QUATERNARY FAULTING IN THE NEW MADRID SEISMIC ZONE IN SOUTHERNMOST ILLINOIS

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ABSTRACT

This year's activity focused on structures that are part of the Fluorspar Area Fault Complex (FAFC) in Massac County, Illinois. Most large faults in the FAFC run southwest from bedrock upland into the northern Mississippi Embayment, where they trend directly in line with the New Madrid Seismic Zone. These faults apparently originated during Cambrian rifting and have undergone several episodes of reactivation under different stress regimes.

Late Tertiary and Pleistocene sediments are displaced along elements of the FAFC at several sites in Massac County. Neogene structures are narrow (≈10 to 200 m) grabens bounded by near-vertical faults that strike NE, N-S, and NNW. Grabens appear to be products of transtensional forces; however, the amount and direction of strike-slip displacement are undetermined. Vertical separation of at least 30 m has taken place on the "Metropolis formation", a fluvial deposit of early to middle Pleistocene (pre-Sangamonian) age. Minor offsets (1 m or less) have been observed on Sangamonian and Wisconsinan-age deposits in a few places. No tectonic disturbance of Holocene sediment has been observed.

A swarm of small (max. mag. 3.6) earthquakes took place north of Olmsted in Pulaski County in February, 1984. Most of the larger quades had focal depths of 5 km or less. A plot of hypocenters yields a tight oval-shaped cluster about 2 X 5 km with the long axis northeast. A northeast-trending fault, mapped from well data along the northwest side of the earthquake swarm, is a possible source. The inferred fault is parallel with known Quaternary faults to the east in Massac County.

INTRODUCTION

This year's NEHRP research focused on Neogene faulting in Massac County, Illinois (Fig. 1). Neogene faults in Massac County are part of the Fluorspar Area Fault Complex (FAFC), which originated as normal faults in the Reelfoot Rift during Cambrian time. Most faults in the FAFC trend northeast, and are in line with the New Madrid Seismic Zone southwest of the report area (Figs. 1 and 2).

Previously (Nelson et al., 1996 and 1997) we documented several large faults that displace Mounds Gravel (Pliocene to early Pleistocene), but only small displacements of younger Pleistocene deposits. This year we identified several grabens that produce large offsets of Pleistocene units younger than the Mounds. In particular, a unit of fluvial sediment informally called the Metropolis formation is downthrown 10m to more than 30m into narrow NE-, NNE-, and NNW-trending grabens. The Metropolis represents early and middle Pleistocene time and contains the Sangamon Geosol at the top. Small (1 to 2 m wide and deep) grabens locally displace alluvium that is younger than the Metropolis and therefore of Wisconsinan or possibly early Holocene age.

STRATIGRAPHY

Paleozoic bedrock

In the primary study area, Massac County, Paleozoic bedrock is almost entirely concealed by younger deposits, and is known only from well records. Limestone formations of the Mammoth Cave Group, mid-Mississippian age, are at the bedrock surface in most of the county (Fig. 3). Formations identified from well records include, in acsending order, the Fort Payne Formation and the Ullin, Salem, St. Louis, and Ste. Genevieve Limestones. Chesterian (Upper Mississippian) strata occur in the northern part of the county and consist of interbedded sandstone, shale, and limestone assigned to formations too numerous to mention.

In some areas where limestone is at the bedrock surface, deep dissolution took place prior to Cretaceous sedimentation. Resulting deposits of residual chert fragments, sand and clay may exceed 10 m thick.

Tuscaloosa (Post Creek) Formation

A basal Cretaceous unit of light-colored chert gravel intermixed with variable amounts of sand, silt, and clay has been assigned to the Tuscaloosa Formation by previous geologists (Fig. 3). Harrison and Litwin (1997) recently proposed renaming this unit the Post Creek Formation in Illinois, because "Tuscaloosa" here is much younger than the type Tuscaloosa.

The Tuscaloosa (Post Creek) is sporadic in occurence and highly variable in thickness in the report area. Where present, it is typically 3 to 20 m thick, but may exceed 50 m in the City of Metropolis #4 water well. Where only driller's logs or cuttings are available, distinguishing Tuscaloosa gravel from residual chert or weathered bedrock can be impossible. Samples that consist entirely of angular, broken chert fragments (no rounded pebbles) were judged to be residuum.

Gravel of the Tuscaloosa is composed largely of subrounded to well rounded chert pebbles that are off-white to light gray, opaque, slightly porous, and slightly tripolitic. Gray to brown chert pebbles that display bioclastic texture are less common. The matrix is largely fine to very coarse, unsorted quartz sand intemixed with dark gray silt and clay. The Tuscaloosa apparently contains much pyrite, which oxidizes to white, fibrous sulphate minerals and attacks paper sample packets, causing them to turn spotty brown and disintegrate.

McNairy Formation

The McNairy occurs throughout the study area, except in a small area west of Joppa, where well samples indicate Mounds Gravel directly overlying Tuscaloosa Gravel. The area of no McNairy is on an upthrown block northwest of the Lusk Creek Fault Zone.

The McNairy thickens from a feather edge at the northern border of the Embayment to approximately 60 m near the Ohio River. A short distance south of the river in Kentucky, three wells penetrated 67 to 76 m of McNairy. Original thickness undoubtedly was greater; McNairy is almost everywhere unconformably topped by either Mounds Gravel or Pleistocene deposits.

The McNairy consists of interbedded and interlaminated clay, silt, and sand, along with very minor amounts of gravel, lignite, and iron/manganese oxides. Clay and silt are mostly medium to dark gray, bluish gray, and brownish gray, laminated to massive, and very micaceous. Sand comes in various colors, but most of it is light gray, yellowish gray, or brownish gray. Bright red and orange sand is common in surface exposures but not at depth. Most sand is very fine to fine-grained, dominantly quartz with conspicuous mica, and it shows crossbedding and planar to ripple lamination. Although the McNairy tends to fine upward overall, the internal stratigraphy is highly variable. No marker beds were found that were traceable for lateral distances greater than about 1 kilometer.

Owl Creek through Jackson Formations

The following units (in ascending order) overlie the McNairy Formation in the Mississippi Embayment immediately south and west of our primary study area: Owl Creek Formation (latest Cretaceous), Clayton Formation and Porters Creek Clay (Paleocene), and Wilcox, Claiborne, and Jackson Formations of Eocene age (Pryor and Ross, 1962; Ross, 1964; Kolata et al., 1981; Olive, 1980). In Massac County these units may have been originally present but were eroded prior to deposition of Mounds Gravel - with a few small but significant exceptions.

Porters Creek Clay and Clayton Formation were identified in a gully near the Illinois Central Railroad south of Round Knob in Massac County. These units appear to be confined to a small, down-faulted block. Brightly colored sand recovered from drill cores at the Maple Grove School and Melferd Krueger farm, and exposed at the northwest corner of the old Metropolis city landfill, resemble sands of the Wilcox Formation. All three of these sites are interpreted to lie within grabens, and will be discussed further in the chapters on individual structures.

Massac formation (informal unit)

The informal name Massac formation (Fig. 3) is used herein for a succession of Neogene sand, silt, and clay encountered in a drill core at the depth of 33 to 92 m at the James Weaver property in northern Massac County (SW¼ SW¼ NW¼, Sec. 33, T14S, R5E, Reevesville 7.5-minute quadrangle). Sand of the Massac is mostly gray to yellow, very fine to medium quartz sand with rare mica and rare small, rounded white to gray quartz and chert granules. Silt is medium to dark gray, sandy, generally massive and mottled. Clay is dark gray to black and along with silt, contains abundant peaty (not coalified) organic matter. Some layers of the lower part of the Massac from the core could be called sapropel.

Fossil pollen from depths of 44.5 and 91.2 m was examined by R.W. Litwin and N.O. Frederiksen (both of the USGS). They identified the flora as being between late Miocene and early Pleistocene age (Nelson et al., 1997). The Massac underlies the Pleistocene Metropolis formation in the Weaver borehole. The absence in the Massac of chert pebbles derived from Mounds Gravel implies that the Massac is older than the Mounds.

The Massac formation at the Weaver drillsite is preserved within a deep, narrow graben along a segment of the Hobbs Creek Fault Zone (Fig. 2).

The Massac formation may occur in other down-faulted blocks in Massac County. Sediments that resemble Massac crop out in grabens along Barnes Creek. Sand and silt from a borehole at the Maple Grove School near Joppa also resemble Massac. Dark silts from the latter were processed for spores and pollen, but proved to be barren (Russel A. Peppers, ISGS, personal communication 1997).

Mounds Gravel

Previously called Lafayette Gravel, the Mounds was designated as the lower part of "continental deposits" on geologic maps in western Kentucky (Olive, 1980). The Mounds is a unit of reddish orange to brown chert gravel, containing a matrix and occasional thin interbeds of sand. Rounded chert pebbles that bear a glossy bronze patina are characteristic. Well rounded granules and small pebbles of white quartz are common. The sand is mostly medium to very coarse, subangular to well rounded quartz, with a lesser portion of chert. The Mounds is mostly unlithified, but lenses of conglomerate cemented by iron oxide are common in outcrops.

The distinctive bronze patina on Mounds pebbles is produced by iron oxide. It is believed to be a geochemical product of ground-water conditions during deposition of the gravel. Recessed surfaces on pebbles commonly have a high gloss, whereas protruding surfaces are dull and worn. Such pebbles apparently were eroded and redeposited after formation of the patina. Chunks of cemented chert-pebble conglomerate within the Mounds further attest to multiple cycles of erosion and deposition.

In most of northern Massac and Pope Counties, south of the Cache Valley, the Mounds Gravel is an upland deposit that overlies either McNairy Formation or Paleozoic bedrock. The base of the Mounds seems to be nearly level and consistent in elevation within small areas. Across the area the elevation of the base of the Mounds gradually rises from a little above 400 feet (130 m) in western Massac to above 550 feet (170 m) in eastern Pope County. In this report we refer to Mounds at such elevations as "high Mounds" (Fig. 4). High Mounds is rarely thicker than about 15 m and is overlain unconformably by Pleistocene loess and colluvium.

Near the Ohio River, the Mounds occurs at much lower elevation and is called "low Mounds" (Fig. 4). The low Mounds overlies McNairy Formation at elevations of 250 to 295 feet (76 to 90 m), largely below normal stage of the Ohio River. Elevation of the base of the low Mounds gradually rises eastward. More than 200 boreholes outline geometry of the low Mounds deposit. The gravel occupies a paleovalley that is 8 to 11 km wide and has a nearly flat bottom and steep walls (Fig. 5). The low Mounds paleovalley roughly coincides with, but is much wider than the modern Ohio River floodplain. Low Mounds ranges from less than 3 m to about 17 m and averages about 10 m thick. It is overlain by the Metropolis formation or locally, by younger units.

Olive (1980) identified four terrace levels of "continental deposits" (i.e. Mounds Gravel) in western Kentucky. Our low Mounds is the same as Olive's lowest or 290-foot level. Our high Mounds corresponds to one or more of Olive's higher levels.

Metropolis formation (informal unit)

The name Metropolis formation is used informally for a unit that overlies low Mounds near the Ohio River or McNairy Formation farther north (Figs. 3, 4, and 5). It corresponds roughly to "terrace deposits" mapped in southernmost Illinois by Pryor and Ross (1962) and Ross (1964); and accurately correlates to Pleistocene "silt and sand deposits" mapped near Paducah, Kentucky by Finch (1966 and 1967). *The Metropolis formation is a key unit to interpret Neogene tectonic activity in the area.*

The Metropolis is principally silt and sand, with lesser amounts of clay and gravel. These sediments are largely unsorted to poorly sorted; the term diamicton commonly is appropriate. Strong color mottling in shades of gray, brown, yellow, and orange is characteristic. Most of the sediment is deeply weathered and has undergone multiple, stacked levels of soil formation. Burrowing is widespread and in many layers is pervasive. Burrow types include (1) intricate networks of small (≈1 cm) sand-filled, sinuous tubes probably made by small arthropods, (2) larger (5-10 cm) vertical, cylindrical tubes similar to *Crotavina* or crayfish burrows, and (3) very large (15-40 cm across) roughly cylindrical burrows and compound burrows, of unknown origin.

The Metropolis contains thin intervals of well sorted, clean sand and gravel that show lamination and bedding. Gravels have erosional bases and define the bottoms of fining-upward sequences. One of the few large outcrops, on a gullied hillside near the Cook Coal Terminal between Joppa and Metropolis, showed faint sets of inclined (10-20°) concave-upward bed sets that truncate one another. These probably represent lateral accretion sets that developed on the point bars of small, meandering stream channels.

Gravel in the Metropolis is predominantly chert but includes small rounded quartz pebbles and granules, as in the Mounds. A small proportion of pebbles at most sites have the bronze, glossy finish typical of the Mounds Gravel. The majority of pebbles in the Metropolis are bleached to gray or off-white and have worn, pitted surfaces. Examples of broken pieces of well-rounded pebbles bearing Mounds patina (more or less abraded) are fairly common. the obvious conclusion is that gravel in the Metropolis was reworkd from the Mounds. Evidently, the geochemical conditions that formed bronze patina on Mounds pebbles no longer were operative during deposition of the Metropolis.

The principal deposits of Metropolis overlie the "low Mounds Gravel" in its broad paleovalley along the Ohio River. In this area the Metropolis varies in thickness from 5 to 24 m. Its contact to the Mounds has not been observed on outcrop, and borehole data are not adequate to determine whether it is sharp or gradational. The upper surface of the Metropolis, mantled by loess, forms a broad, level to gently sloping surface that Alexander and Prior (1968) called the Metropolis terrace. This terrace is most noticeable in southern Massac County between Metropolis and Joppa, where the top of the terrace is at 360 to 390 feet (110 to 120 m) above sea level.

The Metropolis formation also extends north of the low Mounds paleovalley along modern Massac and Barnes Creeks (Figs. 4, 5). Here the Metropolis occurs as eroded terrace segments along one or both valley walls. The upper surface of the terrace rises gradually from 390 feet (120 m) along lower Massac Creek to 470 feet (143 m) on upper Barnes Creek. Except where it is downthrown into grabens, the Metropolis is rarely thicker than 6 to 8 m along Massac and Barnes Creek. These two streams have unusually broad, flat bottomlands and may be classified as underfit. Evidently Barnes and Massac Creeks, unlike most small streams in the area, are of Illinoian and older vintage.

To date no direct absolute or biostratigraphic dating of the Metropolis formation has been accomplished. The Metropolis has the Sangamon Geosol developed at the top and is overlain in turn by the Loveland, Roxana, and Peoria Silts (loesses). The Loveland is thin and discontinuous; where present, the Sangamon Geosol penetrates both Loveland and uppermost Metropolis. Strongly developed paleosols reminiscent of the Yarmouth Geosol (pre-Illinoian) are developed within the Metropolis. The Metropolis overlies what is presumably the youngest Mounds Gravel having an inferred early Pleistocene age, as mentioned above. In the Weaver core the Metropolis overlies Massac formation that lacks Mounds-type chert pebbles and contains pollen of Pliocene to possible early Pleistocene age. These relationships indicate that the Metropolis is entirely Pleistocene and probably spans the Illinoian and older stages.

To summarize, the Metropolis formation is interpreted as fluvial sediment that was deposited during early to middle (Illinoian and older) Pleistocene time. The streams that deposited this unit were probably small, sluggish, and sinuous to meandering. Deposition was slow, intermittent, and marked by prolonged episodes of bioturbation, weathering, and pedogenesis. The main drainage system was inherited from the "low Mounds river" near the present Ohio; Metropolis sediment also accumulated along tributaries to this drainage.

Equality Formation

The Equality Formation is a unit of dominantly massive to laminated silt and clay with minor sand and gravel, and it is of Wisconsinan (Late Pleistocene) to early Holocene age. The Equality is widespread across Illinois and neighboring states, and is largely attributed to lacustrine environments.

In the report area the Equality Formation consists mainly of dark brownish to bluish gray, partly laminated clay and silt that contains large amounts of plant matter. Minor amounts of silt and chert gravel (reworked from older formations) occur at the base of the formation. The Equality occupies lowlands near the Ohio River east of Metropolis, and extends partway up the valleys of Massac Creek and other tributaries (Figs. 4, 5). We have not observed it above an elevation of 350 feet (110 m) in the study area.

