. All hanging wall fractures are truncated by the English Hill fault. Without any kinematic knowledge for these fractures, it is impossible to determine

Table 1 Luminescence data and age estimates for samples from English Hill, southeast Missouri (data from the University of Illinois Luminescence Dating Research Laboratory).

Field number and trench	Lab number	Method[1,2]	Temp. (°C) time(s)[3]	Equivalent dose (grays)	Luminescence age est. (Ka)[4]	Anomalous Fading Ratio[5]	Field ID of unit
6-11-96-1	UIC594	TL-Total Bleach:8h UV	250-400	84.4 + 10.6	22.7 + 3.5	0.98 + 0.03	Peoria Loess
Old Quarry		TL-Total Bleach:16h SL	250-400	79.2 + 10.6	21.3 + 3.4		
Trench		IRSL[6]-Total Bleach:1h SL	2-90	93.2 + 5.7	25.4 + 2.5		
6-11-96-2	UIC595	TL-Total Bleach:8h UV	250-400	78.8 + 11.8	21.9 + 3.3	0.98 + 0.03	Peoria Loess
Old Quarry		TL-Total Bleach:16h SL	250-400	73.6 + 11.8	20.5 + 3.2		
Trench							
6-11-96-3	UIC611	TL-Total Bleach:8h UV	250-400	98.4 + 10.6	28.3 + 3.4		Roxana Silt
Old Quarry		TL-Total Bleach:16h SL	250-400	97.3 + 10.2	28.0 + 3.4		
Trench							
6-11-96-4	UIC610	TL-Total Bleach:8h UV	250-400	106.5 + 10.7	31.8 + 3.0		Roxana Silt
Upper Rainbow		TL-Total Bleach: 16h SL	250-400	106.4 + 10.7	31.8 + 3.4		
6-11-96-5	UIC601	TL-Total bleach:8h UV	250-400	61.6 + 9.8	17.0 + 2.7		Peoria Loess
Upper Rainbow		TL-Total Bleach:16h SL	250-400	63.6 + 9.8	17.6 + 2.8		
6-11-96-6	UIC605	TL-Total Bleach:8h UV	250-400	73.6 + 7.5	18.4 + 2.2		Colluvial
Upper Rainbow		TL-Total Bleach:16h SL	250-400	74.8 + 7.5	18.7 + 2.2		Wedge
		IRSL[6]-Total Bleach:1h SL	3-59	75.8 + 2.4	19.3 + 1.7		
6-26-96-1	UIC599	TL-Total Bleach:8h UV	250-400	103.2 + 3.8	28.0 + 2.6		Roxana Silt
Tuesday		TL-Total Bleach:16h SL	250-400	103.9 + 3.7	28.0 + 2.6		
Trench							
6-26-96-2	UIC600	TL-Total Bleach:8h UV	250-400	75.9 + 8.6	20.6 + 2.7		Peoria Loess
Tuesday		TL-Total Bleach:16h SL	250-400	76.9 +8.6	21.0 + 2.7		
Trench							
6-28-96-1	UIC602	TL-Total Bleach:8h UV	250-400	92.4 + 9.2	25.6 + 2.6		Peoria Loess
Tuesday		TL-Total Bleach:16h SL	250-400	94.0 + 9.4	26.0 + 2.6		
Trench		IRSL[6]-Total Bleach:1h SL	2-90	93.5 + 9.4	25.6 + 2.5		
4-6-97-2	UIC625	TL-Total Bleach:8h UV	250-400	122.9 + 11.9	42.0 + 5.0	0.98 + 0.01	Roxana Silt
Upper Rainbow		TL-Total Bleach: 16h SL	250-400	121.0 + 11.9	40.0 + 5.0		
4-6-97-3	UIC629	TL-Total Bleach:8h UV	250-400	133.1 + 16.6	42.0 + 5.0	1.00 + 0.01	Roxana Silt
Upper Rainbow		TL-Total Bleach:16h SL	250-400	137.5 + 16.6	44.0 + 5.0		

[1] All TL measurements were made with a Corning 5/58 and HA-3 filters in front of the photomultiplier tube. Samples were preheated to 124 °C for 48 hrs prior to analysis.

[2] Hours of light exposure to define residual level for TL analysis. "SL" is natural sunlight in Chicago, Illinois. "UV" is light from 240 watt General Electric sunlamp bulb which is dominated by UV spectra.

[3] Temperature range used to calculate equivalent dose.

[4] All errors are at one sigma and calculated by averaging the errors across the temperature or time range.

[5] All samples were tested for anomalous fading by storing irradiated (100 to 450 gy) samples for at least 32 days and comparing the luminescence signal to an unstored aliquot. Anomalous fading between 1.00 and 0.90 indicate little or no fading within analytical resolution.

[6] Infrared stimulated luminescence.

Note: The 8 hours UV exposure is believed to result in full resetting of TL, particularly for loess that received extended light exposure during deposition and prior to burial, and is the favored age estimate.

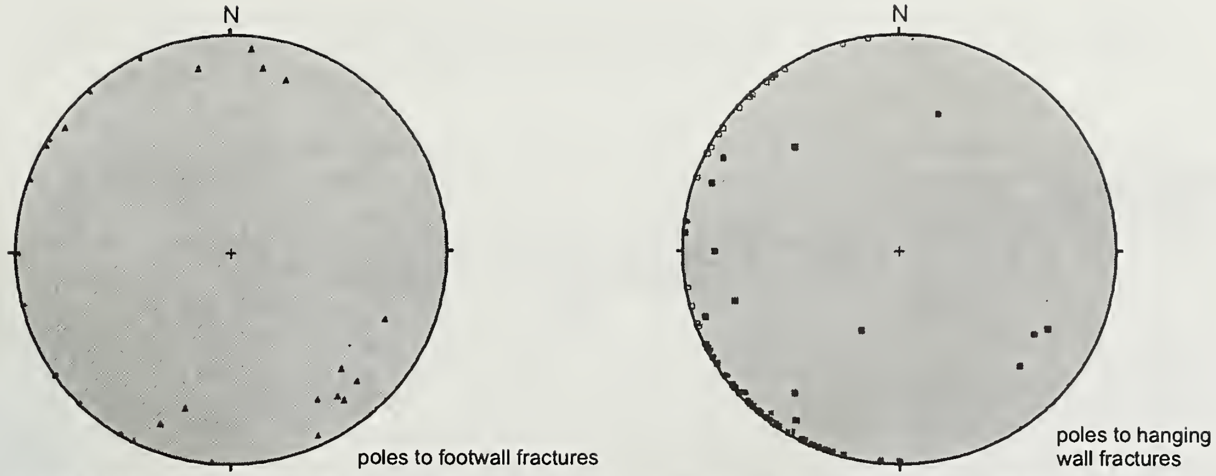


Figure 15 Equal-area lower hemisphere stereonets showing poles to fractures in Peoria Silt in the footwall and hanging wall of the English Hill fault at the Old Quarry trench.

if they represent horizontal shear that is compatible with northwest-southeast extension or an earlier northeast-southwest extensional fabric.