The Equality was mapped as "Lacustrine deposits" near Paducah, Kentucky by Finch (1966 and 1967). These sediments are attributed to an ancient lake called Lake Paducah (Finch et al., 1964), which existed along what is now the Ohio River during the Wisconsinan Epoch. A radiocarbon age of about 21,000 years B.P. was obtained from mollusc shells 7.6 to 9.1 m below the top of the Equality Formation near Paducah (Olive, 1966). The paleo-shoreline of Lake Paducah is well marked by sand and gravel bars or spits at the mouths of many tributaries at about 355 ft (108.5 m) elevation in Kentucky (Finch et al., 1964; Olive, 1966). We mapped similar sand and gravel bars in Illinois at the same elevation, allowing us to compile the shoreline of Lake Paducah for both Kentucky and Illinois (Fig. 4).

Silt and clay that contain abundant, well-preserved plant material are exposed in the banks of Massac Creek north of Metropolis. These sediments include both Equality Formation and younger, Holocene alluvium. Fossil wood from elevation 355 ft. or 108.5 m along Massac Creek yielded a radiocarbon age of 10,260 ± 70 years B.P. Another sample from the junction of Mud and Massac Creeks at elevation 315 feet yielded a radiocarbon age of 2,660 ± 90 years B.P. Fine-grained alluvial sediments and Equality Formation are lithologically similar and not readily distinguishable.

Viewing the map of Lake Paducah (Fig. 4), note that the shoreline largely parallels the limit of the Metropolis formation at slightly lower elevation. Evidently the lake formed in the same valley where low Mounds Gravel and Metropolis formations accumulated. The west end of the lake is sharply cut off on a line running NNE through the city of Metropolis. What dammed the valley in such a fashion? Fisk (1944, Plate 20) noted this geomorphic anomaly and labelled it "Metropolis Gap". Fisk envisioned Metropolis Gap as a divide that separated a west-flowing stream west of Metropolis from an east-flowing stream that joined the Tennessee and Cumberland Rivers, which at that time flowed into the Cache valley. Our mapping shows that "Metropolis Gap" and the west end of Lake Paducah closely follow mapped and projected segments of the Hobbs Creek and Barnes Creek Fault Zones. Did uplift along these faults create Lake Paducah?

To date we have observed no tectonic deformation of the Equality Formation. Many outcrops of undeformed Equality occur along Massac Creek, in line with the Barnes Creek Fault Zone and Massac Creek graben.

Loess

Loess in the Mississippi Valley is compact, massive silt interpreted as aeolian dust derived largely from large river valleys during Pleistocene interglacial episodes. Nearly all upland surfaces in the report area are mantled in loess.

Three loess units of regional extent occur in the report area: the Loveland (oldest), Roxana, and Peoria Silts (Fig. 3). In addition, silts that may be older loesses underlie the Loveland in places. These older silts, however, have not been named or mapped in southern Illinois.

The Loveland Silt, of late Illinoian age, is typically a strongly mottled, clay-rich silt in shades of gray, yellow, and orange. Much of the character of the Loveland results from pedogenic overprinting by the Sangamon Geosol. Distinguishing Loveland from upper, silty phases of the Metropolis formation can be difficult. The Loveland is discontinuous in the report area and generally less than 1.0 m thick.

The Roxana Silt of mid-Wisconsinan age normally is a slightly sandy silt that is medium brown to reddish brown. The weakly developed Farmdale Geosol overprints the Roxana. Distinguishing the Roxana from the overlying Peoria Silt can be difficult. The Roxana is widespread, but not ubiquitous, ranging up to at least 2 m thick in Massac County.

The youngest loess is the Peoria Silt. Present almost everywhere, the Peoria is typically 2 to 3 m thick and lightly mottled in shades of light yellowish gray to yellowish brown. The modern soil is developed in the Peoria, which (with local exceptions) is the youngest natural geologic unit found in upland settings.

Loveland, Roxana and Peoria loesses provide a recognizable stratigraphic framework that can be used to date neotectonic features in upland settings. All loess is susceptible to dating via thermoluminescence; the Peoria and Roxana are well within the range of radiocarbon dating. During this study we sought trenching sites where Neogene faults pass under, or through loess deposits. Only one such site (Kelley railroad cut) was identified this year and subjected to intensive study.

Alluvium

Alluvium occurs along all streams in the region and includes the youngest naturally occuring sediments. The thickest and most extensive deposits are in the Ohio River floodplain and the Cache Valley (Fig. 4). We made no effort to subdivide or catergorize alluvium except where it overlies faulted Neogene strata.

Alluvium is well exposed overlying faulted Metropolis formation and older units along the banks of Barnes Creek. This alluvium generally is 2 to 3 m thick and consists of chert gravel at the base grading upward through sand to silt that resembles loess at the top. These sediments are distinctly stratified and exhibit crossbedding and imbrication of gravel clasts. In most cases the entire alluvial sequence is horizontal and undeformed, truncating faulted and folded older strata with angular unconformity. A few examples were found of small grabens (1 m or less deep and wide) in which basal alluvial gravels were downdropped. These grabens are truncated by undisturbed younger gravels and sands. More discussion of grabens that displace alluvium are presented under the heading Barnes Creek Fault Zone.

STRUCTURAL GEOLOGY

Rock Creek Graben

The Rock Creek Graben is one of the major grabens of the FAFC. It trends NE-SW, displacing Paleozoic bedrock from Union County, Kentucky on the northeast to Massac County, Illinois on the southwest. In Massac County the fault zone enters the Mississippi Embayment; its extent here is poorly known due to scarcity of surface exposures and subsurface data.

Previously we observed outcrops of folded and faulted McNairy Formation in line with part of the Rock Créek Graben in eastern Massac County. We also noted clay-lined fractures or clay veins in exposures of the Mounds Gravel close to the graben. These exposures indicated definite post-Cretaceous and possible Pliocene or younger tectonic activity within the Rock Creek Graben (Nelson et al., 1996 and 1997).

In June, 1997 we revisited a segment of Mallard Creek (NE¼ SW¼, Sec. 20, T15S, R6E, Massac County, Paducah NE quadrangle) where we previously had seen deformed McNairy Formation. Heavy rains the preceding winter deeply eroded several cutbanks of Mallard Creek and revealed a fault zone not previously visible. This fault exposure, further improved using a backhoe, yields the first definitive evidence for Quaternary tectonic deformation within the Rock Creek Graben.

The backhoe exposure shows a complex zone of high-angle faults approximately 8 m wide affecting McNairy and some younger sediments (Fig. 6). The zone includes several faults that strike N10°E to N35°E (subparallel with the graben) but also tow faults that strike N55°W (perpendicular to the graben). Most faults displace the McNairy and are truncated at the base of overlying Quaternary gravel.

Near the west end of the bank a fault that trends N10°E/90° juxtaposes McNairy on the east with Metropolis formation on the west. The Metropolis is strongly mottled and burrowed, gray to yellowish orange silty sand that contains scattered chert pebbles reworked from the Mounds Gravel. Vertical separation on the base of the Metropolis is a minimum of 1 m; Metropolis is missing from the upthrown, eastern block. A younger gravel (Qg2 in Fig. 6) truncates the fault. Gravel Qg2 is strongly mottled and deeply weathered and composed of reworked Mounds chert pebbles in a clay-rich matrix. The paleosol features of Qg2 are typical of the Sangamon Geosol.

Near the middle of the backhoe cut, gravel Qg2 is itself downthrown into a graben roughly 1 m wide, 1 m deep, and trending N30°E. The top of Qg2 and the younger units Qg1 and Qs are not offset.

In order to test the possibility that larger, concealed grabens containing Quaternary sediment occur along Mallard Creek (as at Barnes Creek), we drilled several test holes along the south bank of the creek. All of these holes encountered McNairy immediately underlying Holocene silt and gravel, thereby negating presence of large Quaternary offsets.

The Mallard Creek exposure documents at least two episodes of fault movement. Most of the displacement is post-Cretaceous but pre-Sangamonian, as evidenced by lack of displacement of gravel Qg2. The graben near the middle of the cut displaces the Sangamon Geosol but not the overlying, presumably Holocene gravel and silt. The last fault movement at Mallard Creek, therefore, probably took place during the Wisconsinan Epoch.

The kinematic setting of Mallard Creek exposure is poorly known because, as usual, no slip indicators could be found. The presence of near-vertical faults of diverse trend, outlining tilted blocks of inconsistent attitude, points to a significant component of strike slip.

Barnes Creek Fault Zone

The Barnes Creek Fault Zone is part of the FAFC, southeast of and parallel with the Hobbs Creek Fault Zone. The Barnes Creek is mapped in Paleozoic bedrock from western Hardin County across Pope County (Fig. 2). Entering Massac County, the fault zone displaces the McNairy Formation and younger units in the Mississippi Embayment. Seismic data (Sexton et al., 1996) indicate faults offsetting McNairy extend directly into Paleozoic bedrock. Streambank exposures along Barnes Creek and Massac Creek showed widespread faulting of the McNairy and small (1-2 m) displacements of the Metropolis formation. Holocene sediments are not affected (Nelson et al., 1996, 1997).

Drilling in 1997 showed that Pleistocene offsets along the Barnes Creek Fault Zone are much larger than previously suspected. We drilled into three grabens in which the Metropolis formation is downthrown 10 to more than 30 m. Stratigraphic information from drilling also provides closer constraints on timing of fault movement.

Westerman graben. The largest and easternmost graben along Barnes Creek is named the Westerman graben after landowner Cecil Westerman. The graben is exposed in the bed of Barnes Creek in the

SE¼ NE¼ SE¼, Sec. 9, T15S, R5E, Massac County, Metropolis 7.5-minute quadrangle.

Torrential rains during the winter of 1996-97 deeply eroded the streambed and revealed many structures previously concealed by modern gravel. We hired a backhoe operator to improve the exposures further. Trenching showed a graben trending N35°E and about 75 m wide, containing gravel and diamicton of the Metropolis formation juxtaposed against McNairy Formation on both sides (Fig. 7). On the southeast margin of the structure is about 0.9 m of silty to sandy clay that contains small white, pink and gray chert pebbles. This material may be Massac formation (late Tertiary); it overlies the McNairy and is overlain by Metropolis diamicton. The McNairy dips steeply inward on both flanks and is offset by smaller faults. All structures are truncated by undisturbed, horizontal Holocene sediments.

Geoprobe borehole # BC-7 was drilled to a depth of 104 feet (31.7 m) along the centerline of the graben on the north bank of Barnes Creek. The following strata were penetrated:

0 to 2.3 m	**Holocene** silt, grading down to fine sand
2.3 to 3.8 m	**Holocene** or late Pleistocene silty chert gravel and diamicton
	Metropolis formation
3.8 to 7.9 m	Pebbly silt and sand, diamicton with reworked Mounds chert pebbles, mostly massive; where discernable bedding dips 30° or steeper.
7.9 to 11.1 m	Sand, with small gray chert pebbles (no patina).
11.1 to 13.1 m	Silt, dark brown, abundant plant matter; bedding dips 40-45°.
13.1 to 15.1 m	Sand, with gray chert pebbles.
15.1 to 31.7 m	Pebbly silt, sand, diamicton, and gravel, with reworked Mounds chert pebbles. Bedding dips 45-50° in upper part, possible near-vertical bedding near bottom of hole.

Sand and silt at 7.9 to 15.1 m were initially interpreted on the basis of lithology as Massac formation (late Miocene to early Pleistocene). Thus the cross section (Fig. 7) was drawn showing a slice of Massac formation overlying a reverse fault that repeats the Metropolis formation in borehole # BC-7. However, fossil pollen from silt at about 12 m depth in #BC-7 yielded probable Quaternary age (Norman Frederiksen, USGS, letter dated 2/6/98). This information indicates that the silt is probably part of the Metropolis formation, and not the older Massac formation, as shown in Fig. 7.

Parallel normal and reverse faults in the same structure argue for either a large component of strike slip or (less likely) two or more episodes of faulting under different stress fields.

The Westerman graben does not deform the Holocene floodplain sediment along Barnes Creek. Considering that the Metropolis formation is pre-Sangamonian, the last movement of the graben was no younger than Wisconsinan.

Fault "H". A structure we call fault "H" is exposed along Barnes Creek 120 m west of the Westerman graben. Fault "H" strikes N35°E, parallel with the Westerman graben, and dips 50°NW. McNairy Formation in the hanging wall northwest of the fault is horizontal (Fig. 8). In the footwall McNairy dips 40-50° southeast and is sharply overlain by gray gravel and silt having a similar attitude. The gravel/silt unit is largely light gray, weakly laminated argillaceous silt that contains scattered well-rounded white to gray quartz and chert granules. The basal 0.6 m is largely sand and gravel, also composed of white to gray chert and quartz pebbles. None of the pebbles show a trace of bronze Mounds patina. No fossils were found; black-stained silt proved to be inorganic and barren of spores or pollen. The gray silt/gravel unit is lithologically similar to the Massac formation.

Streambed exposeures and shallow boreholes show that the Massac(?) formation east of fault "H" is folded into a syncline having steep northwest and gentle southeast flanks (Fig. 9). Fault "H" is interpreted as a high-angle reverse fault, bringing McNairy on the northwest up and over Massac(?) formation. This fault possibly is part of a positive flower structure associated with strike-slip faulting at depth.

Horizontal Quaternary gravel truncates the upturned McNairy and Massac(?) strata along fault "H" (Figs. 8 and 9). The dull brownish gray gravel lacks the bright colors, strong mottling and weathering features associated with the Metropolis formation and Sangamon Geosol. This gravel therefore may be Wisconsinan, or even Holocene. A thin layer of this gravel is downdropped along the fault surface, sandwiched by McNairy Formation. Also, a narrow vein or fissure filled with gray clay extends upward through the gravel (Fig. 8). There appears to be a slight normal offset (northwest side down 5 to 10 cm) in the upper part of the gravel. The fault and clay vein terminate at the base of loose fine sand that is undoubtedly Holocene.

Fault "H" apparently underwent a large reverse displacement in late Tertiary or Pleistocene time, followed by a minor episode of extension and normal movement. The time of last movement is not known, but appears to be post-Sangamonian and may be Holocene.

Terrace graben. The terrace graben is the only structure near Barnes Creek that has obvious effect on topography, offsetting a Pleistocene fluvial terrace north of the creek. The graben is about 400 m northwest of the Westerman graben and has a subparallel trend of N50°E.

As exposed along the creek, the terrace graben appears to be a half-graben having the main fault on the northwest side. This fault is a steeply dipping normal fault that juxtaposes Metropolis formation on the southeast with McNairy on the northwest. The downthrown block is less than 100 m wide and is folded into an assymetrical syncline, having a steep northwest flank and gentle southeast one. The amount of displacement is not known, but appears to be less than 10 meters.

North of Barnes Creek a marshy swale is in line with the terrace graben (Fig. 10). The swale is about 100 m wide and trends NE-SW. East of the swale the Westerman farm buildings stand on a prominent terrace at 430-435 feet (131-133 m) elevation. West of the swale is a low terrace segment at about 415 feet (126.5 m) elevation. The swale is at about 405 feet (123.5 m) elevation, and it is level with the wide floodplain of Barnes Creek.

We explored terrace stratigraphy with a number of hand-auger borings and three Geoprobe cored test holes. Results of the Geoprobe borings are as follows:

Borehole BC-6, on high terrace southeast of graben

0 to 1.8 m	**Peoria Silt**, with modern soil
1.8 to 2.7 m	**Roxana Silt**
2.7 to 4.1m	**Loveland Silt?** sandy silt is strongly mottled in yellowish brown to orange, and contains scattered chert granules. This may be Metropolis formation.
4.1 to 5.8 m	**Metropolis formation,** sandy and pebbly clay, strongly mottled as above, reworked Mounds chert pebbles common.
5.8 to 7.3 m	**McNairy Formation,** gray to orange, laminated, fine-grained micaceous sand.

Borehole BC-4, on low terrace northwest of graben

0 to 3.0 m	**Silt,** probably Peoria and Roxana.
3.0 to 5.2 m	**Metropolis formation,** strongly mottled pebbly silt in the upper part grades to coasre sand and gravel at the base.
5.2 to 5.5 m	**McNairy Formation,** interlaminated light gray to yellowish gray micaceous silt and sand.

Borehole BC-5, in swale within graben

0 to 2.9 m	**Alluvium,** brown silt at the top grades downward through orange to brown sand with scattered pebbles, to 0.6 m of chert gravel at base.
2.9 to 21.6 m	**Metropolis formation,** multiple fining-upward sequences of silt, sand, and gravel each 0.6 to 3 m thick; gravel is reworked Mounds chert.
21.6 to 21.8m	**McNairy Formation,** interlaminated light gray silt and sand are very micaceous, and the bedding steeply inclined.