A notable difference in soil profile thicknesses was observed across the English Hill fault. In the footwall, the modern soil developed in the Peoria Loess is welded to the buried Farmdale soil in the Roxana Silt, resulting in a soil profile that extends from the surface all the way down to the Sangamon Geosol. In the hanging wall, however, modern soil development is restricted to the uppermost 0.3 to 1.0 m. The footwall soil profile is anomalously thick for the area and probably indicates formation in a trough or depression that experienced relatively high rates of water influx. This suggests the possibility of multiple episodes of faulting, forming the graben structure and subsequent faulting along the English Hill fault.

Upper Rainbow Trench The overall style and repetitious nature of tectonic deformation at English Hill is revealed in the Upper Rainbow trench (fig. 16). From cross-cutting relations and stratigraphy, four episodes of deformation are recognized that include normal (or transtensional), strike-slip, and thrust (or transpressional) faulting. Reactivation of individual faults is strongly suggested. Early Tertiary faulting, indicated by the presence of localized unconformities at the base of the Wilcox Group, reflects uplift and erosion of tens of meters of section—faults that offset only Wilcox and older units, and the abrupt thickening of the Wilcox Group across fault A. This is important because it indicates a pre-Quaternary ancestry to English Hill faulting.

Neotectonic episode 1 The oldest neotectonic episode identified at the Upper Rainbow trench was contemporaneous with deposition of an unnamed Quaternary gravel that lies beneath the Roxana Silt. The field identification of Roxana Silt is confirmed by TL age dates of 42.5 ± 5.0 ka and 31.8 ± 3.0 ka (Harrison et al., 1997). Timing is constrained by faults that offset the lower contact of the gravel but not the upper, and by the thickening of this gravel across fault B (fig. 16) from less than 1 m in the footwall to about 3 m in the hanging wall. Faults active during this episode are normal, strike NS45°–50°E, and are a consequence of northwest-southeast extension. Because the Sangamon Geosol is not developed on the gravel deposits, this faulting is thought to have occurred near the Sangamon–Wisconsinan boundary at about 55 to 53 ka.

Neotectonic episode 2 The second episode at the Upper Rainbow trench involved low-angle thrust faulting on faults C, D, E, F, and G (fig. 16). All of these structures dip to the northwest and place older units over younger. The youngest unit displaced by thrust faults is the Wilcox Group (Eocene); however, in other nearby trenches, the Sangamon Geosol is cut by thrust faulting. Unfaulted Peoria Loess overlies thrust faults in other trenches (Harrison et al., 1997). Normal faults of the first episode are truncated by thrust faults at several locations. In the footwall of fault D, S-folds in the McNairy

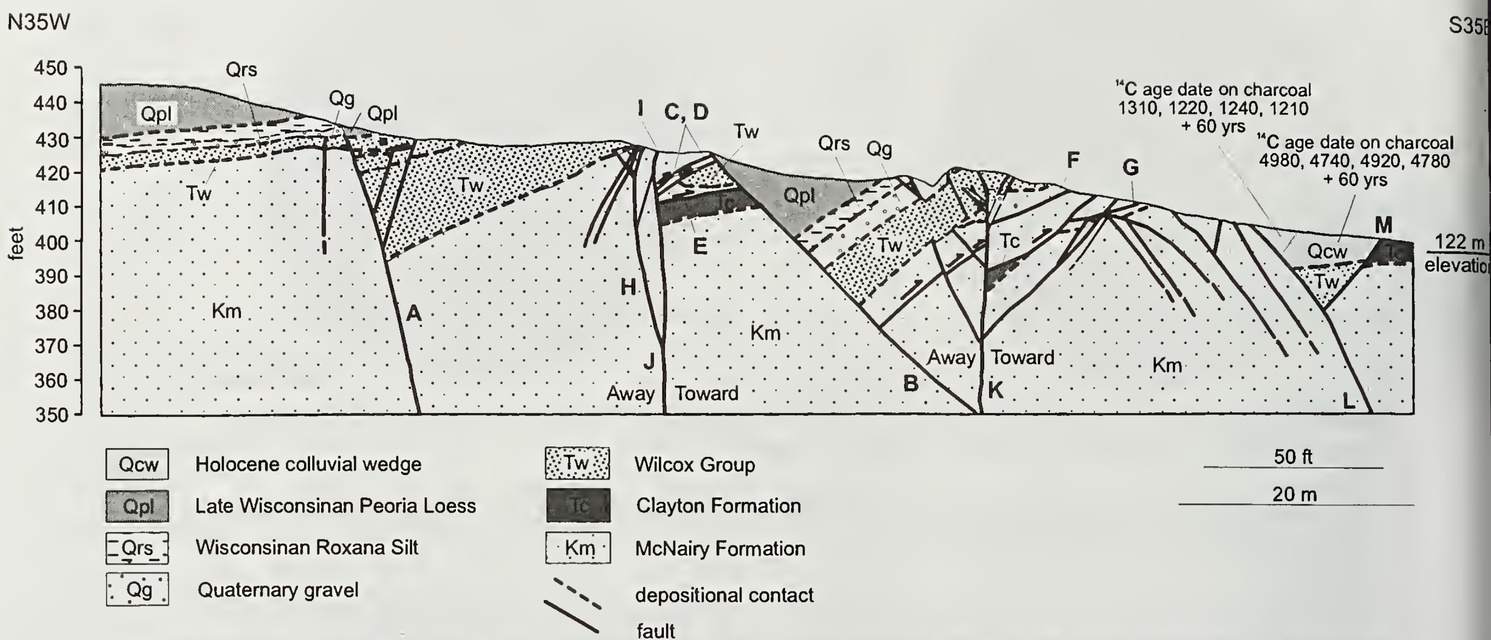


Figure 16 Section of the Upper Rainbow trench at English Hill. Evidence for at least four episodes of deformation is found here, the youngest of which displaced colluvium less than 1,300 years old.

Formation and drag on the unconformity between the McNairy Formation and Wilcox Group indicate top-toward-S35°E motion, which is consistent with slickenside striations and mullions observed on all thrusts (fig. 8f). This thrust-faulting episode is interpreted as the result of northwest-southeast-directed horizontal compression and is believed to be contemporary with the faulting observed at Albrecht Creek, Happy Hollow, and Sassafras Canyon and produced by similarly oriented stress.

Neotectonic episode 3 The third episode of neotectonism involves the late Wisconsinan Peoria Loess. This episode consists of strike-slip and normal faults, which because of similar age constraints, interpreted stress orientations, and geologic relations, are believed to be contemporaneous.