The base of the Metropolis formation is downthrown about 18 m in the swale relative to the terrace segments on both sides. The Metropolis in the graben is more gravelly than usual, and the numerous upward-fining sequences are striking. They suggest that the graben subsided intermittently during deposition of the

Metropolis. After each episode of subsidence, the resulting depression was filled by stream sediments.

The final episode of movement here plainly took place after deposition of the youngest part of the Metropolis formation. On the high terrace the Metropolis is overlain by the Loveland Silt, within which the Sangamon Geosol is developed. This evidence indicates that the youngest Metropolis sediment is no younger than late Illinoian age. Unanswered is whether any displacement took place during, or after deposition of one or more loesses. No loess was found in the Geoprobe borehole drilled into the graben. Additional drilling or trenching may allow us to determine whether Loveland or younger loesses are deformed in this structure. The bottomland setting and high water table are not favorable for a deep trench.

Pipeline graben. A third deep graben containing Metropolis formation was identified along Barnes Creek near a gas pipeline (Fig. 11). The structure exposed in the streambed is about 90 m wide; both bounding faults strike about N10°W. The western boundary fault is a high-angle reverse fault (dip about 75°) that displaces laminated sand of the McNairy on the western, upthrown side against burrowed, red silty sand of the Metropolis formation on the east (Fig. 12). Bedding of the McNairy dips steeply east adjacent to the fault, exhibiting normal drag. The eastern boundary fault is poorly exposed, but dips nearly vertically. McNairy east of this fault is folded into an asymetrical syncline (Fig. 11), which is not consistent with drag folding from down-to-the-west displacement.

Three Geoprobe boreholes were drilled to determine the amount of displacement. Holes BC-1 and BC-2 were drilled within the graben and hole BC-3 east of the graben (Fig. 11). Drilling indicates that the Metropolis formation in the graben is downthrown at least 10 m.

Near the east margin of the pipeline graben, a smaller graben that strikes N40°W and is about 1 m wide is exposed in the streambed. The small graben displaces brown gravel at the base of alluvium that overlies the Metropolis formation with an angular unconformity (Fig. 13). Basal alluvial gravel also is slightly offset along the eastern boundary fault of the pipeline structure. Younger layers of alluvial gravel and silt truncate all faults, and are not deformed. Age relationships of the alluvium are poorly constrained, but the exposures point to fault movement during Wisconsinan or, possibly, early Holocene time.

The pipeline graben differs in trend from most faults in the Barnes Creek Fault Zone. This graben may be a cross-fault that connects larger, northeast-striking faults within the zone. Other Neogene faults in Massac County, including those near Round Knob and in the Kelley railroad cut, have similar NNW trend. The juxtaposition of subparallel compressional (reverse fault) and extensional (graben) features, plus the "wrong-way" drag in McNairy east of the graben, imply that the pipeline graben has a component of strike-slip.

Another interesting feature is the miniature graben between the terrace and pipeline grabens. The miniature graben strikes northeast and contains alluvial silt and gravel downthrown into McNairy Formation (Fig. 14). The McNairy is nearly horizontal and shows no offset across the graben. Gravel within the graben is downthrown more than 1 m, and contains soil features typical of the Sangamon Geosol. Because McNairy outside the graben lacks Sangamon features, we infer that fault movement was post-Sangamonian (i.e. Wisconsinan to early Holocene). A dark brown gravel, probably Holocene, truncates the miniature graben (Fig. 14).

Massac Creek graben, revisited

A Neogene graben of substantial displacement was identified near Massac Creek in northern Massac County (Nelson et al., 1996 and 1997). Existence of this structure, previously suspected from outcrop and water-well data, was confirmed by a 92-meter-deep, continuously cored borehole (ISGS #R-1 Weaver) drilled in 1995. The Massac Creek graben is part of the Hobbs Creek Fault Zone, which in turn is part of the Dixon Springs Graben within the FAFC (Fig. 2).

We originally interpreted the strata from # R-1 Weaver as: 0 to 4.5 m Holocene alluvium, 4.5 to 33 m Mounds Gravel, and 33 to 92 m of Massac formation. Fossil pollen from the Massac formation indicated an age between late Miocene and early Pleistocene - equivalent to no previously known unit in the northern Mississippi Embayment. Neogene sediments within the graben are juxtaposed with McNairy Formation and Paleozoic bedrock outside the graben (Nelson et al., 1996 and 1997).

We re-examined the #R-1 Weaver core in 1997, after drilled at Barnes Creek showed thick sections of Metropolis formations in several grabens. On the basis of this study we re-interpreted the interval from 4.5 to 33 m as Metropolis formation rather than Mounds Gravel (Fig. 15). The interval consists of silty sand and sandy silt, interbedded with pebbly diamicton and coarse sand and gravel. Colors are brightly mottled in yellows, oranges, reds, and grays. Although a few chert pebbles bear the Mounds bronze patina, most are worn, pitted, and bleached. Lamination is poorly evident; where present it is steeply dipping, contorted, and sheared. These lithologies are characteristic of the Metropolis formation.

The Massac formation in # R-1 Weaver contains rare, well-rounded white to dark gray quartz and chert granules. These granules are similar to those found in Eocene units of the northern Mississippi Embayment, and unlike the larger, brown, glossy chert pebbles that compose the Mounds Gravel. (Such pebbles, albeit bleached and worn, are a major constituent of the Metropolis formation). The absence of pebbles derived from the Mounds implies that the Massac formation is older than the Mounds Gravel.

Identifying the upper unit as Metropolis, not Mounds shifts fault movement from probable Pleistocene to definite Pleistocene. More precise dating of fault movement is not available now. A sample of dark gray clay from the upper part of the Metropolis section at a depth of 6.5 meters was examined by Norman Frederiksen of the USGS, who reported the sample to be barren of spores and pollen.

Further clues as to the structure of the graben are provided by the log of the water well at the James Weaver residence, approximately 100 m west of the site of # R-1 Weaver. The water well was drilled by Paul Horman of Metropolis, whose logs are generally reliable. "Red gravel" at a depth of 240 to 302 feet (73 to 92 m) is likely to be Mounds, unlikely to be either Metropolis or McNairy Formation. The cross section (Fig. 15) shows a possible configuration of the Massac Creek graben.

The Massac Creek structure is currently our most spectacular example of a Neogene graben. The magnitude of Pleistocene displacement is equalled only by the Westerman graben at Barnes Creek, and Massac Creek contains at least 60 m of a Neogene unit (Massac formation) previously unknown in the region. This structure is slated for further study, including high-resolution seismic profile(s) and additional drilling, under our current NEHRP grant (Award No. 1434-HQ-97-GR-03195).

Round Knob Area

Faults that displace units as young as Pleistocene were identified near the village of Round Knob (Fig. 2) during this mapping season. The principal exposures are in a cut along the Illinois Central Railroad, which runs north-south through the center of the N½ of Sec. 11, T15S, R4E, Massac County, Metropolis 7.5-minute quadrangle.

A fault that strikes NW or NNW is inferred to cross the railroad near the north side of Section 11 (Figs. 2, 16). The fault juxtaposes white, clay-rich laminated sand of the McNairy Formation on the southwest against coarser orange sand of the McNairy on the northeast. McNairy strata on both sides of the fault dip east at 15° to 30°. The fault surface is concealed by slope wash.

Tilted Metropolis formation overlying McNairy is visible in a deep gully east of the tracks on the northeast side of the fault. Bedding of McNairy and Metropolis are approximately parallel, striking NNW and dipping about 20°ENE, into the hillside. Such a dip suggests a rotational landslide block. However, the top of the railroad cut is level, with no sign of a slump; and mature tree trunks on the steep slope have vertical trunks. Also, a landslide after railroad construction could not account for the Metropolis overlying different facies of the McNairy on opposite sides of the tracks. Therefore, we conclude that the structure probably is tectonic.

Southward along the railroad are numerous small exposures of McNairy, Mounds Gravel, and Metropolis formation. Elevations of contacts vary in short distances, and locally bedding in Mounds and Metropolis is tilted at 10-15°. Exposures are too fragmentary to define the trend and displacement of any faults.

A deep gully just north of the overpass of Seilbeck Road on the east side of the tracks (SW¼ SW¼ NE¼, Sec. 11, GT15S, R4E) reveals an unusual succession:

TOP - slope wash and vegetation

0.9 m	**Roxana Silt**
0.6 m	**Loveland Silt**, with Sangamon Geosol
0.3 m	**Colluvium**, quartz and chert pebbles mixed with silt.
2.4 m	**Metropolis formation**, diamicton grading downward to sand and gravel, strongly mottled in red, yellow, and gray, gravel of reworked Mounds chert pebbles to 10 cm across, bedding attitude N55°E/10-13° SE; planar vertical clay-lined joints mostly strike N-S to N15°W. Lower contact concealed.
≤1.0 m	**Covered**
0.6 m	**Porters Creek Clay (Paleocene)**, light olive gray, stiff, massive to weakly laminated, slightly silty, conchoidal fracture.
0.8 m	**Clayton Formation (Paleocene)**, very sandy clay is olive to greenish gray, highly glauconitic, burrowed, blocky to weakly laminated.
1.1+ m	**McNairy Formation**, sand with clay laminae, micaceous, no glauconite.

This is the only place in Massac County where the Porters Creek Clay or Clayton Formation are known. The Mounds-McNairy contact is 10 to 20 m higher in nearby hills and no Clayton, Porters Creek or Metropolis are present. The gully may occupy a graben that subsided both before and after deposition of the Mounds Gravel. In pre-Mounds time the Clayton and Porters Creek were downdropped and preserved (Fig. 16). Thus, these two marine formations must have originally extended north of their present outcrop limits. Subsequently the land surface was eroded, Metropolis formation deposited on top of Porters Creek, and the graben sank again, tilting and fracturing the Metropolis. The faults that presumably bound the inferred graben, unfortunately, are not visible, and the trend of the graben is not known.

Raum Fault Zone

The Raum Fault Zone is about 5 km southeast of the Lusk Creek Fault Zone and runs parallel with the latter (Fig. 2). The northeast part of the Raum in Pope County is composed mainly of northeast-dipping faults that apparently merge with the Lusk Creek at depth (Bertagne and Leising, 1991; Weibel et al., 1993). The Raum widens and becomes more complex toward the southwest in Massac County (Nelson, 1996). Post-Cretaceous displacement is documented at Reineking Hill, where McNairy Formation is downthrown into a narrow graben bordered by Mississippian sandstone (Nelson et al., 1996 and 1997).

Choat area. A southwest extension of the Raum Fault Zone was mapped this season near the former village of Choat, about 9 km northwest of Metropolis. The fault zone trends about N35°E and is in line with the Reineking Hill graben mentioned above. The Mounds-McNairy contact is offset and tilted; clay-lined joints and small faults were observed in these units in gravel pits northeast of Choat and in borrow pits near the former Metropolis city landfill. Sharply linear ridges and ravines parallel the fault trend across a distance of 5 km from the Ohio River. Together, these features inply a fault zone of horsts and grabens, bounded by high-angle faults and at least several hundred meters in width.

Faulted Metropolis formation is exposed in a streambank along a NNE-trending linear ravine near the Ohio River (NW¼ NE¼ SE¼, Sec. 19, T15S, R4E, Joppa 7.5-minute quadrangle). Two parallel faults that strike N25°E/80-85°NW outline a block of sandy silt about 40 cm wide, juxtaposed with gravel on both sides (Fig. 17). Clay-lined fractures are parallel with the faults. Although the direction and amount of slip could not be determined, this feature resembles small grabens in the Barnes Creek Fault Zone. As at Barnes Creek, the structure here is truncated by horizontal, undisturbed Holocene alluvium.

Evidence for a larger graben is given by two well records near Choat (Fig. 18). The log of a water well at the Melferd Krueger residence (SW¼ SW¼ NW¼, Sec. 17, T15S, R4E) reads as follows:

0 to 30 ft (0 to 9.1 m)	**Clay**
30 to 60 ft (9.1 to 18.3 m)	**Sandy clay**
60 to 80 ft (18.3 to 24.4 m)	**Gravel**
80 to 150 ft (24.4 to 46 m)	**Fine sand/soapstone**
150 to 380 ft (46 to 116 m)	**Gray clay/fine white sand**
380 to 400 ft (116 to 122 m)	**Gravel**

The well did not reach Paleozoic bedrock, which must lie below 122 m depth or -6m elevation below sea level. This compares with bedrock top at +60 to +75m in several nearby wells. The bedrock surface (base of Cretaceous) therefore is downthrown a minimum of 65 meters.

In 1997 we drilled a Geoprobe boring close to the Krueger water well. The following strata were cored:

0 to 1.8 m	**Peoria Silt (loess)**, with modern soil
1.8 to 3.6 m	**Roxana Silt**
3.6 to 4.8 m	**Loveland Silt,** with Sangamon Geosol
4.8 to 6.1 m	**Metropolis formation** or colluvium; silty sand with clay matrix and reworked Mounds chert gravel
6.1 to 14.3 m	**Unidentified unit**; brightly variegated, medium to coarse quartzose sand with no mica or pebbles, silty matrix, weakly indurated, lamination dips 20° to 40°. Drilling halted at 14.3 m due to refusal.

The unnamed sand is definitely not Mounds or McNairy. It could be Wilcox (Eocene), a younger Tertiary unit, or even

Pleistocene. The sand is thoroughly oxidized and no fossils or organic matter were observed. We interpret a narrow NNE-trending graben, in which Tertiary and Metropolis strata are downdropped and preserved.

In summary, the Choat segment of the Raum Fault Zone displaces the Mounds Gravel and, at least locally, the Metropolis Formation. The Choat graben has undergone at least 65 m of post-Cretaceous vertical offset.

Additional studies, including seismic reflection, georadar, and core drilling, are planned for the Choat structure.

Altenberger fault

An apparent post-Pliocene fault that links the Raum and Lusk Creek Fault Zones has been mapped in the Joppa 7.5-minute quadrangle. The structure, named Altenberger fault after a local landowner, strikes N25°W and thus is nearly perpendicular with Lusk Creek and Raum fault zones. The Altenberger fault extends from about 1/2 km north of Choat to 1 km northeast of Maple Grove School (Fig. 2).

Water-well records and a few outcrops provide the evidence for this structure. The top of Paleozoic limestone is about 21 m lower south of the inferred fault than to the north. The Mounds-McNairy contact also is about 12 to 20 m lower south of the inferred fault. In the area of closest control, the contact descends 12 to 15 m in a horizontal distance of about 150 m.

The Altenberger feature may not be a tectonic fault. It could be a linear paleochannel in the Mounds Gravel. That hypothesis can be tested by shallow drilling. If an abrupt offset is detected, trenching can be conducted to expose the structure.

Kelley site

During geologic mapping (ISGS funded) in March, 1997 we observed Mounds Gravel in a railroad cut about 4 km NNE of Joppa, Illinois (near center E½, Sec. 1, T15S, R3E, Massac County, Joppa 7.5-minute quadrangle). This observation was surprising because the Mounds-McNairy contact is 30 m higher in elevation at a gravel pit about 500 m south of the railroad. Further investigation revealed that Mounds Gravel is confined to the central part of the cut, and flanked on both sides by McNairy strata that dip steeply inward. Recognizing another possible graben, we focused efforts on the site.

The Kelley cut was constructed in 1994 for a railroad spur that delivers coal to a nearby electrical generating station. (The name "Kelley" is taken from a signboard at a switch within the cut). The cut bisects a small hill that is elliptical in map view and rises about 25 m above the adjacent Cache Valley bottoms. When visited in 1997, both sides of the cut supported thick growth of grass except in small gullies or wash-outs that revealed disturbed Mounds and McNairy.

Electric Energy, Inc. provided us with engineering diagrams, including logs of borings made prior to building the railroad. These provided useful geologic background, but shed no light on the nature of the Kelley anomaly. Photographs taken during construction do not show the Kelley cut in profile. The next step was to explore both sides of the cut using soil probes, hand augers, and judicious trenching of key contacts using hand tools. The U.S. Natural Resources Conservation Service cooperated in drilling several shallow test holes using a Giddings rig from the top of the hill.

These efforts indicated that the Mounds Gravel occupies a keystone-shaped block about 60 m wide, flanked by McNairy strata (mainly fine-grained, orange sand). On the south side of the railroad, both Mounds-McNairy contacts dip steeply inward and appears to be faulted (Fig. 19). The east contact trends about N5°W/85°W, and the west contact N25°E/90°E. Bedding in the McNairy dips inward on both sides, and abruptly steepens to nearly vertical adjacent to the contacts with the Mounds (Fig. 19). This folding apparently reflects drag along the boundary faults. Bedding of the mounds is poorly defined, but lenses of sand near the west margin dip 40-50° east. Colloidal soil clay within pore spaces of the gravel was jumbled after emplacement.

Soil probing showed that the hill is mantled with Roxana and Peoria Silts and locally, an older silt believed to be Loveland. Most interesting, the loess/Mounds contact was synclinal on both sides of the railroad. The Loveland(?) loess was confined to the trough of the syncline, and both Roxana and Peoria thickened toward the axis of the trough. This evidence suggested late Pleistocene, or even Holocene tectonic activity.

In October, 1997 we cleared soil from the north side of the railroad cut across the full width of the inferred graben, using a large, track-mounted backhoe. The lower part of the slope, beyond the reach of the backhoe, was explored by three pick-and-shovel trenches and a number of small test pits. The base of the slope, protected by riprap, was not cleared. The surface was cleaned using hand tools, logged, and photographed, resulting in a full-width profile of the Kelley structure (Fig. 20). After study, the soil was replaced and the slope was reseeded to prevent erosion.

Trenching revealed a synclinal feature involving the Mounds Gravel and younger units. The Mounds-McNairy contacts north of the railroad do not dip as steeply as on the south side of the tracks. The east contact trends about N20°W/20°SW and appears to be a tilted depositional contact rather than a fault. Westward the Mounds is truncated by a nearly vertical contact, that may be a small fault. On the west side the Mounds-McNairy contact trends N10°E/55°SE. Indications of shearing were observed along the contact, but slip indicators were indefinite. Bedding of the McNairy near the contact showed variable attitudes, most dips in the range of 20° to 40° eastward.

Overlying the Mounds Gravel were the following five units in ascending order:

1. Reworked Mounds gravel, composed of pinkish to brownish gray chert gravel in a matrix of silt and sand. Most pebbles bear a well-developed bronze patina. Colloidal clay is absent from pore spaces. The gravel thickens from 0.6 m on the margins to nearly 2 m near the center of the trough, but is concealed below riprap in the deepest part of the structure. Bedding and imbricated pebbles indicate deposition by water. Whether this is Mounds that was eroded and re-deposited, or in-place Mounds subjected to soil formation, is uncertain.
2. Bright reddish orange silt that is strongly mottled and contains layers of reworked Mounds-type chert gravel. This unit is interpreted as pre-Illinoian loess and/or colluvium containing the Yarmouth Geosol and possibly older geosols. This unit (henceforth called Yarmouthian silt) is confined to the central part of the structure and is at least 1.5 m thick, with the base concealed.
3. Loveland Silt (loess), containing the Sangamon Geosol. The Loveland is about 0.6 m thick and is confined to the central part of the trough.
4. Roxana Silt (loess), which thickens from about 1 m on both margins to more than 2 m in the low point of the structure.
5. Peoria Silt (loess) thickens from 2 m on the margins to nearly 5 m in the trough of the structure. The top of the Peoria was truncated and overlain by artificial fill during railroad construction.

The Yarmouthian silt and Loveland Silt are confined to the low, central part of the trough, in what may be a half-graben (Fig. 20). These silts are oxidized and not gleyed, indicating that they accumulated in a well-drained setting rather than in a wet depression. Thus they probably accumulated on an upland surface rather than along a valley floor or in a depression. Preservation of these units only along the axis of the structural trough implies that they were downwarped after deposition, and eroded from the flanking highs prior to deposition of Roxana Silt.

The Roxana and Peoria Silts both thicken into the structural trough, but no faults or other structures were found that cannot be attributed to ordinary soil-forming processes. Thickening of Roxana and Peoria loesses into the structure might reflect continued subsidence during Wisconsinan time, or merely drifting of windblown dust into a low place, analogous to drifting snow.

Some of us (Denny and Devera) propose that the Kelley structure may be a Mounds paleochannel rather than a tectonic feature. According to the channel hypothesis, deformed bedding along the margins of the structure reflects slumping or bank collapse along the sides of the channel. Denny and Devera point out that the Kelley structure does not line up with any known fault and has not been mapped away from the railroad cut. It lacks clearly exposed faults, systematic jointing, and other features that might be expected in a tectonic structure.

In rebuttal, the wedge of oxidized (well-drained) Yarmouthian and Loveland silt at the trough axis is difficult to explain in a paleochannel. The normal or "interfluve" base of Mounds near Kelley is about 30 m above the level of the railroad tracks. If a narrow channel were cut below this level, it should have been filled with gravel well above the top of the railroad cut. If the channel were abandoned, sediments that later filled it would accumulate in standing water and be gleyed rather than oxidized. Also, the inward dips of McNairy bedding are typical of known Neogene grabens (e.g. Barnes Creek, Reineking Hill, New Columbia) rather than of paleoslumps, which typically are rotated away from the channel margin.

More work is needed to clarify the origin of the Kelley structure. A seismic reflection profile may show whether the feature is underlain by faults. A drillhole along the axis of the trough below track level also could test paleochannel vs. graben theories. The presence of Tertiary units below Mounds Gravel, or continuation of Mounds to considerable depth (≥20 m) would rule in favor of tectonic origin.

Lusk Creek Fault Zone (Maple Grove area)

The Lusk Creek Fault Zone is the northwest boundary fault of the FAFC and an important element of the Reelfoot Rift. The Lusk Creek joins the Rough Creek-Shawneetown Fault System at its northeast end (Fig. 1). Traced southwest, the Lusk Creek is directly in line with the linear band of intense seismicity northeast of New Madrid. A seismic reflection profile (Bertagne and Leising, 1991) shows that the Lusk Creek was active in Cambrian time, with the southeast side downthrown as a normal fault.

The Lusk Creek has been reactivated several times following Cambrian rifting. The only Neogene activity previously demonstrated is at New Columbia, Illinois, where the Mounds Gravel is downdropped into a narrow graben. The New Columbia graben (Fig. 2) is about 1.5 km northwest of and strikes parallel with the Lusk Creek master fault (Nelson et al., 1996 and 1997).

Borehole data indicate that the Lusk Creek Fault Zone extends southwest into the Mississippi Embayment in Massac County (Fig. 2). Near the Ohio River the fault zone strikes N30°E and is probably less than 1/2 km wide. Mississippian bedrock is downthrown about 30 m southeast of the zone. This displacement is much less than that mapped in Paleozoic outcrops along the northeastern part of the Lusk Creek in Pope County. There is little or no relative offset of the bedrock surface (base of McNairy Formation) across the fault zone in Massac County. However, a narrow graben within the fault zone contains Cretaceous, late Tertiary, and Quaternary sediments that are downdropped several tens of meters relative to their counterparts outside of the fault zone.

Two boreholes at the Maple Grove School (SE¼ SE¼ NE¼, Sec. 10, T15S, R3E, Joppa 7.5-minute quadrangle) provide the principal evidence for a graben in the Lusk Creek Fault Zone (Fig. 21). Sample cuttings from a water well drilled at the school in the 1950s are on file at the ISGS. Although the sample set is incomplete, it indicates anomalous conditions. Samples from the surface to 56 feet consist of sand and gravel, apparently Neogene but not including Mounds Gravel. McNairy Formation was logged from 56 to 91 m, then chert rubble (Tuscaloosa or bedrock residuum) from 91m to total depth at 101 m. Other wells and outcrops near the school show that the McNairy Formation is at the surface (or covered by 3-5 m of loess) away from the school. The water well therefore indicates that the top of the McNairy is downdropped a minimum of 50 m at Maple Grove School.

We drilled a continuously cored borehole using a Geoprobe about 10 m northeast of the existing water well. The log of the cored hole is as follows:

0 to 1.9 m	**Peoria Silt**, with modern soil
1.9 to 3.5 m	**Roxana Silt**
3.5 to 4.9 m	**Loveland Silt**, with Sangamon Geosol
4.9 to 11.6 m	**Metropolis formation**; the upper 1.5 feet sandy silt with scattered chert granules, the remainder diamicton containing reworked Mounds chert gravel
11.6 to 23.2 m	**Unidentified unit** of sand and silt.

The unidentified unit is chiefly fine to medium-grained sand that varies from light gray to deep reddish gray and brownish orange. The sand contains a little silt matrix but no clay or gravel, and only a trace of mica. An interval of light to dark brownish gray, sandy and clayey silt was cored from 17 to 19 m. The dark silt was processed for fossil pollen, but none was found (Russel A. Peppers, 1997 pers. comm.). Layering, where visible, is steeply inclined and contorted.

The unidentified unit is definitely not Mounds Gravel or McNairy Formation. Lack of chert pebbles strongly suggests that it is older than the Mounds. Among known units, it most closely resembles the Wilcox Formation (Eocene), but it could be a younger unit (Massac formation), as found in the Massac Creek graben.

The Maple Grove boreholes document a narrow graben that underwent at least two episodes of post-Cretaceous movement (Fig. 21). The first movement was probably Pliocene or older and the second, which displaced Metropolis formation, took place during the Pleistocene. Future NEHRP studies planned for Maple Grove include seismic reflection and/or georadar profiles to delineate subsurface structure, and a continuously cored borehole to bedrock within the graben.

Post Creek Cutoff

Not much new research was conducted on the Post Creek structure during the past year, but several new developments are worthy of mention.

To recapitulate, a graben-like structure occurs near the mouth of Post Creek Cutoff (NW$\frac{1}{4}$ SE$\frac{1}{4}$, Sec. 2, T15S, R2E, Alexander County, Bandana 7.5-minute quadrangle). It is exposed in a deep gully and was core-drilled by Kolata et al. (1981). The Mounds Gravel is dropped downward at least 20 m relative to Mcnairy Formation, and folded into a syncline whose axis trends slightly east of north. The marginal contacts exposed in the gully dip 40° to 50°. Core drilling showed that the McNairy-Bedrock contact is downdropped about 27 m along the east edge of the feature. Kolata et al. (1981) proposed that the structure was a product of solution collapse of the underlying Mississippian limestone. Nelson et al. (1996) argued for possible tectonic origin but conceded that the evidence is inconclusive.

Flooding of the Ohio River rendered the site inaccessible for much of the field season. Revisiting the gully in October of this year, we discovered a newly exposed fault, about 20 m east of the steeply dipping east margin of the structure. The fault strikes N20°W and dips very steeply west, offsetting beds of the McNairy Formation a minimum of 1.5 m. Drag folds and micro-faulting are consistent with extensional tectonics and normal faulting with the west side downthrown (toward the larger structure). No slip indicators were found.

New mapping and drilling raised the question of whether the Post Creek structure contains Metropolis formation in addition to Mounds Gravel. Revisiting the site in October, we confirmed that the sand overlying gravel along the axis of the structure is indeed Mounds, as previously reported. The sand is uniformly reddish orange (not mottled or strongly burrowed) and the chert pebbles floating within have the bronze patina typical of Mounds but not of Metropolis.

Early in 1996 Martitia Tuttle of the University of Maryland observed and photographed an apparent fault in Mounds Gravel along Post Creek Cutoff 2 km north of the previously known structure. The fault observed by Tuttle strikes northwest and is in line, but different in trend from the larger structure. She observed the fault at a low stage of Post Creek; high water levels rendered it inaccessible during this field season.

The origin of the Post Creek structure remains questionable. A high-resolution seismic survey and additional test drilling are planned to address the tectonic vs. solution-collapse hypotheses of its origin.

Olmsted earthquake swarm

During the winter of 1983-1984 a swarm of small earthquakes occurred north of Olmsted, Pulaski County, near Lock and Dam # 53 on the Ohio River (Stauder et al., 1984; Stover, 1988). Activity began intermittently in November, 1983 and abruptly peaked in mid-February, 1984, when a total of 142 events were recorded by the St. Louis University Earthquake Center (SLUEC). These tremors took place over a 19-day period, but the great majority happened on February 14-16 (Fig. 22). The largest quake, of magnitude 3.6, occurred late on the 14th and was felt by residents of southern Illinois, western Kentucky, and southeastern Missouri (Stover, 1988, p. 67). Another 17 events during February registered magnitudes of 2.0 or greater (SLUEC, unpublished data).

We plotted hypocenters for the February, 1984 earthquakes, as recorded by SLUEC, on a map of southern Illinois (Fig. 23). Ninety percent are clustered into a northeast-trending oval area about 5 km long and 2 km wide immediately north of Lock and Dam # 53. The remaining 10% of hypocenters are scattered north, west, and southwest of the main cluster. Hypocentral data probably have a spatial error of roughly 1 km; larger events being more precisely located (Robert Herrmann, SLUEC, verbal communication, 1997).

Focal depths calculated by the SLUEC are remarkably shallow. All but two of the 15 largest events (mag. 2.0 or greater) were at depths of 1.2 to 5 km. Many small tremors have listed focal depths greater than 10 km, but these smaller events are less accurately located than the larger ones.

Allowing for uncertainty in locations, the 1984 Olmsted earthquake swarm appears to be concentrated along a northeast-trending structure at a depth of 5 km or less. These depths lie within Paleozoic bedrock and the upper part of Precambrian "basement".

A possible fault, striking northeast and displacing the top of Paleozoic bedrock about 100 m down to the southeast, has been mapped near Lock and Dam # 53 on the basis of water-well records. The inferred fault passes along the northwest edge of the main cluster of hypocenters (Fig. 23). If the earthquakes took place along this fault, a southeast dip (normal faulting) would be indicated. Detailed surface mapping in the area revealed few outcrops of Cretaceous and Tertiary strata; none were visibly deformed.

The inferred fault corresponds with part of the "America Graben" mapped by Ross (1963). Northeast-trending faults in Paleozoic bedrock near Oldsted also were mapped by Kolata et al. (1981). The extent and history of these faults are poorly known, but they run parallel with major structures of the Reelfoot Rift and Fluorspar Area Fault Complex.

In conclusion, the 1984 earthquake swarm near Olmsted may have taken place along a southeast-dipping normal fault that is part of the Reelfoot Rift.

Commerce Geophysical Lineament

The Commerce geophysical lineament (CGL) is a straight, northeast-trending alignment of gravity and magnetic anomalies that parallels the northwest margin of the Reelfoot Rift from Arkansas to western Indiana (Fig. 1). It is associated with current seismicity (Langenheim and Hildenbrand, 1997; Hildenbrand and Ravat, 1997) and with intricate Pleistocene to early Holocene tectonic faulting in the Benton Hills area of Missouri, only a few miles from the Illinois border (Harrison et al., 1997).

Where it crosses southern Illinois, the CGL has subtle surface expression. Several northeast-trending faults of small displacement coincide with the CGL in Illinois. Few of these faults are exposed; those that are displace no materials younger than Pennsylvanian. Linear bedrock bluffs along the northwest border of the Cache Valley in Alexander County are structurally intriguing, but no faults are exposed along them.

Operating under an EDMAP grant from the USGS, Christine Wiscombe of Southern Illinois University, Carbondale remapped a portion of the Thebes 7.5-minute quadrangle in Alexander County with the focus on possible tectonic faulting of Quaternary terrace sediments. She targeted two sites for backhoe trenching to uncover possible faults.

Wiscombe's first trenching site was on a bench interpreted as a Pleistocene terrace in line with a mapped fault in Paleozoic bedrock. A slight declivity along the terrace top suggested fault offset. The trench was excavated to a depth of about 4 m across the declivity, exposing the Peoria and Roxana Silts. No evidence of tectonic deformation was observed. Randomly oriented, vertical fractures in the loess apparently were products of ordinary soil-forming processes.

A second trench was opened on the floodplain of Sammons Creek in line with a fault that displaces Silurian bedrock. The trench, which did not reach bedrock, revealed deformed alluvium. Unfortunately, rapid influx of groundwater into the trench prevented detailed study, so no conclusions could be drawn as to the structure exposed.

CONCLUSIONS

This study documents widespread tectonic faulting in Massac County, Illinois during the Pleistocene Epoch. The pattern of structures is consistent: narrow grabens, a few tens to a couple hundred meters wide, trending mostly N 20-40° E, although some run nearly N-S to N20°E. These grabens are clearly part of the Fluorspar Area Fault Complex, a regional system of fractures that originated in the same Cambrian rifting ebvent that gave rise to crustal fractures in the seismically active New Madrid area. Every major fault zone of the FAFC in this part of Illinois (Lusk Creek, Raum, Hobbs Creek, Barnes Creek, and Rock Creek fault zones) displaces Pleistocene strata.