Right-lateral strike-slip motion, indicated by subhorizontal mullions and striations and the vergence direction of subsidiary shears, occurred on northeast-striking and steeply dipping faults H, I, J, and K (fig. 16). The mismatch of stratigraphy across faults J and K suggests at least several meters of horizontal displacement. Cross-cutting relationships show that strike-slip faulting is younger than the thrust faulting; and from exposures in nearby trenches, strike-slip faulting is known to cut Peoria Loess (Harrison et al., 1997). A northeast-southwest-oriented maximum horizontal stress direction is interpreted for episode 3 (fig. 8g).

Normal faults A and B, both of which offset Peoria Loess, are interpreted as transtensional structures that have moved contemporaneously with the strike-slip faults. Fault A and an antithetic fault bound a nearly symmetrical graben that displaces the Peoria Loess approximately 1.2 m. Fault B is the master fault for an asymmetrical half graben that displaces Peoria Loess about 15 to18 m. Fault B can be traced to the present erosional surface where a 1.0-m scarp occurs. Slickenside striations and displacement indicate that this normal faulting is the result of northwest-southeast extension, compatible with that interpreted for the strike-slip faulting (fig. 8g).

Additional evidence for a contemporaneous development of strike-slip and normal faults is provided by Tertiary and Quaternary beds in the hanging wall of fault B; they are rotated to about 30° dips, but only as far as strike-slip fault K, where they abruptly flatten out. The Cretaceous–Tertiary contact immediately southeast of fault K does not show the same rotation as contacts between faults B and K. This suggests a genetic relationship between these structures. Furthermore, formational in the hanging wall of fault B strike N60°-70°E, at an acute angle to the N42°E-striking fault B. A similar rotation of beds is observed in the hanging wall of fault A. The implied clockwise rotation is consistent with right-lateral strike-slip motion on faults J and K.

A TL age of 17.0 ± 2.7 ka was derived for the lower third of the Peoria Loess in the hanging wall of fault B, and similar TL ages for Peoria Loess have been determined elsewhere at English Hill (Harrison et al., 1997). These data provide a conservative maximum age constraint for this faulting episode. Considering that the entire thickness of the Peoria Loess is cut by these faults, a Holocene age of faulting seems reasonable.

Neotectonic episode 4 Faults L and M at the southeastern end of the Upper Rainbow trench bound a graben containing Holocene colluvial-wedge material and Wilcox Group sediments. Fault L strikes N80°E and dips 60°SE; slickenside striations rake 90°, indicating dip-slip. This fault extends to the surface where a small 0.3 m-high scarp occurs. The colluvial-wedge material is believed to have been deposited against a surface scarp along fault L. Adjacent to the fault this material consists of about 2.4 m of poorly sorted micaceous silt, loess-like silt, fine to medium quartz and glauconite sand, pebbles, and cobbles, as much as 5 cm in diameter, derived from Cretaceous and Cenozoic units. It fines outward, away from the fault, to sand and silt. Radiometric ^{14}C age dates on charcoal from the colluvial wedge are strongly bimodal: 4980 ± 60 yrs, 4740 ± 50 yrs, 4920 ± 60 yrs, and 4780 ± 50 yrs; 1310 ± 60 yrs, 1220 ± 50 yrs, 1240 ± 50 yrs, and 1210 ± 50 yrs. Although strongly sheared, all younger charcoal was found overlying older charcoal, indicating progressive movements and deposition. A TL age of 18.4 ± 2.2 ka was obtained from the colluvial-wedge material, suggesting that most of the silt fraction was derived from Peoria Loess and was not re-exposed to sunlight long enough to reset the luminescence signal. Subsequent to deposition, the colluvial-wedge material was dropped down by reactivation of fault L, accompanied by movement on fault M, which strikes N75°W and dips 28° to 57°NE. This movement sheared the colluvial-wedge material and produced numerous slickenside surfaces in it adjacent to both faults.

Two, and possibly three, episodes of faulting are indicated by these data. Initial movement along fault L, interpreted as probably part of episode 3, produced a surface scarp against which the colluvial-wedge material was deposited. The bimodal ages and distribution of charcoal suggest two movements and pulses of deposition. A final episode faulted the colluvial material after 685-860 AD.

Stop 5: Holly Ridge

Location Approximately 2 km southwest of the small community of Idalia and 10 km northeast of Dexter, in the NW SW NW Sec. 33, T26N, R11E, Stoddard County, Missouri, Dexter 7.5-minute quadrangle (fig. 17). UTM coordinates are 4,082,600 N and 242,450 E in grid zone 16.

Site Description An artificial excavation in an auto salvage yard reveals complex faulting that displaces units as young as Holocene. The key question is whether the faults are of tectonic or landslide origin.

The Holly Ridge site is named after the Holly Ridge Conservation Area, which is located ½ km to the west (fig. 17). Most faults at the site trend NE-SW and would pass through the Conservation Area if they are laterally continuous.

The site is on the steep southeast-facing escarpment of the Bloomfield Hills segment of Crowley's Ridge (fig. 17). Like the Benton Hills, the Bloomfield Hills have an unusual, highly asymmetrical drainage pattern that suggests the hills have been tilted toward the northwest. Most of the larger north- and west-flowing drainages on Crowley's Ridge appear to be beheaded along the southeast-facing escarpment. Lick Creek, northwest of Idalia, exemplifies this pattern (fig. 17). Notice how the steep, nearly linear southeast-facing scarp truncates the northwest-trending drainage that has a much gentler gradient.

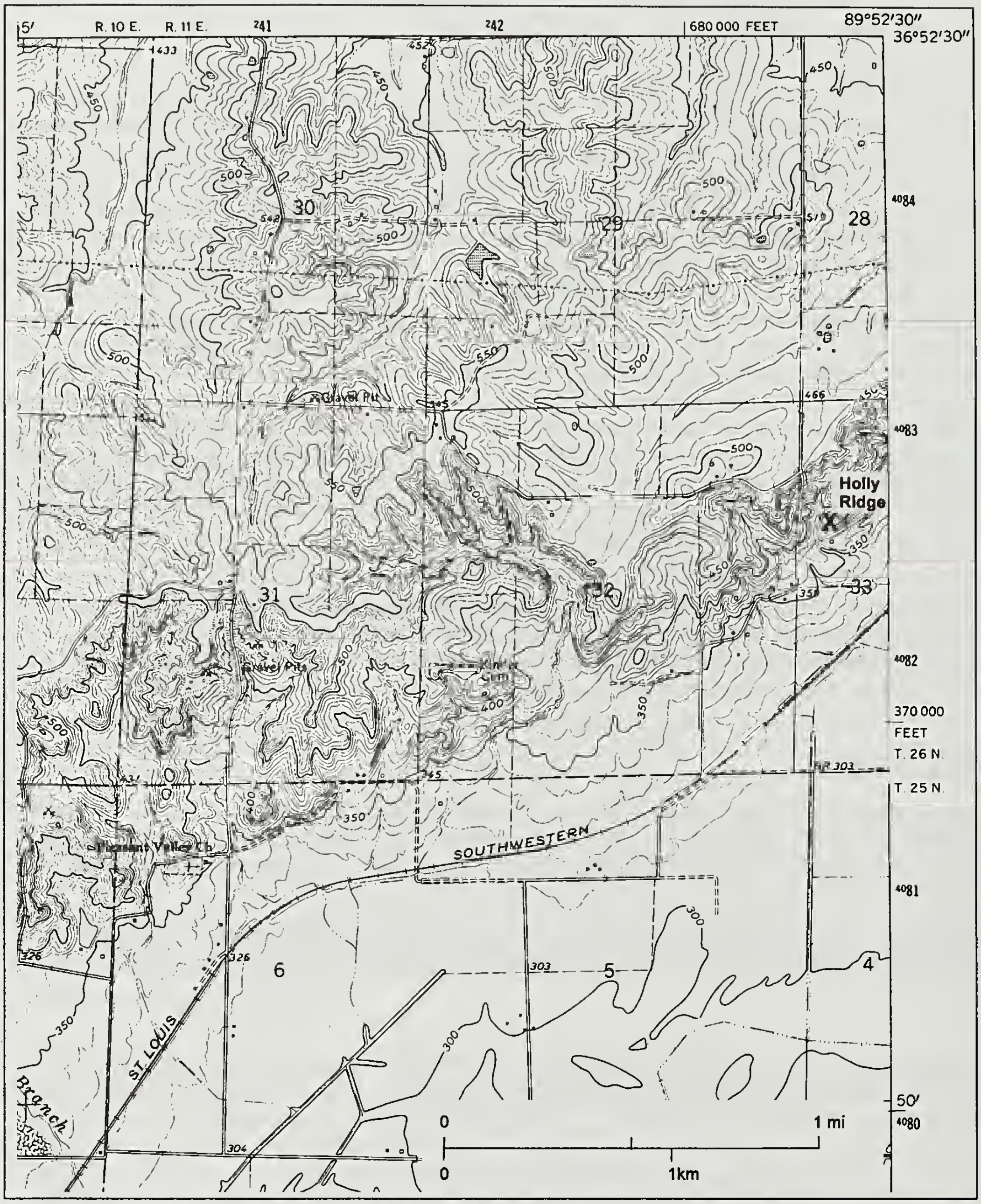


Figure 17 Holly Ridge site, Dexter 7.5-minute quadrangle.

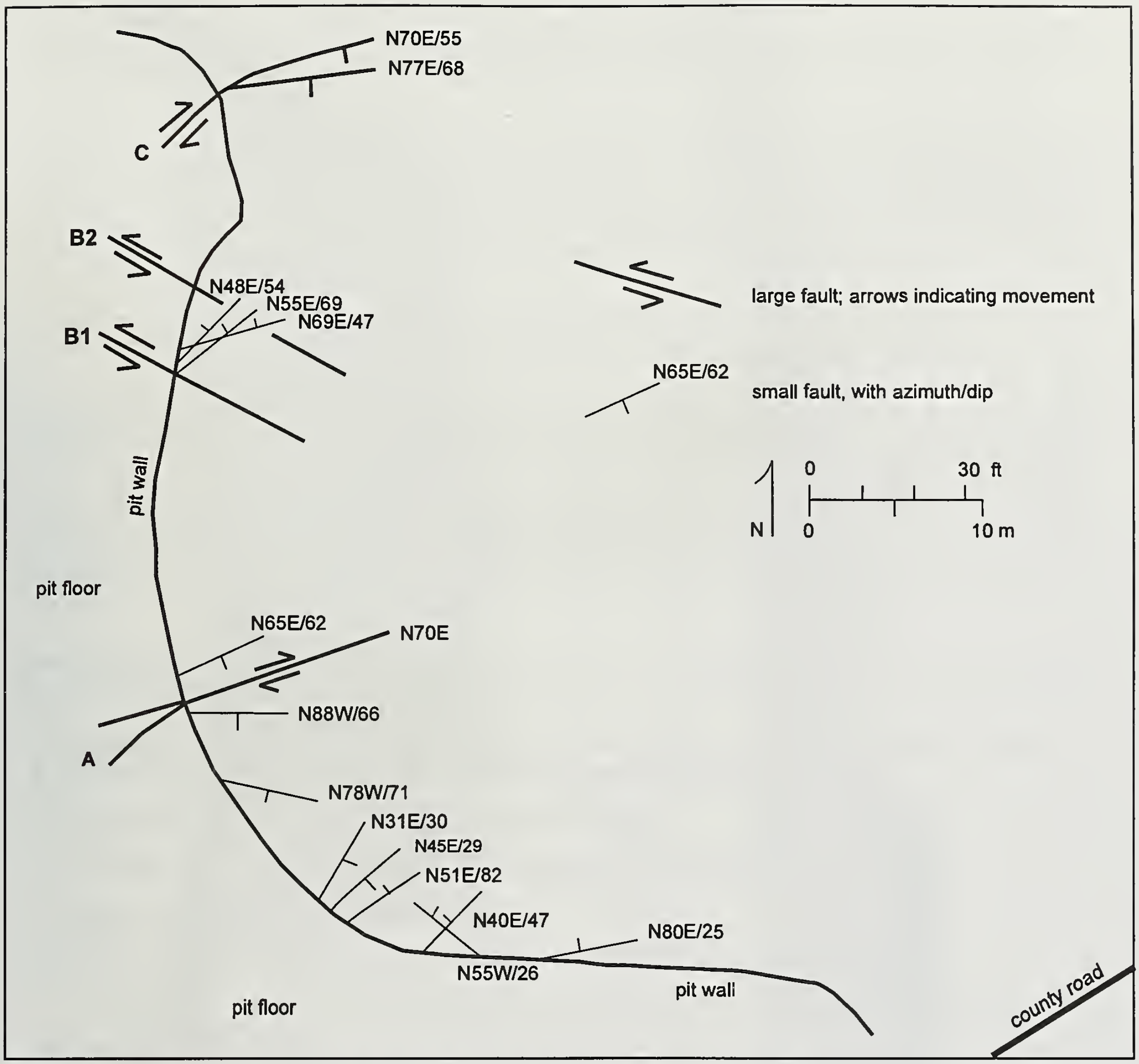


Figure 18 Plan view of excavation at the Holly Ridge site shows measured fault orientations.

Faulting at the Holly Ridge site was discovered in October 1997 when the owner of the salvage yard excavated the hillside to make flat ground on which to store his inventory. The face was excavated further, cleaned, and logged in November 1997. The excavation curves around the nose of a small ridge and is about 75 m long (fig.18). The logged exposure begins immediately northwest of a county gravel road and trends west, curving to the north-northeast and then curving back to the northwest. Overall trend of the cut is roughly normal to the escarpment of the Bloomfield Hills.