The kinematics of faulting are poorly known. Although the graben structures suggest extension, several grabens contain parallel normal and high-angle reverse faults. Such a configuration suggests a component of strike slip. But as of yet, we are unable to document the magnitude or even the direction of horizontal slip in Massac County. Good slip indicators are available on faults in Paleozoic bedrock north of Massac County, but these may reflect much older, pre-Tertiary episodes of movement. The unlithified sediments of the Embayment do not preserve slickensides or mullion. En echelon folds and fracture sets, indicative of strike slip, have not been observed, nor have any features that could serve as piercing points.

Our knowledge of the timing of movement is much improved over that presented in earlier reports (Nelson et al., 1996 and 1997). The "Massac formation" of late Miocene to early Pleistocene age (≈1 to 8 m.y. old) is downthrown at least 100 m into the Massac Creek structure. The Pliocene to early Pleistocene Mounds Gravel (≈1 to 2 m.y. old) exhibits offsets of 30 to 60 m at several sites. The younger Metropolis formation, a pre-Sangamonian Pleistocene unit (≈75,000 to 1 m.y old) is displaced 10 to 30 m at several sites. Displacements of Sangamonian and Wisconsinan strata (≈10,000 to 75,000 years old) are small, mostly less than 1 m throw, and not widely distributed. These imprecise figures yield average vertical offsets in the range of 1 to 3 meters per 100,000 at individual sites. Translating this figure to a regional strain rate would be speculative, given lack of knowledge of fault mechanics.

A northeast-striking, southeast-dipping normal fault, mapped from water-well data, possibly was the source of the February, 1984 earthquake swarm near Olmsted, Illinois. The swarm is elongate NE-SW and most of the larger events took place at depths of 5 km or less. The inferred structure at Olmsted is subparallel with most Quaternary faults to the east in Massac County.

Further research, partly supported by current NEHRP funding, is in progress to place better constraints on timing and kinematics of Neogene faulting in Illinois. This research includes:

1.) Shallow, high-resolution seismic profiles at Massac Creek, Choat, Maple Grove, and hopefully Kelley and Post Creek sites. The goal is to image the geometry of faulting at depth (upper Paleozoic through Pleistocene strata) and to define targets for drilling and trenching. Seismic is scheduled for mid-1998.
2.) Ground-penetrating radar surveys of Massac Creek, Choat, Maple Grove, Reineking Hill, and New Columbia sites. These surveys are designed to image shallow (≤10 m) deformation of Pleistocene and Holocene materials, which then can be drilled and/or trenched. Radar is scheduled for mid-1998.
3.) Further drilling at all of the above sites. Multiple shallow (≤ 30 m) boreholes will help define Neogene grabens and provide dateable materials. Deeper, continuous cored test holes are planned for the larger grabens to recover compl;ete sections of graben-fill at least down to the McNairy Formation. Deep drill sites will be selected following seismic work, in late 1998 and 1999.
4.) Trenching studies, to take place at sites defined by the above activities, as well as "targets of opportunity" (such as Kelley) identified during mapping. Defining the amount and direction of strike-slip displacement is a key objectyive of trenching studies.
5.) Absolute age-dating to constrain the time of fault movements at various sites. Methods that we are using now include palynology, radiocarbon, and thermoluminescence.
6.) Additional studies are needed in the Olmsted area. In particular, a seismic reflection profile should be acquired to verify the fault mapped from well data.

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The **bold-faced** reference below resulted directly from research sponsored and supported by NEHRP.

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NON-TECHNICAL SUMMARY

By drilling and trenching we documented faults that displace Pleistocene sediments (≈75,000 to 1 million years old) by as much as 30 meters in southernmost Illinois. Most of these faults run northeast-southwest, directly toward the New Madrid seismic zone. Most faults are nearly vertical and outline narrow (≈10 to 200 meters) downdropped blocks. They have been active many times in geologic history. A swarm of small (magnitude 3.6 and less), shallow (mostly 2 to 5 km deep) earthquakes near Olmsted, Illinois in February, 1984 may have taken place along another northeast-trending fault.

NEHRP Award No. 1434-95-G-2525, "Quaternary Faulting in the New Madrid Seismic Zone in Southern Illinois". W. John Nelson, Principal Investigator, Illinois State Geological Survey, 615 E. Peabody, Champaign 61820. February 20, 1998.

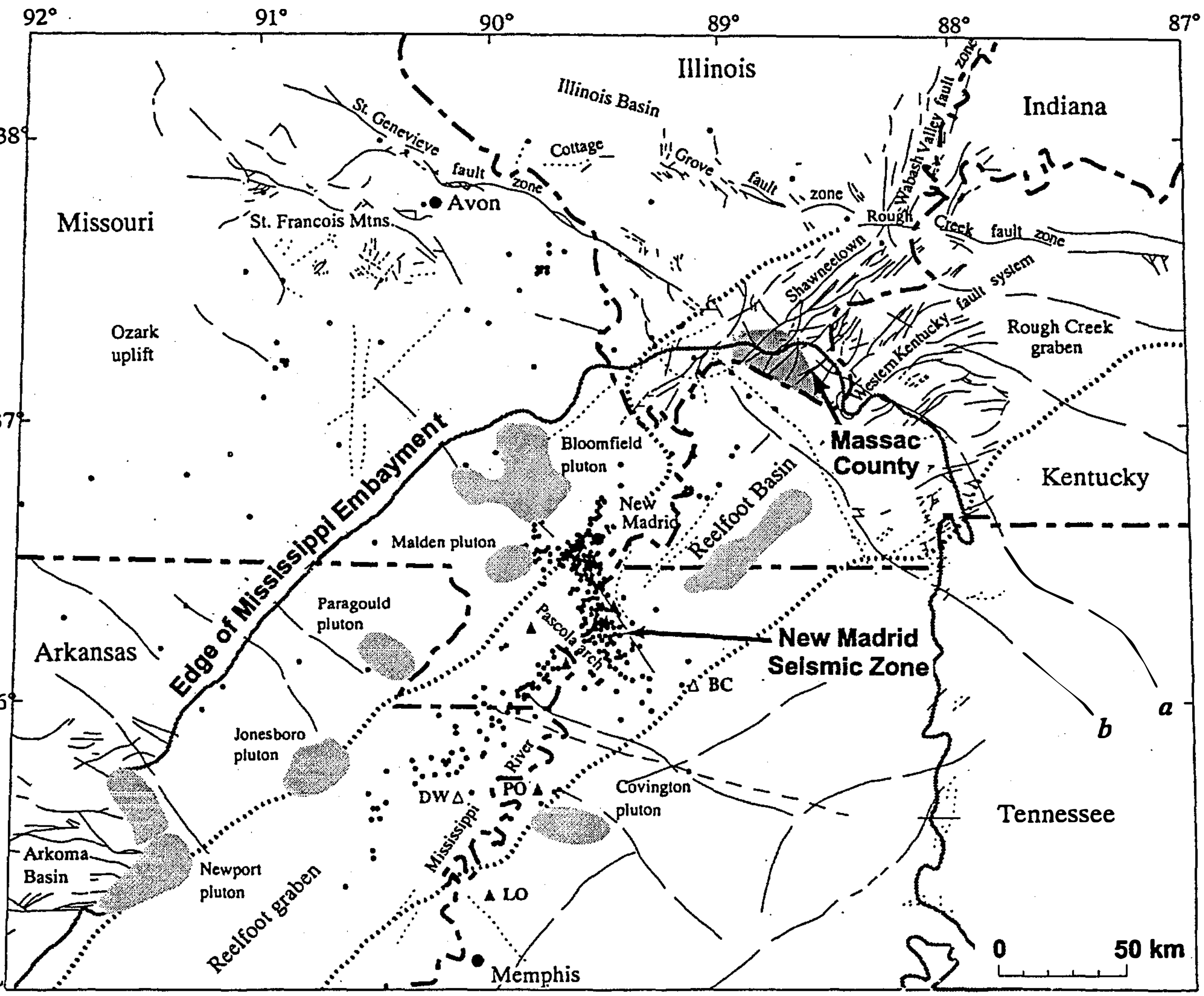


Figure 1. Map (from Hildenbrand and Hendricks, 1995) showing structural features of northern Reelfoot Rift and New Madrid Seismic Zone. Dots represent earthquake epicenters.

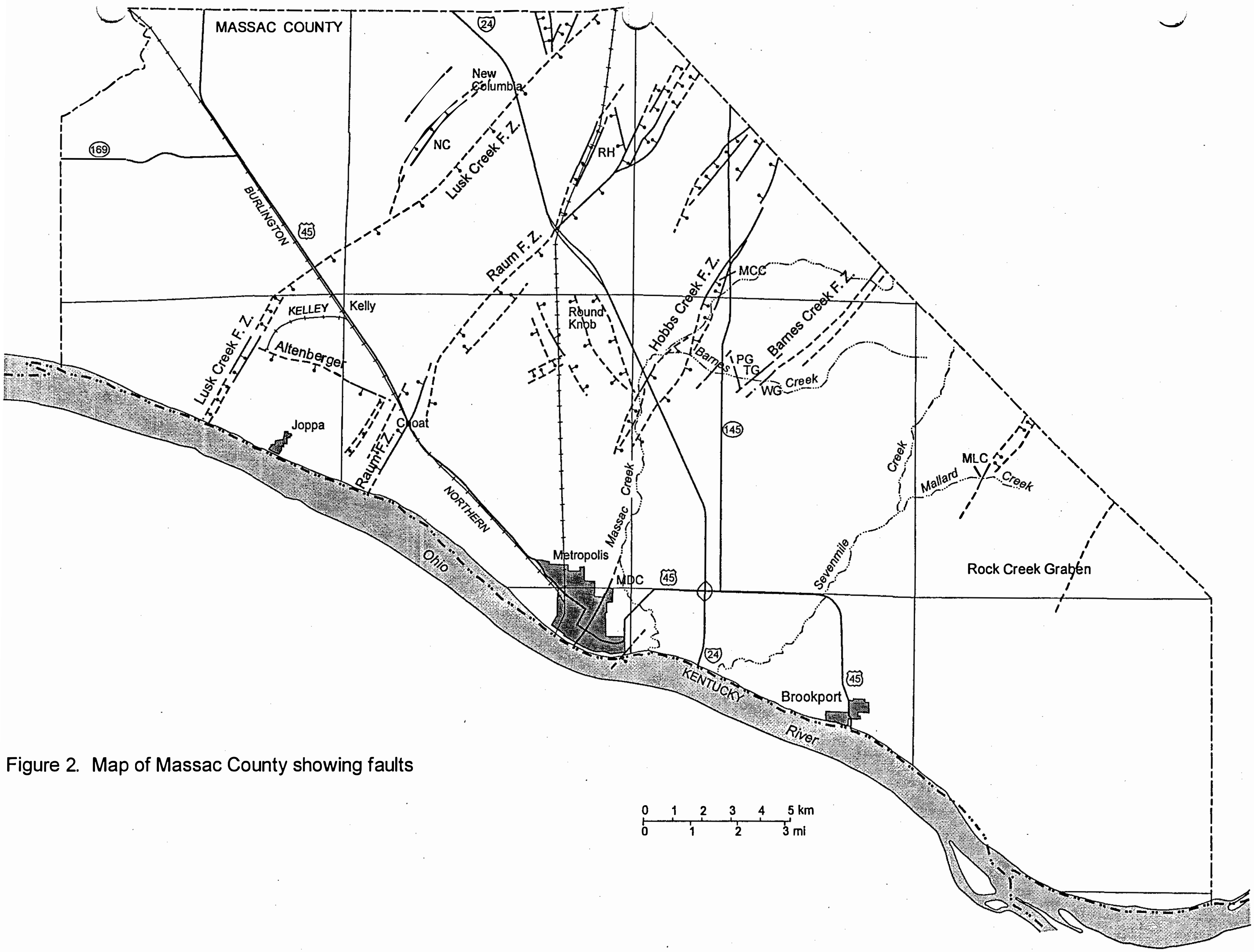


Figure 2. Map of Massac County showing faults

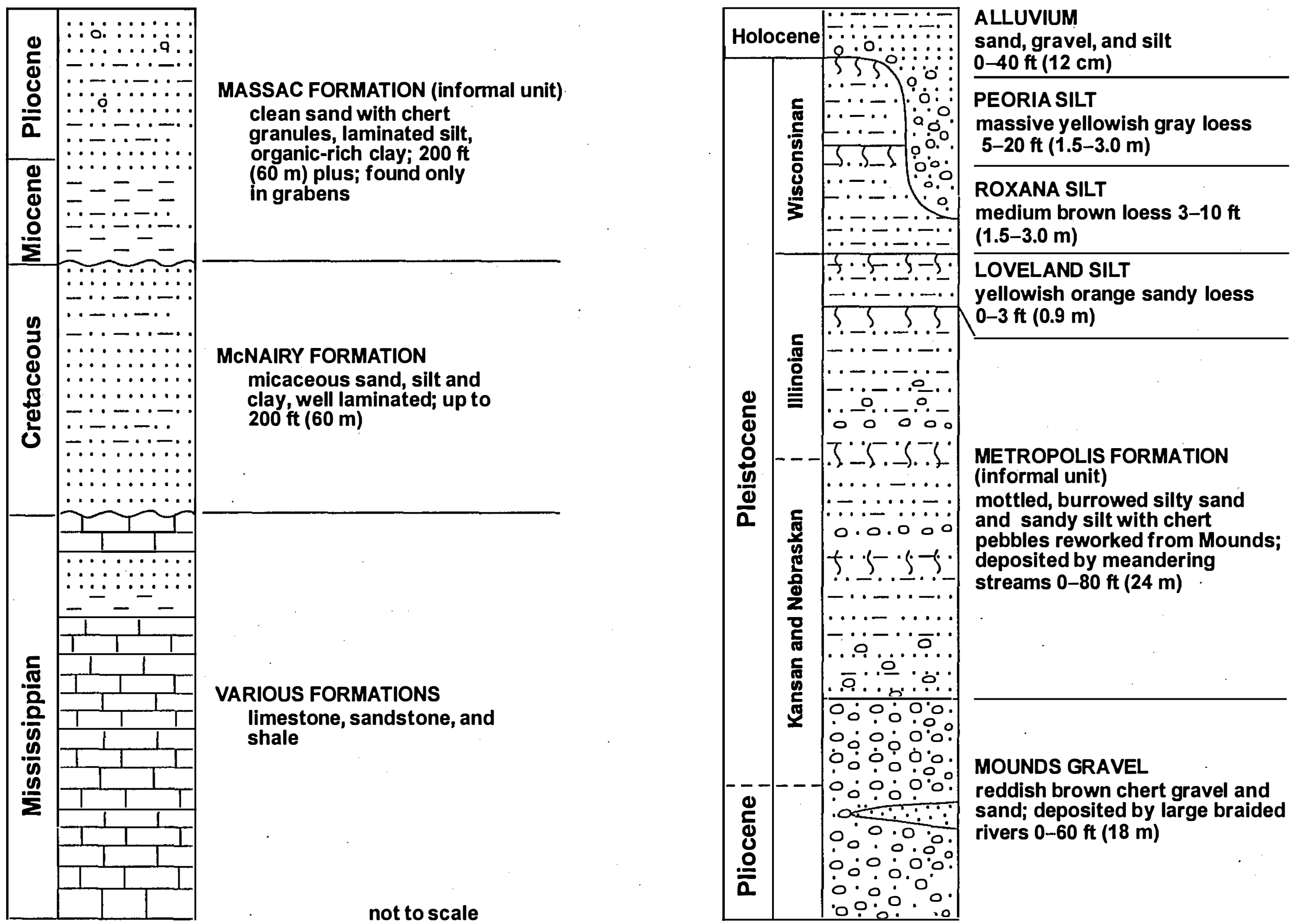


Figure 3. Stratigraphic column

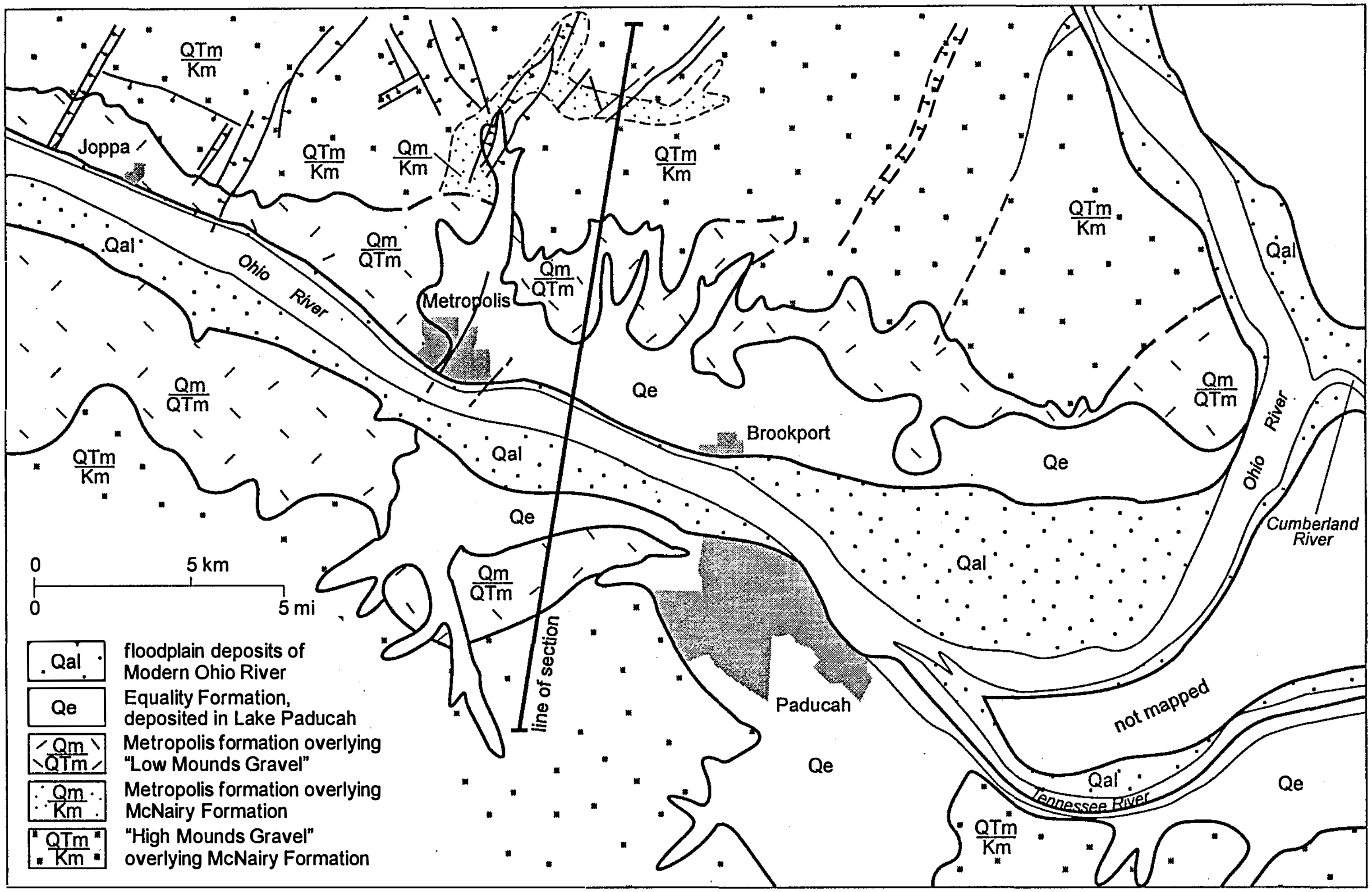


Figure 4. Map showing distribution of high and low Mounds Gravel, Metropolis formation, Equality Formation, and modern floodplain deposits.

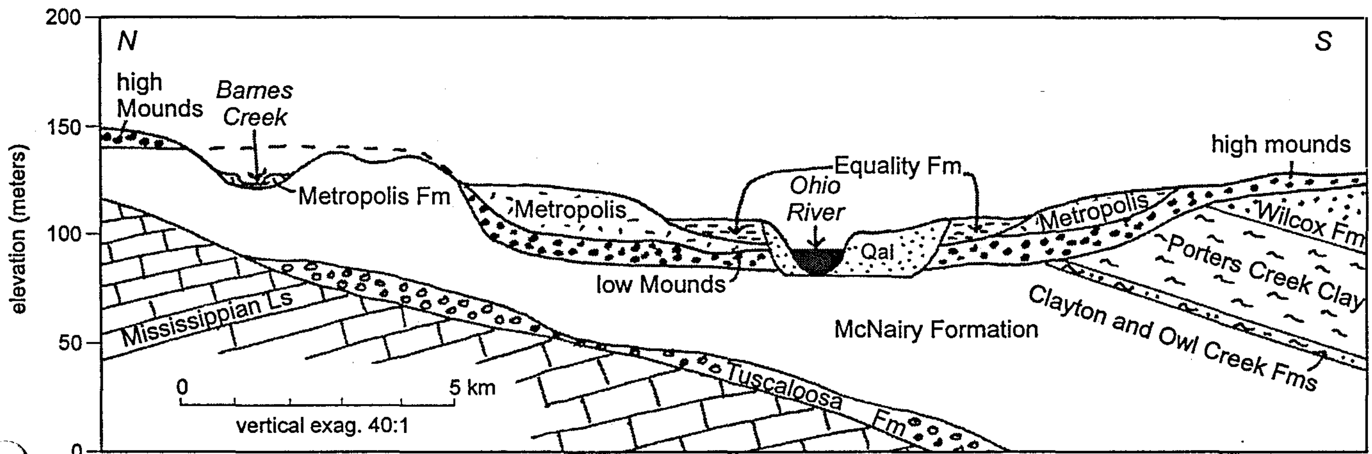


Figure 5. Cross section illustrating relationship of units mapped in Figure 4. This generalized section does not show loess or faults.

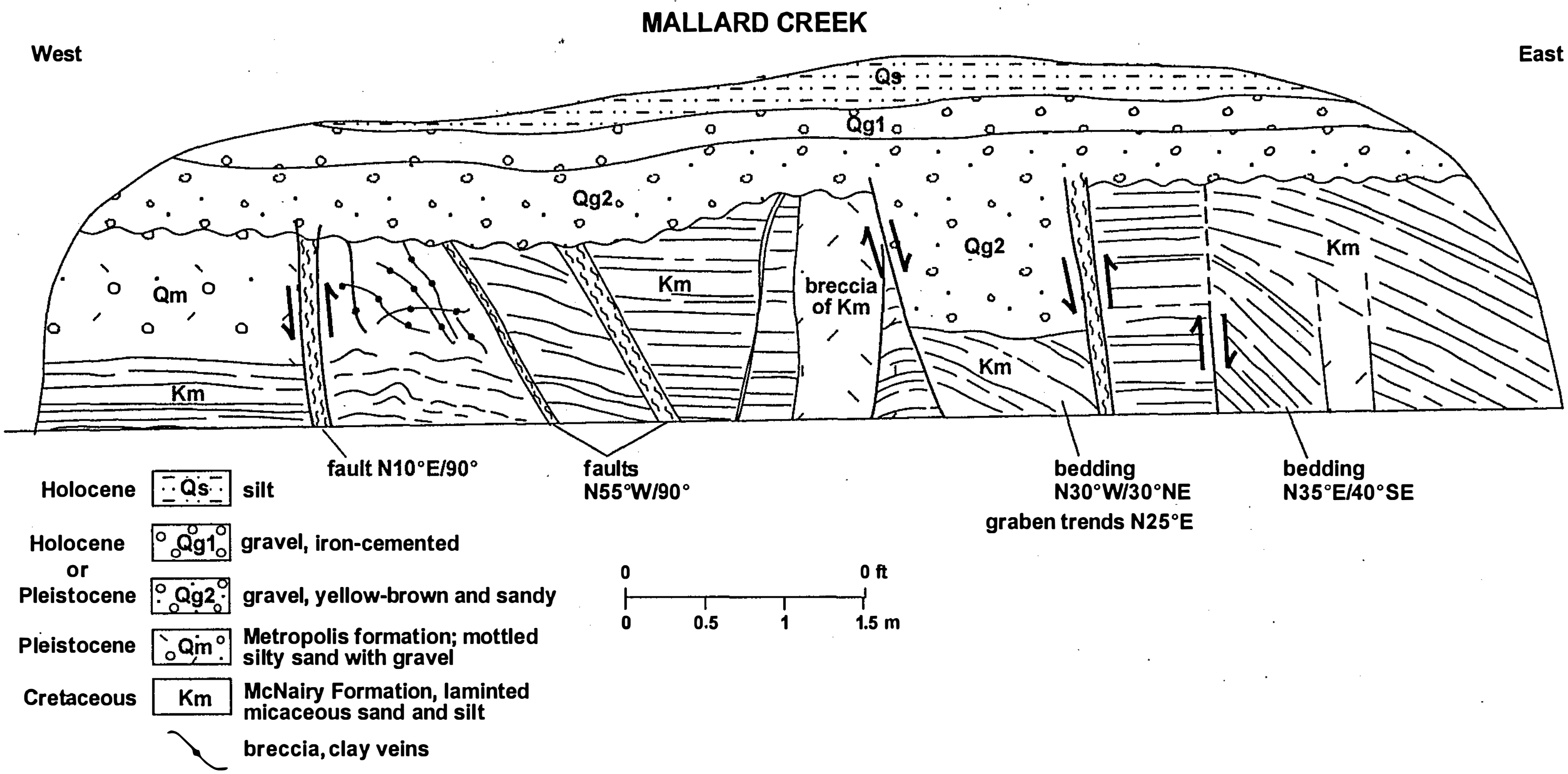


Figure 6. Sketch of fault zone, part of Rock Creek Graben, in excavated bank of Mallard Creek. The faults displace McNairy Formation, Metropolis formation, and a post-Sangamonian gravel Qg2.

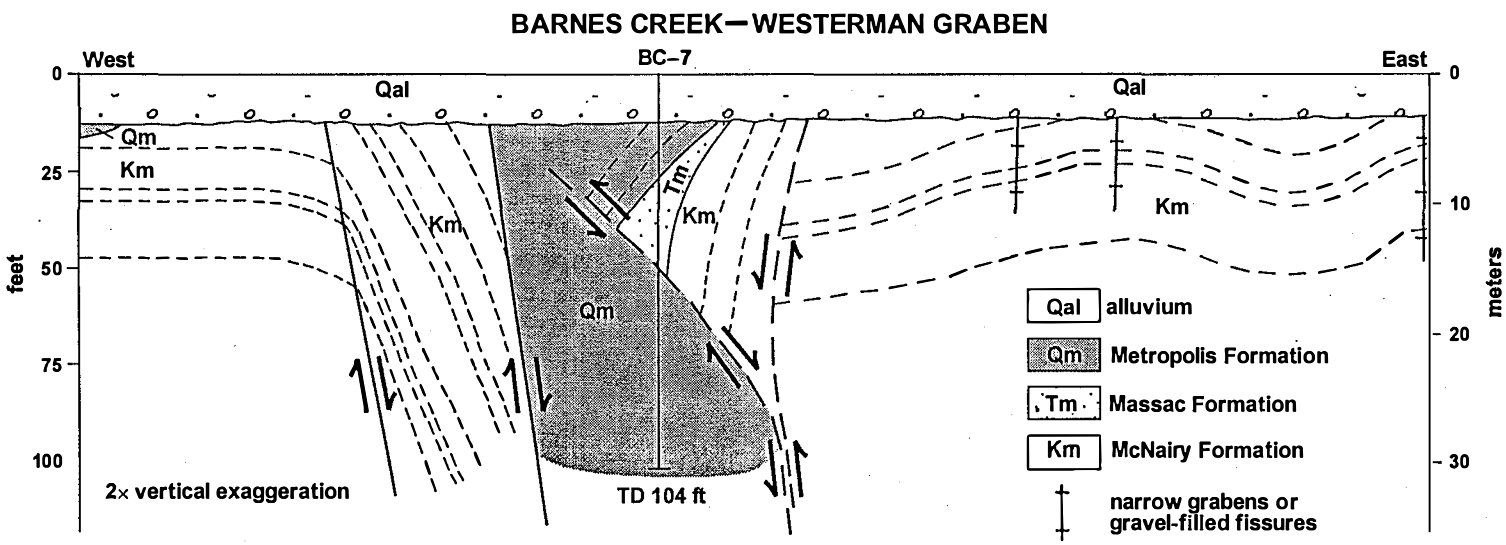


Figure 7. Cross section of Westerman Graben in Barnes Creek Fault Zone, based on streambank exposures and borehole BC-7. The Pleistocene Metropolis formation is downthrown a minimum of 27 m into a structure that contains both normal and reverse faults.

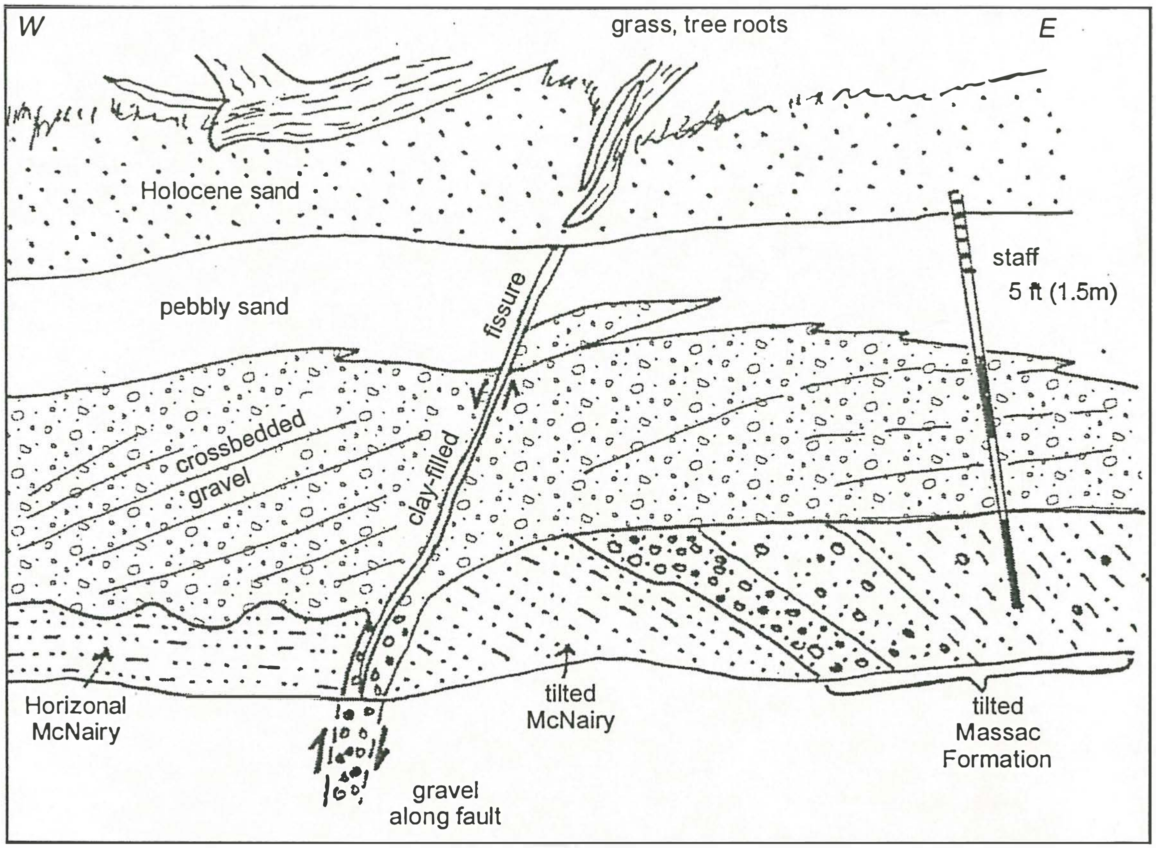


Figure 8. Photograph and sketch (looking north) of fault H along Barnes Creek.