Strata exposed consist of the Peoria Silt (youngest), Roxana Silt, Sangamon (?) Geosol, reworked Mounds Gravel, and Wilcox Formation. The Porter's Creek Clay is not exposed, but is believed to lie about 15 m below the floor of the excavation. Regional dip of Tertiary beds is a fraction of one degree toward the southeast, into the Mississippi Embayment (Grohskopf, 1955).

The basic structure is two horsts and two grabens, outlined by Faults A, B, and C (fig.19). Many smaller faults dissect each of the horsts and grabens. Bedding within Graben I and Horst II is tilted toward the north or northwest, whereas bedding in Horst I and Graben II is more or less horizontal.

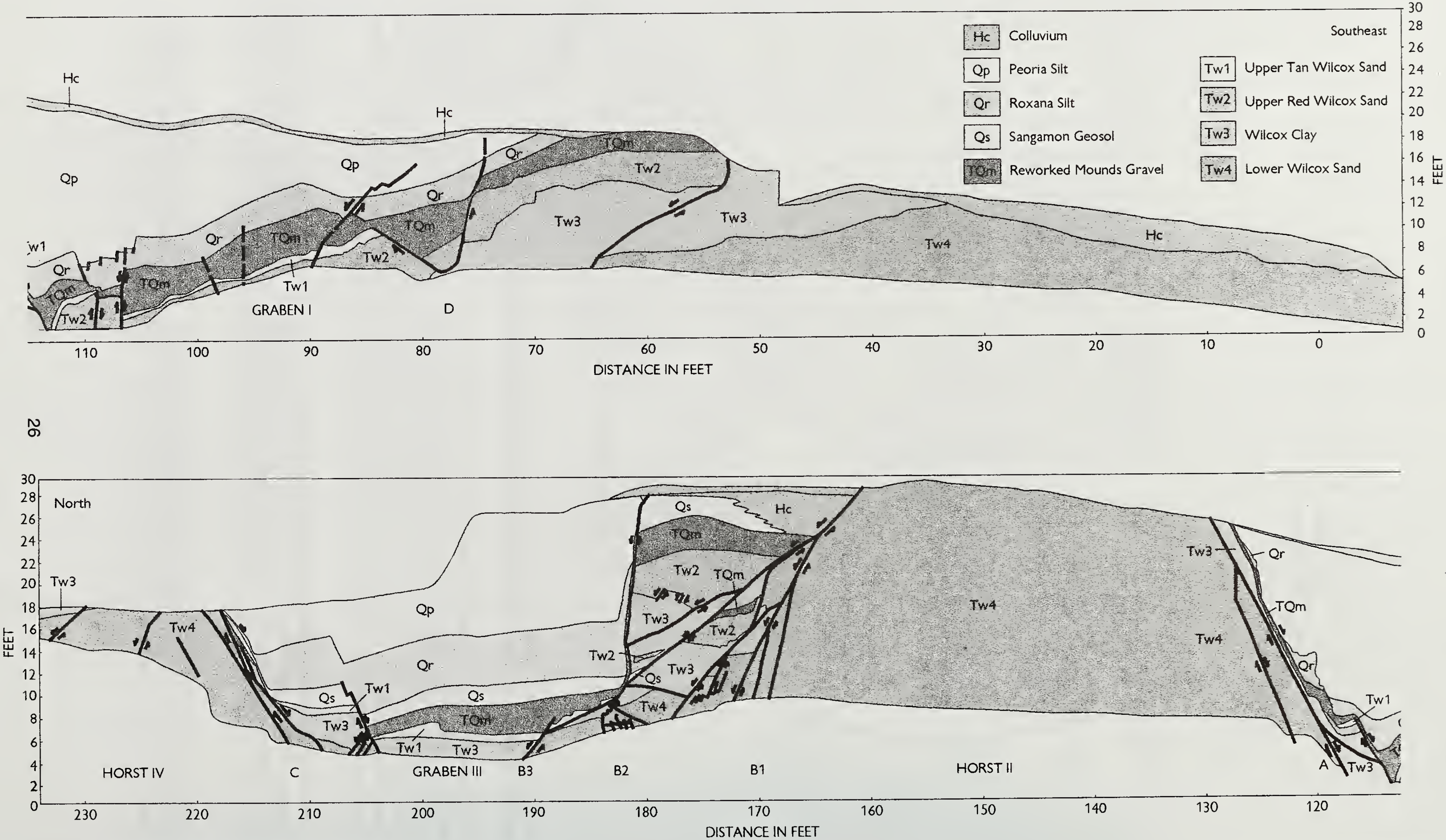


Figure 19 Profile of excavation at Holly Ridge.

Fault A is a normal fault composed of multiple strands that strike from N62°E to N89°W (average N70°E) and dip southeast or south at 62° to 66°. Minimum vertical separation is about 11 m. Because Graben I and Horst II lack common marker beds, maximum separation cannot be determined.

Fault B is a complex shear zone that is 3 to 4.5 m wide and outlined by two major faults, B1 and B2. Both normal and reverse faults occur within the shear zone. Measured strikes range from N46°E to N69°E and dips from 47° to 69° to the northwest. Faults B1 and B2 both are normal faults, whereas Fault B3 is a reverse fault that has 2.7 to 3.0 m of vertical separation at the top of the Wilcox. The overall displacement across Fault B is normal and estimated to be 7 to 9 m down to the northwest.

Fault C, a normal fault, also comprises multiple strands that strike N74° to77°E and dip 55° to 68° south. Vertical separation across Fault C is at least 4.5 m and probably is closer to 7 m.

All three major faults displace the Peoria Silt as well as all older units, and therefore they are inferred to be of Holocene age.

An intriguing topographic feature is found immediately south of the county road at the Holly Ridge site. A low swale runs NE–SW and is bordered on the southeast by a small parallel ridge. This feature suggests additional, concealed deformation, perhaps landslide or perhaps tectonic, in Holocene sediments.

Are the faults at Holly Ridge products of tectonic action or of landsliding? The following points favor the tectonic hypothesis:

- Most faults at Holly Ridge strike northeast, parallel with the strikes of most mapped tectonic faults of the region and with the Commerce geophysical lineament.
- Faults at Holly Ridge dip both upslope and downslope.
- Complex shear zones, as along Fault B, are atypical for landslides.
- Magnitude of offsets is large for a landslide.
- The slope of the escarpment is only about 10%, which is low for landsliding.
- Thickness changes of units across faults (especially Fault D) suggest strike-slip movement.
- Fault B shows evidence of multiple episodes of movement, including an episode of thrust-faulting.
- An east-west seismic-reflection profile near Idalia depicts faulting of Paleozoic through Quaternary strata along the southeast face of the Bloomfield Hills (Stephenson et al., in press).

Other evidence favors a landslide origin for the faulting at Holly Ridge:

- The structure is developed near the base of a slope and parallels the slope face.
- The horst-graben arrangement of fault blocks is characteristic of translational block slides, which are abundant along river bluffs in the central Mississippi Valley (Jibson and Keefer, 1988).
- The few slickensides observed indicate predominantly dip-slip motion.
- The Porter's Creek Clay, which serves as the glide plane for many large landslides in the region, underlies the excavation and dips downhill toward the southeast.
- The small swale and ridge southeast of the road may represent the toe of an old landslide.