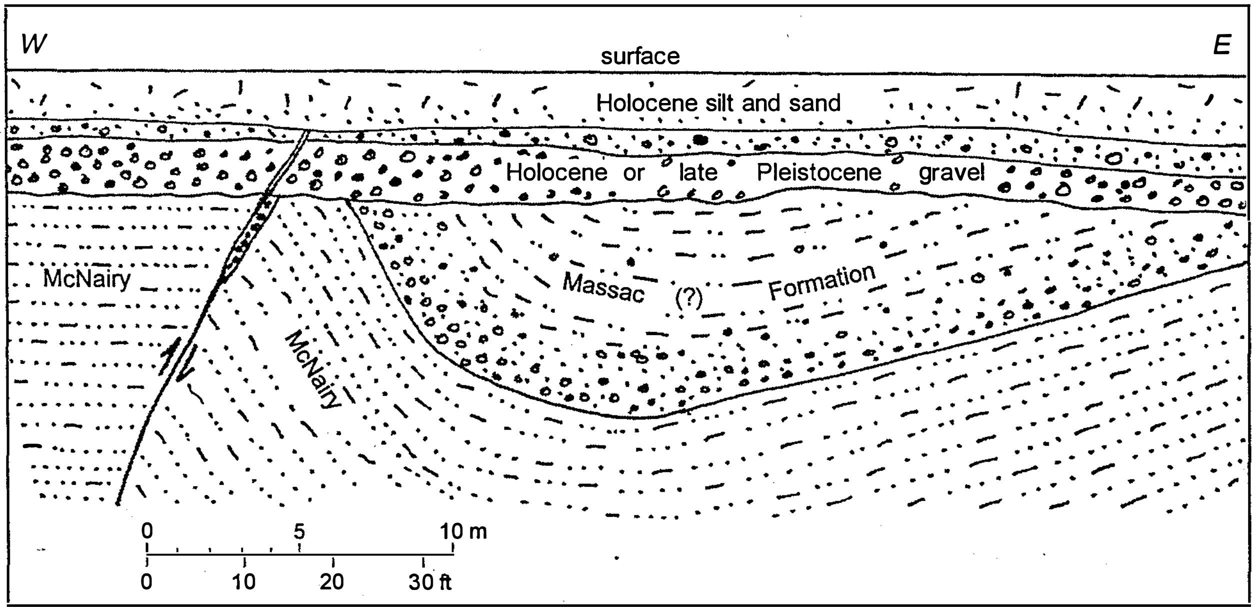


Figure 9. Interpretive cross section of fault H.

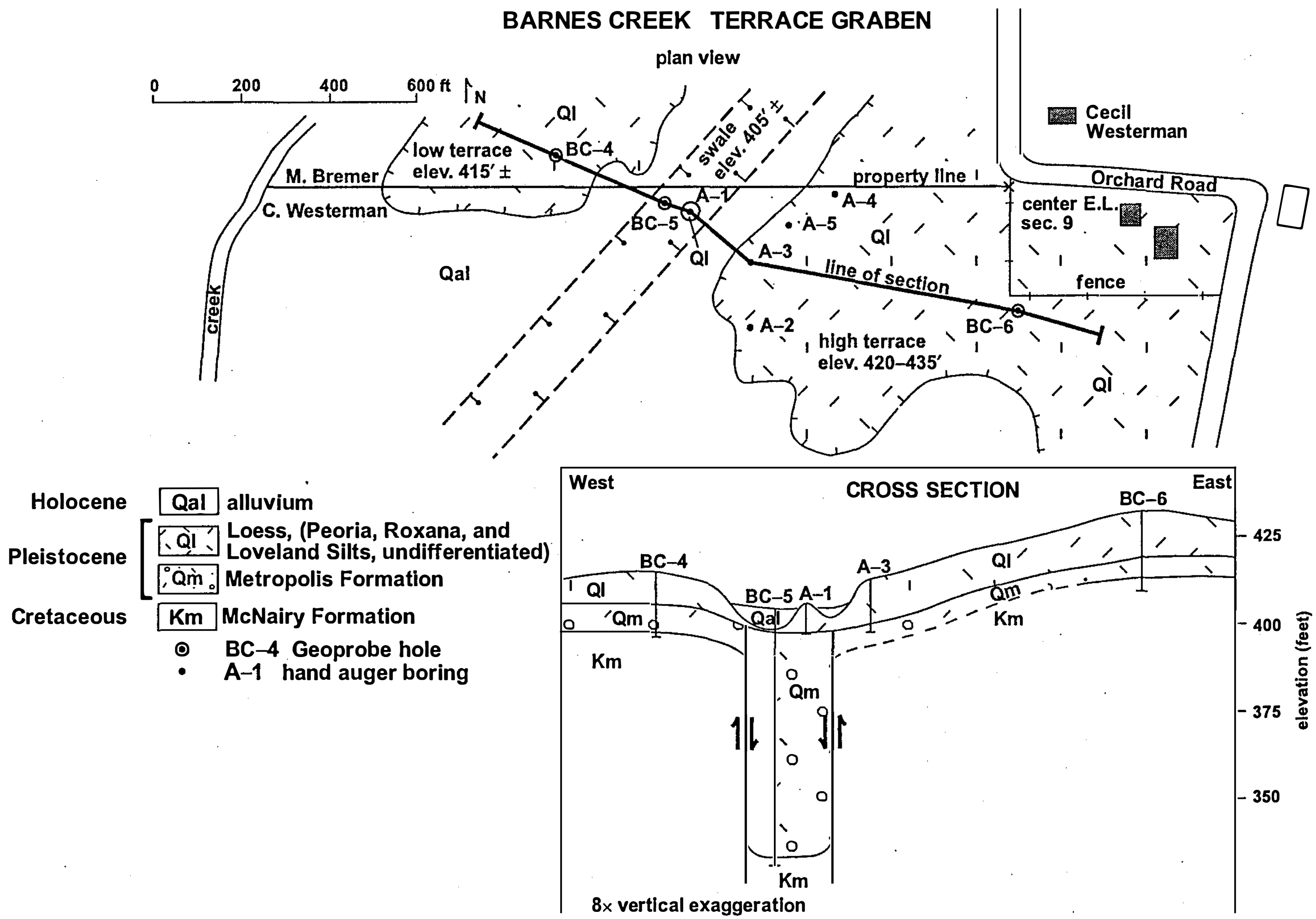


Figure 10. Map and cross section of terrace graben along Barnes Creek.

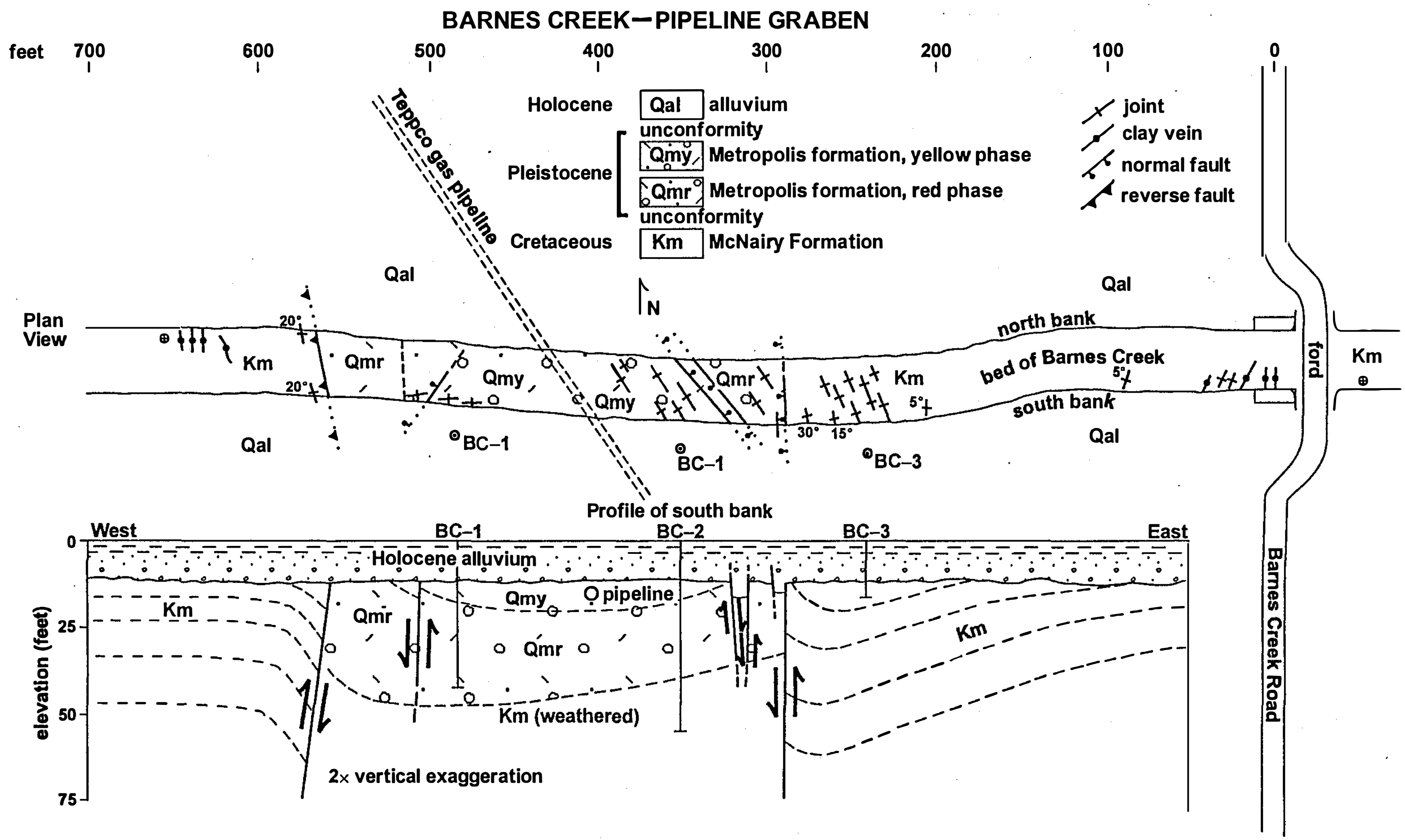


Figure 11. Map and cross section of pipeline graben along Barnes Creek.

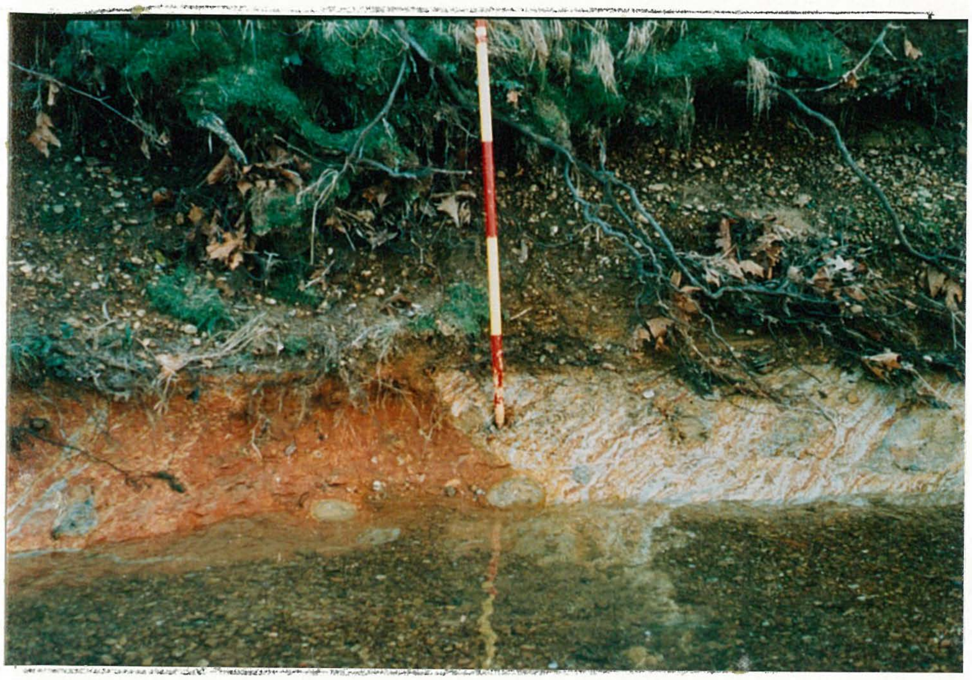


Figure 12. Photograph (looking south) of fault that forms western border of pipeline graben. The west-dipping, high-angle reverse fault displaces white, laminated McNairy Formation on the west against Metropolis formation (red silty sand with large gray burrows) on the east. Note drag fold in McNairy. Graduations on staff 1.0 foot (0.3 m).

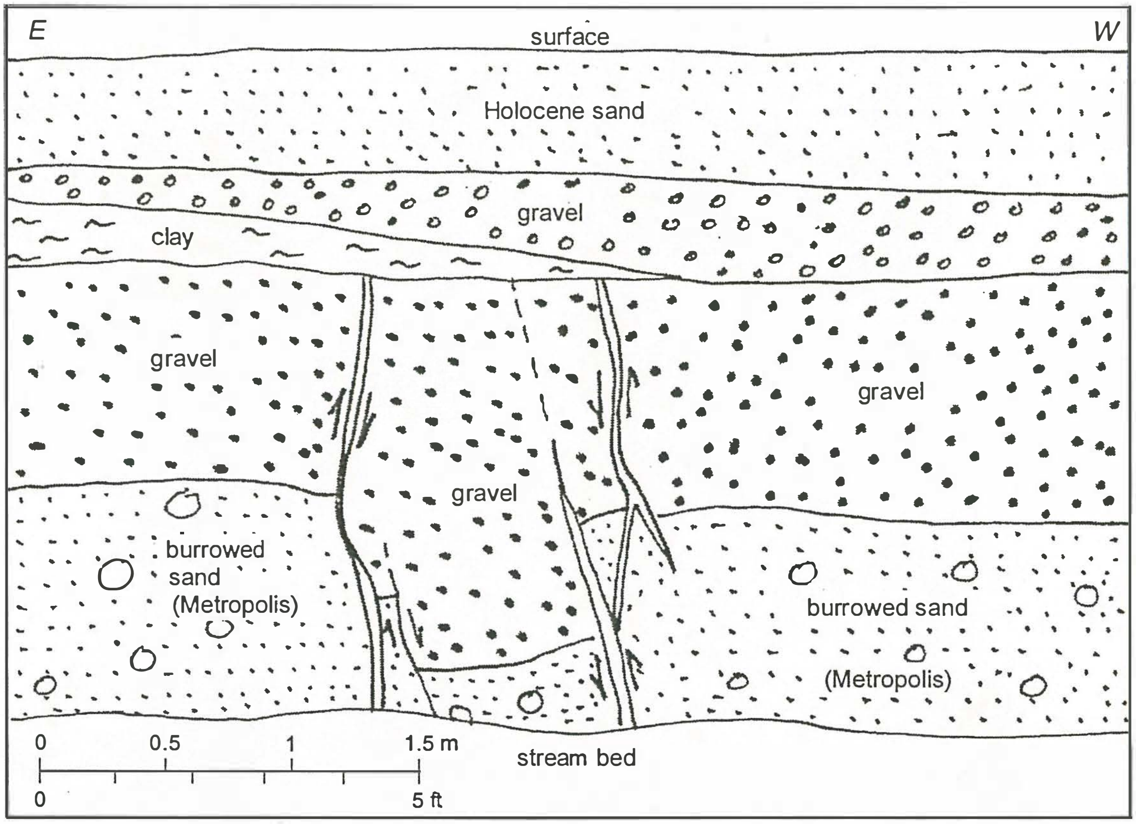


Figure 13. Photograph and sketch of small faults near east border of pipeline graben. Alluvial gravel, younger than Metropolis formation, is downdropped about 1 m between two faults that strike NNW. Younger Holocene sediments are not deformed.

Figure 14. Miniature graben in bank of Barnes Creek just west of, and parallel with terrace graben. Gravel and pebbly silt within graben contains Sangamon geosol; near-horizontal McNairy sand bordering graben lacks geosol features. This structure therefore developed in Wisconsinan, or possibly early Holocene time. Brown Holocene gravel at top of view is not displaced. Note that there is no relative offset of McNairy bedding across the little graben.