Geophysical surveys and/or drilling are needed to resolve the question of how the Holly Ridge structure formed. Even if the structure proves to be a landslide, it may be seismically significant. Hundreds of landslides were triggered by the earthquakes of 1811-1812 at New Madrid (Jibson and Keefer, 1988). Older landslides, triggered by earlier quakes, are likely to be present. Dating older landslides could provide data usable for estimating recurrence intervals for earthquakes in the region.

Stop 6: Dudley Main Ditch

Location Approximately 11 km south-southwest of Dudley and 19 km southwest of Dexter, SW NE NW of Sec. 30, T24N, R9E, Stoddard County, Missouri, Broseley 7.5-minute quadrangle (fig. 20). UTM coordinates are 4,065,250 N, 756,200 E in zone 15.

Site Description Dudley Main Ditch is a paleoliquefaction site. The features are clearly visible only when water levels in the ditch and nearby St. Francis River are low. Similar paleoliquefaction structures at Clodfelter Ditch (about 3 miles south of Dudley Main Ditch) may be visible when those at Dudley Ditch are submerged.

Dudley Main Ditch and several sites having similar features were investigated by Jim Vaughn and colleagues of the Missouri Geological Survey (Vaughn, 1994; Vaughn et al., 1996). These sites are in the Western Lowlands west of Crowley's Ridge and east of the Ozark Uplands (fig. 20). The Western Lowlands represent the abandoned flood plain of the prehistoric Mississippi River. This virtually level plain is underlain by thick, sandy braided-stream deposits of Wisconsinan age, capped by Holocene silt and clay laid down by small meandering streams that currently occupy the valley. Until drainage channels were dug in the early 1900's, much of this area was swampland. Dudley Main Ditch is one of many large channels that were dug to drain the swamps for agriculture.

The paleoliquefaction site is located near the mouth of Dudley Main Ditch, which flows into the channelized St. Francis River (fig. 20). The ditch is approximately 6 m deep and 30 m wide. Its steep banks provide an opportunity to view the soil and sediment profile of the Western Lowlands. Because the banks are coated with silt after every flood, scraping and cleaning are necessary to view liquefaction structures clearly.

A profile of the southeast bank of Dudley Main Ditch (fig. 21) shows sediment layers that pinch and swell and are crosscut by several clastic dikes. Soft-sediment deformation features include deformed layering, ball-and-pillow structures, sand dikes, small dewatering features, and buried sandblows. Two lenticular sand bodies in the lower part of the ditch are interpreted as coalesced, seismically-induced sand blows. Sand dikes apparently mark the locations of vents through which water-saturated sand was expelled. A detailed profile of a feature on the northwest bank of the ditch (fig. 22) depicts cross-cutting relationships produced by two episodes of liquefaction.

Evidence for the age of the liquefaction events is limited. Two radiocarbon dates bracket the two events as occurring between 22,700 and 3,750 years before present. All liquefaction and soft-sediment deformation structures underlie and are truncated by late Holocene meandering-stream deposits.

Dudley Main Ditch lies about 65 km west of the northern end of the New Madrid Seismic Zone (fig. 1). Surficial sand blows dating from the earthquakes of 1811 and 1812 are notably absent here. Sand blows developed out to a maximum distance of about 40 km from the epicenters of the largest 1811-1812 events (Obermeier, 1989). Considering that the site of Dudley Main Ditch was a swamp in 1812 and that the water table was close to the surface throughout southeastern Missouri during the great earthquakes, conditions should have been optimal for inducing sand blows. Therefore, the earthquakes responsible for liquefaction at Dudley Main Ditch probably were centered less than 40 km away. The locations of these quakes are unknown, but the Commerce geophysical lineament is a likely candidate.

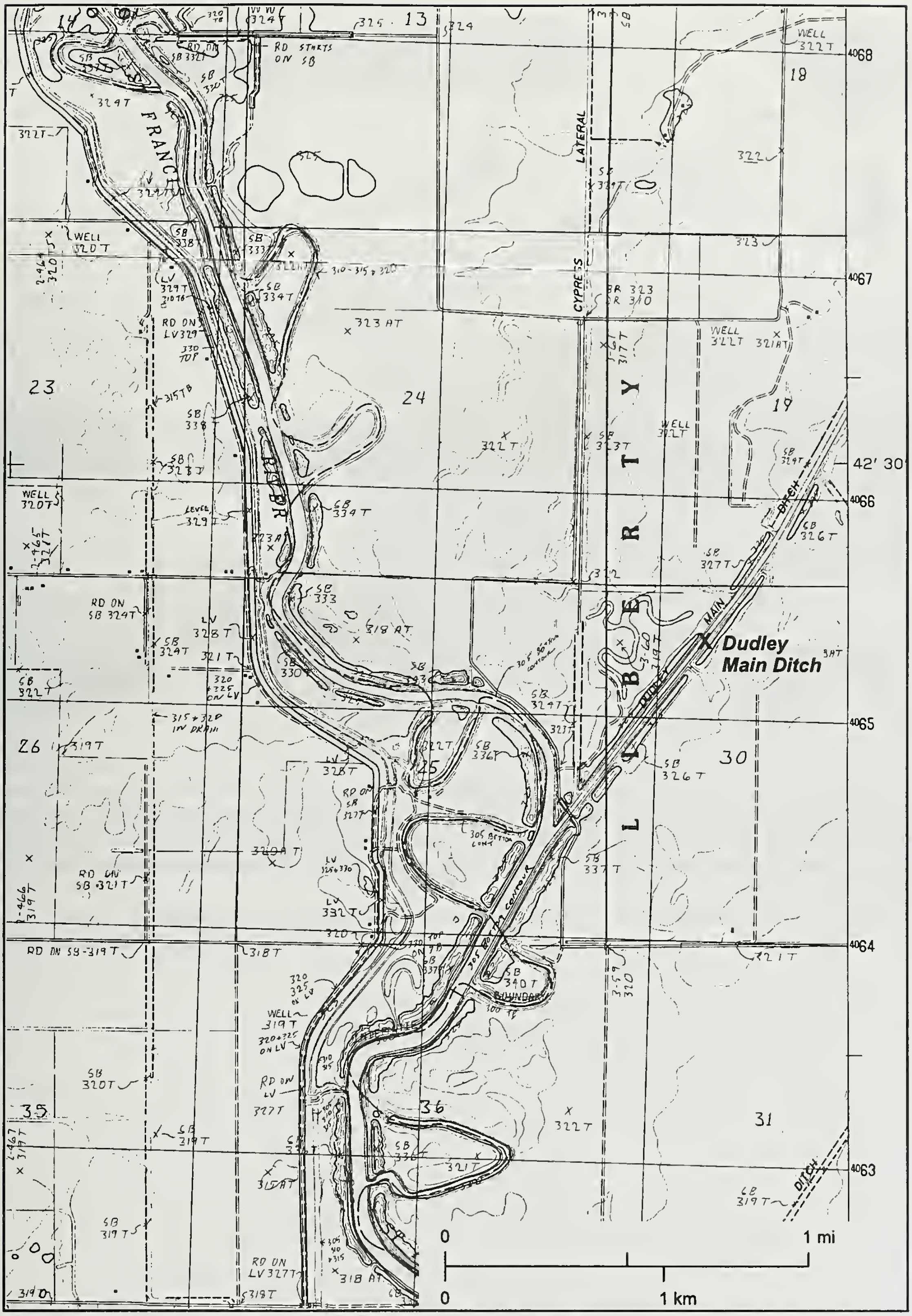


Figure 20 Dudley Main Ditch site, Broseley 7.5-minute quadrangle.

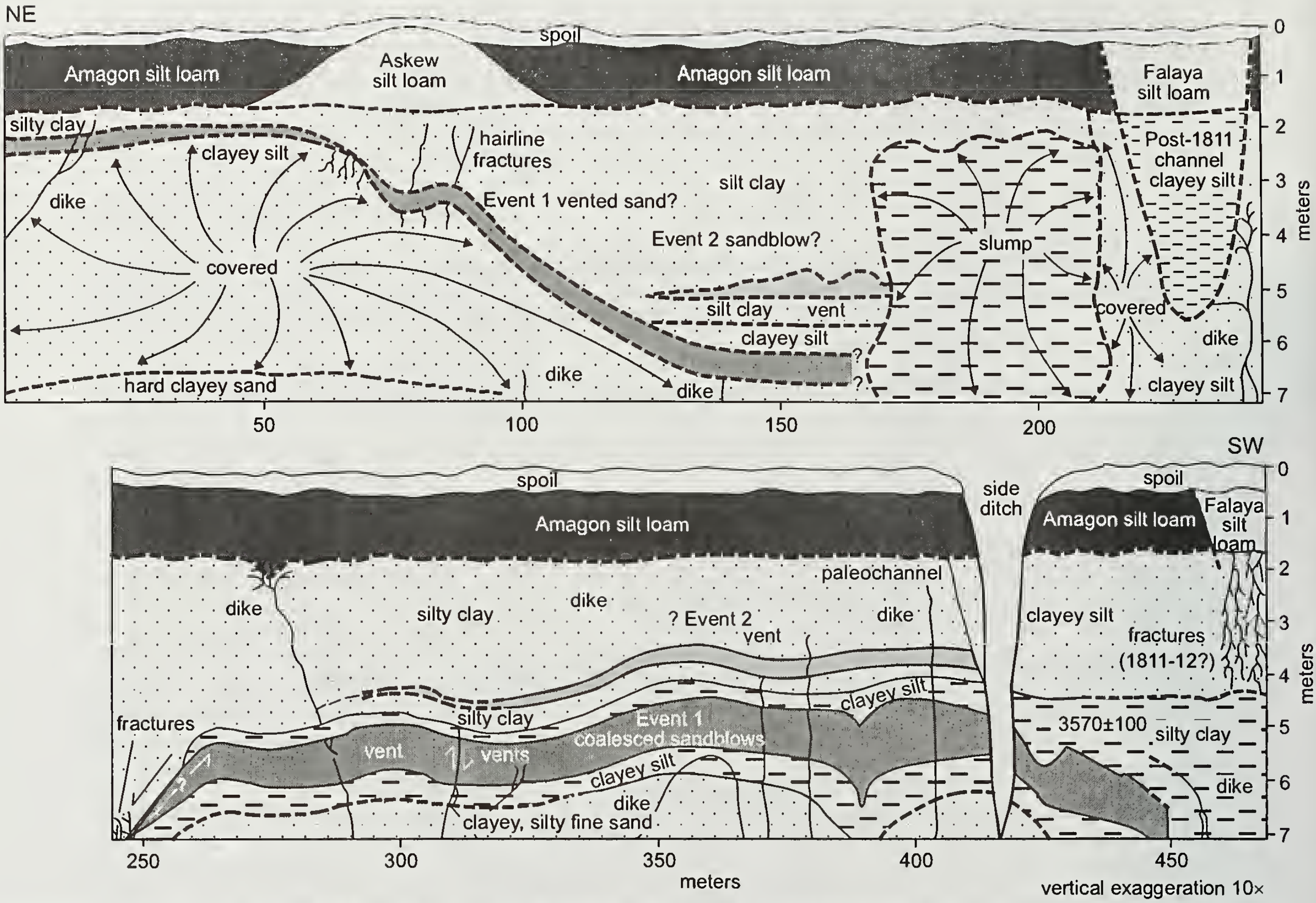


Figure 21 Graphic logs of Dudley Main Ditch depict general stratigraphy and the inferred earthquake features. Note the apparent monoclinal displacements between 10 and 150 m, at 250 m and possibly 450 m. Gentle sinusoidal folding of event 1 and 2 sand volcanoes, crosscutting dikes, and possible mud-sand volcanoes at base of modern soils imply an event 3. Radiocarbon dating of wood at the base of the paleochannel near 425 m provides a minimum age of 3,750 ± 100 yr BP (Teledyne I-16,460) for all three events. After Vaughn et al. (1996).

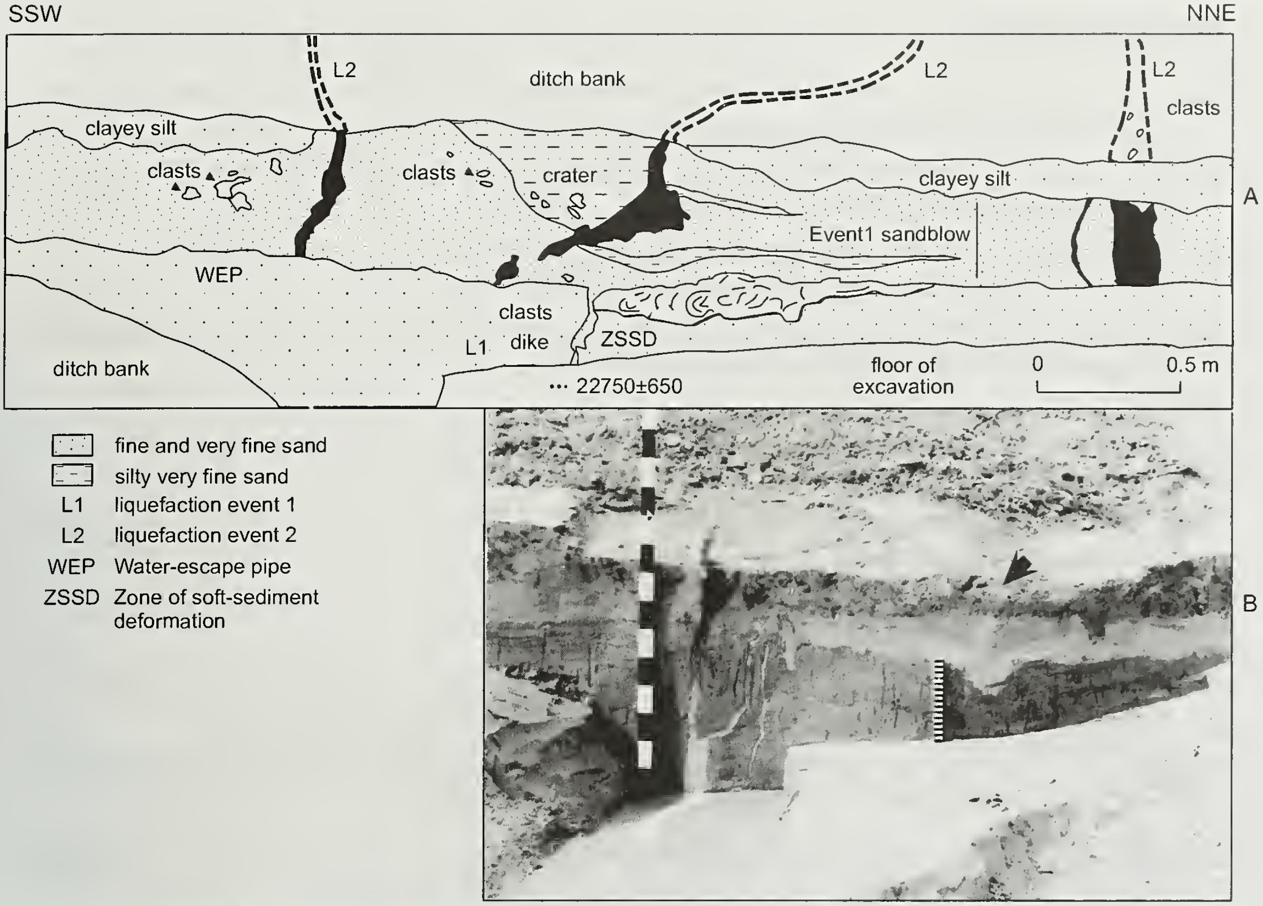


Figure 22 Photograph and sketch of sandblows at a depth 5 to 7 m at the Dudley Main Ditch site. After Vaughn (1994).

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 ± m, shows that another large event occurrred much later.

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 figure 21A.

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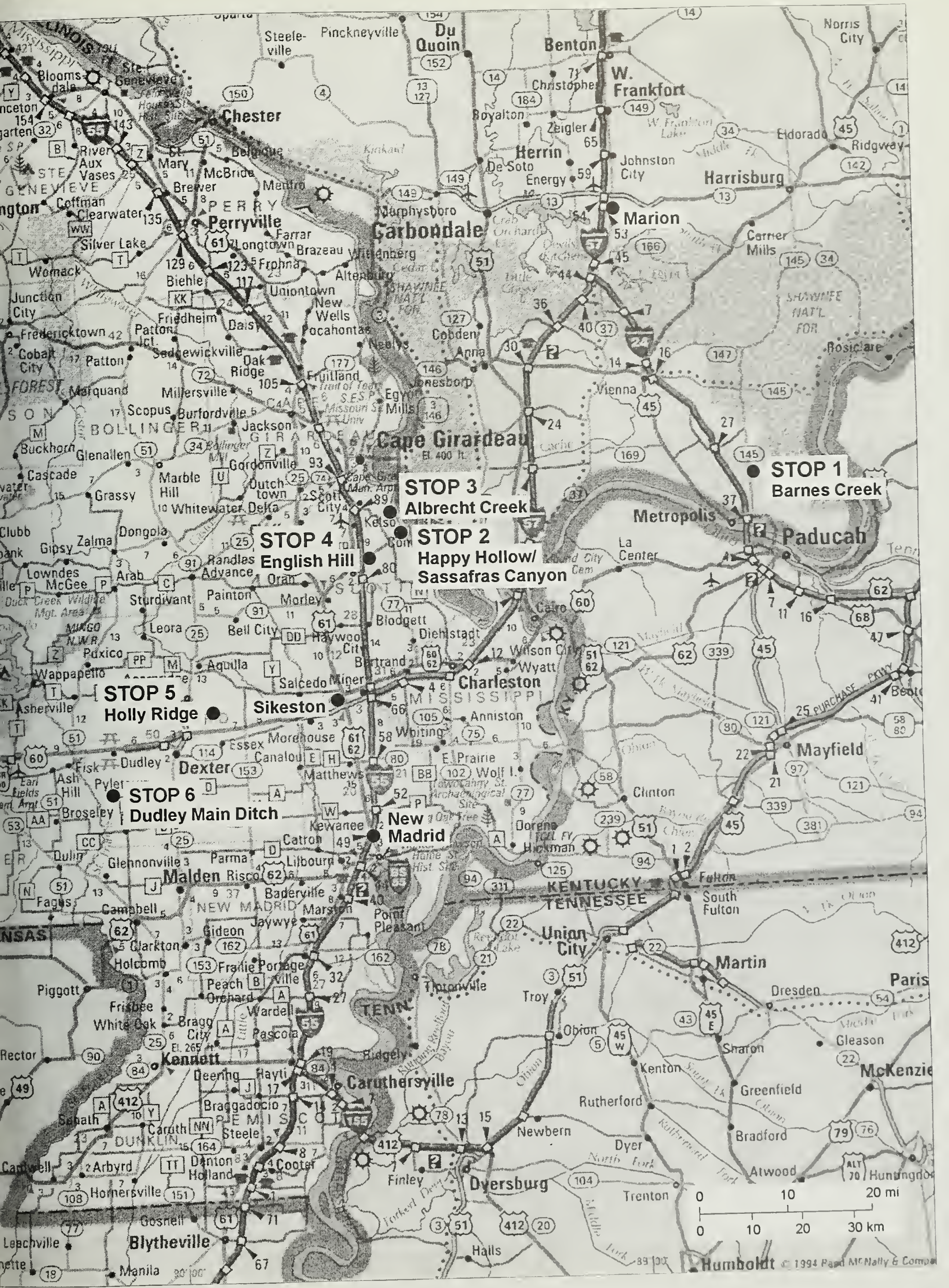
STOP 1
Barnes Creek
STOP 2
Happy Hollow/
Sassafras Canyon
STOP 3
Albrecht Creek
STOP 4
English Hill
STOP 5
Holly Ridge
STOP 6
Dudley Main Ditch
Cape Girardeau
Carbondale
Marion
Paducah
Metropolis
Sikeston
New Madrid
Charleston
Dexter
Malden
Kennett
Caruthersville
Dyersburg
Blytheville
Mayfield
Union City
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