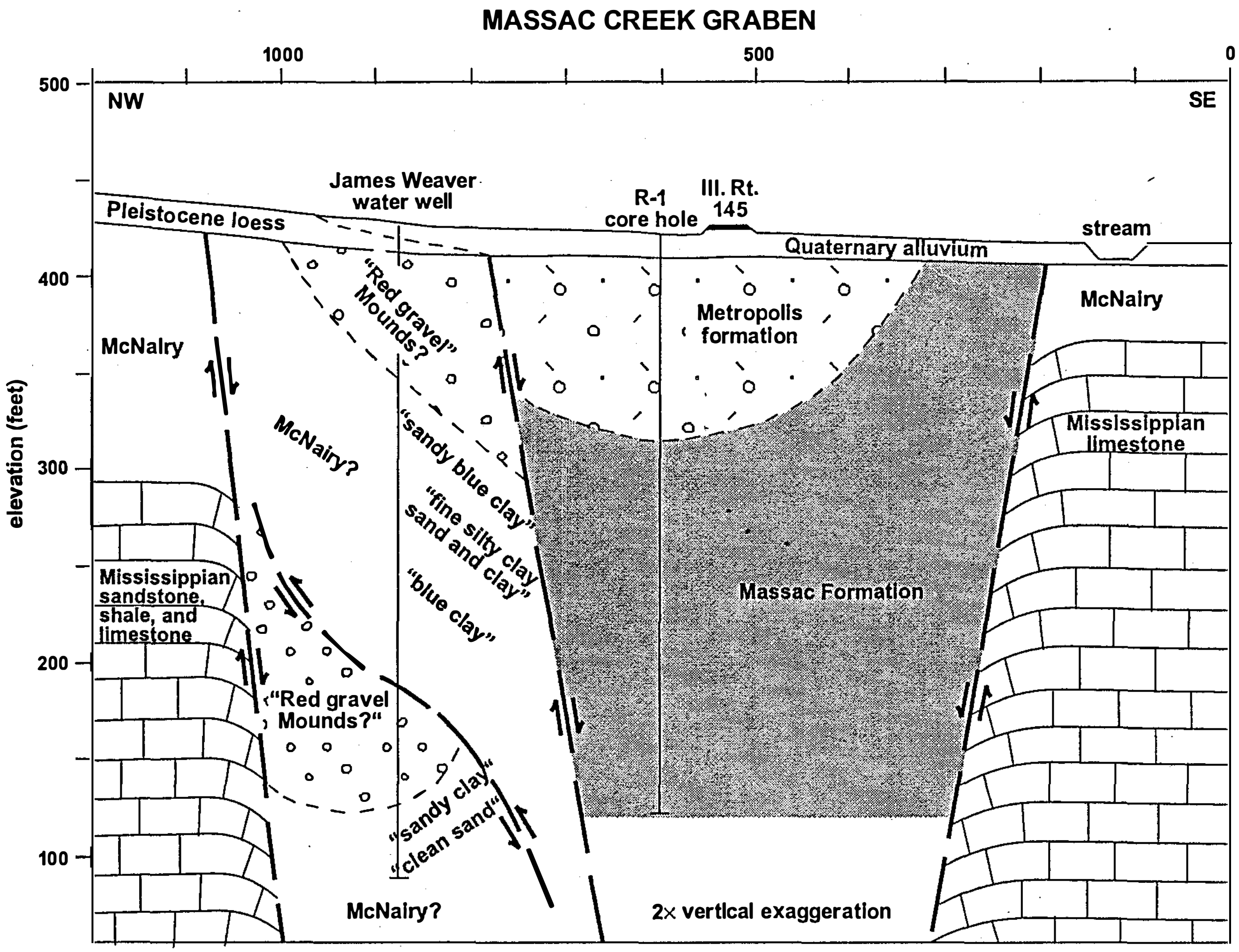


Figure 15. New interpretation of Massac Creek graben, based on ISGS #R-1 Weaver corehole and driller's log of James Weaver's water well. If "red gravel" in water well is Mounds this well penetrated a reverse fault of substantial magnitude.

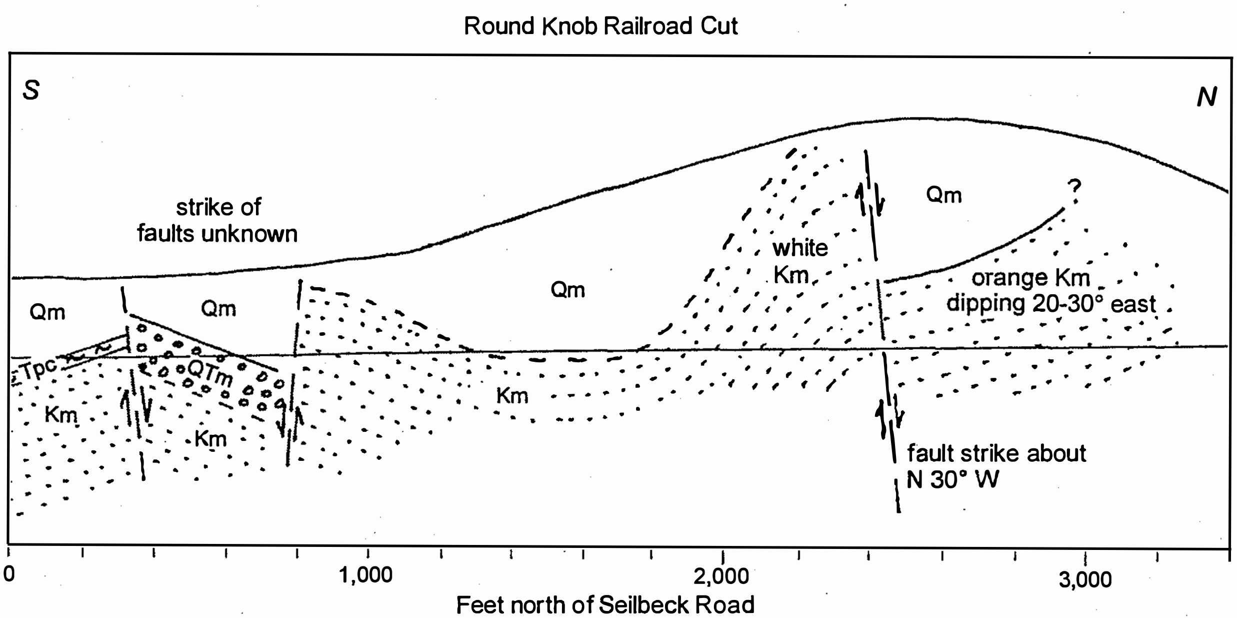


Figure 16. Profile (looking west) of railroad cut south of Round Knob. No faults are exposed, but discordant structural dips and stratigraphy imply that several are present.

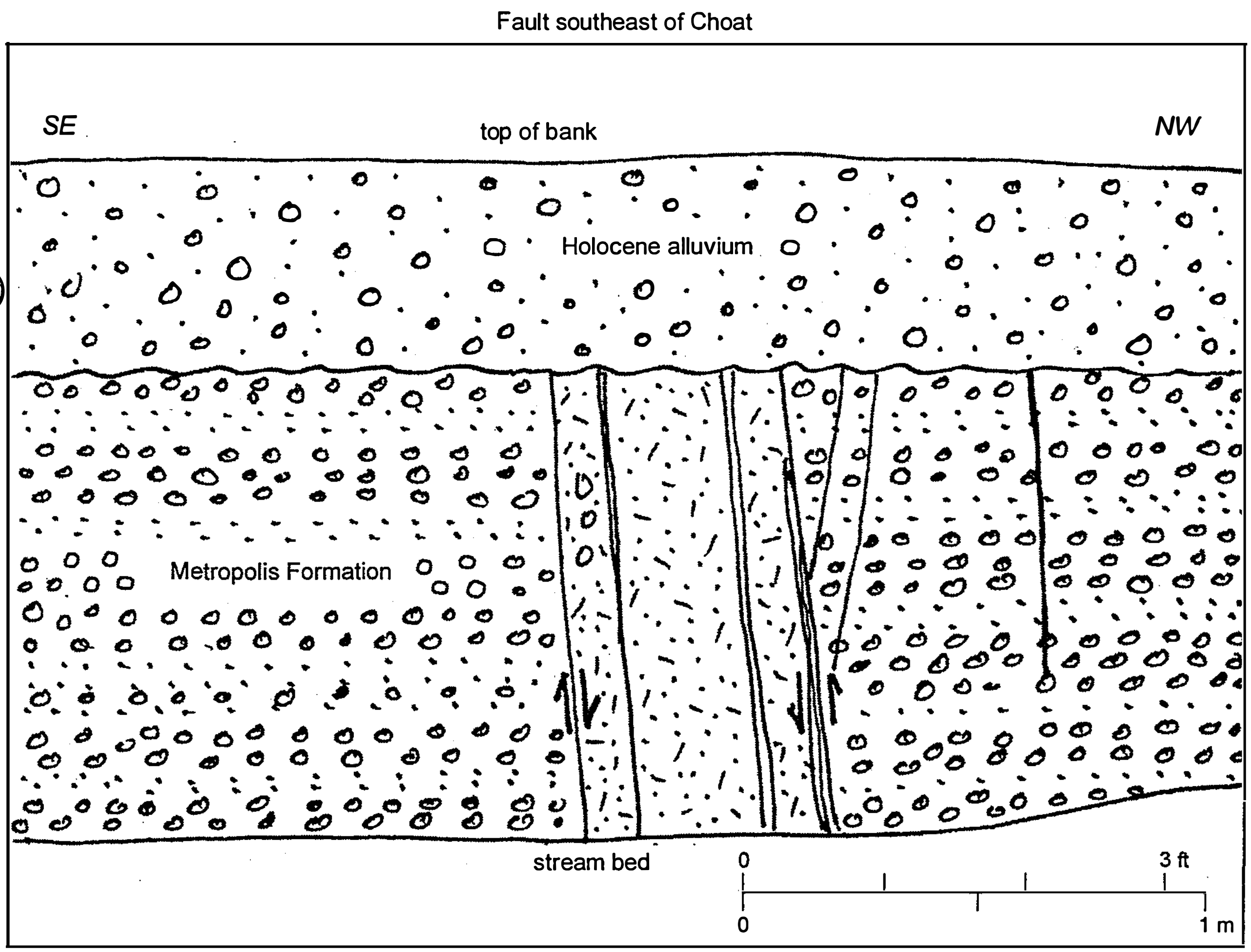


Figure 17. Small fault exposed in streambank southwest of Choat. Faults strike N25°E, parallel with linear ravine. Sandy silt of Metropolis formation is downthrown(?) against gravel of the same formation; structure is truncated by Holocene alluvium. Compare with Barnes Creek miniature graben (Fig. 14).

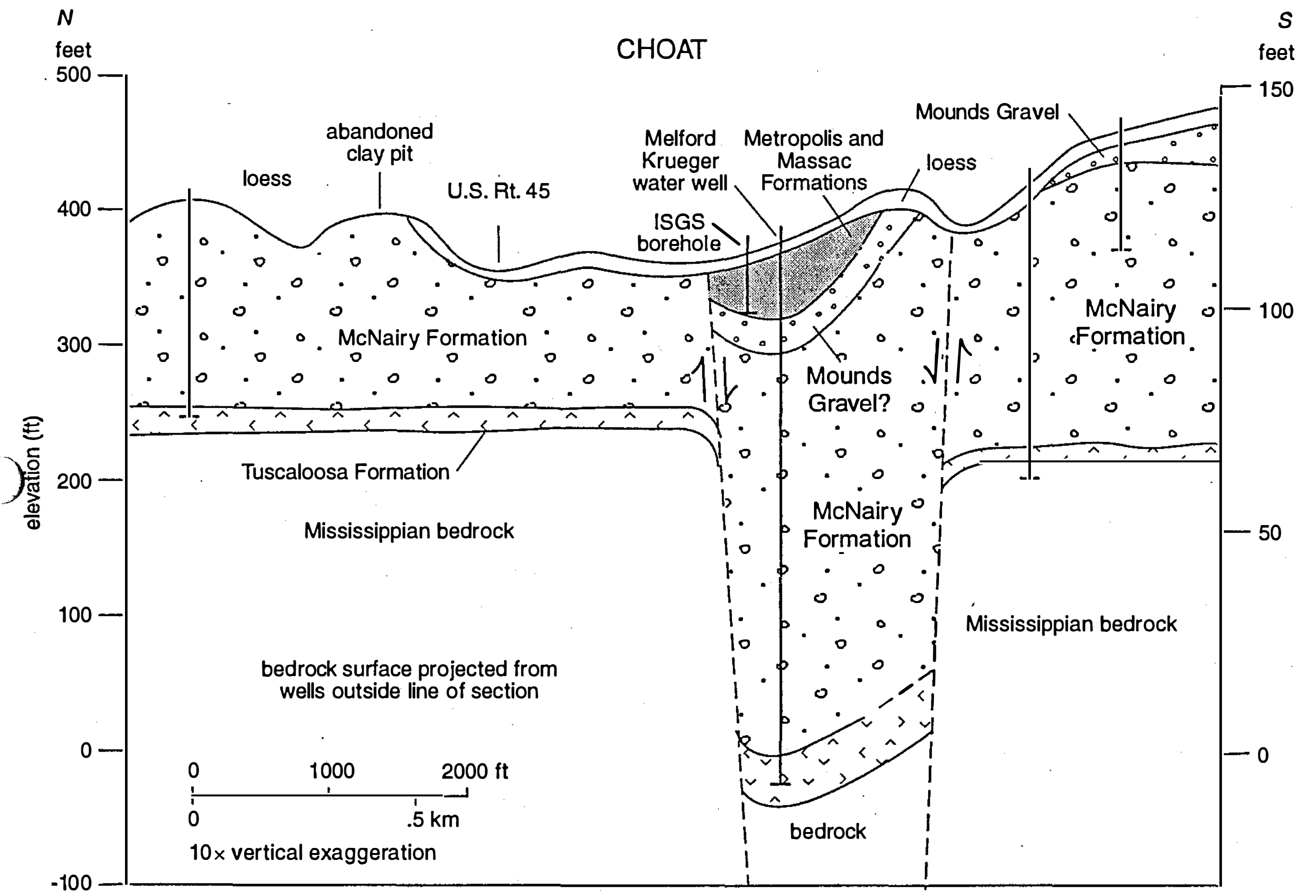


Figure 18. Cross section near Choat, based on outcrop and borehole data. Following the usual pattern, a narrow graben contains downthrown Neogene units.

EAST

WEST

Figure 19. Pair of photos illustrate east and west borders of structure on south side of Kelley railroad cut. Both boundaries appear to be high-angle normal faults that displace Mounds Gravel against the McNairy Formation. The McNairy exhibits sharp drag-folds on both margins of the structure on the south side of the cut. Evidence for faulting on the north side of the cut, however, is less compelling.

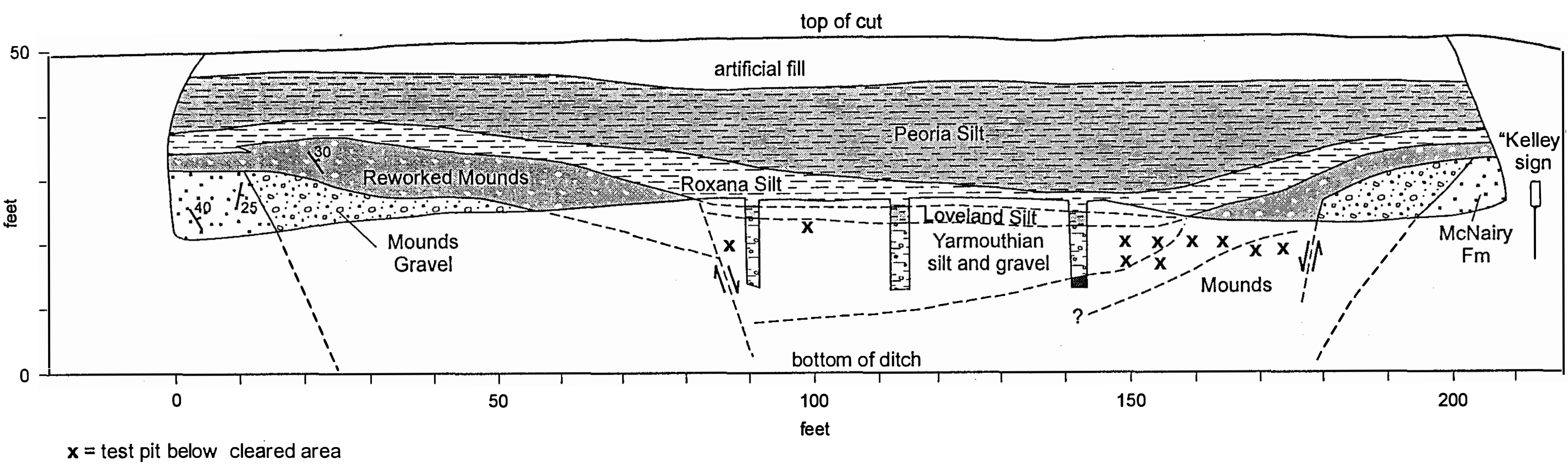


Figure 20. Profile of north side of Kelley railroad cut, as revealed by trenching. Here the boundaries may be tilted stratigraphic contacts rather than faults. The Loveland Silt and underlying Yarmouthian silt are preserved only along the axis of the structure.

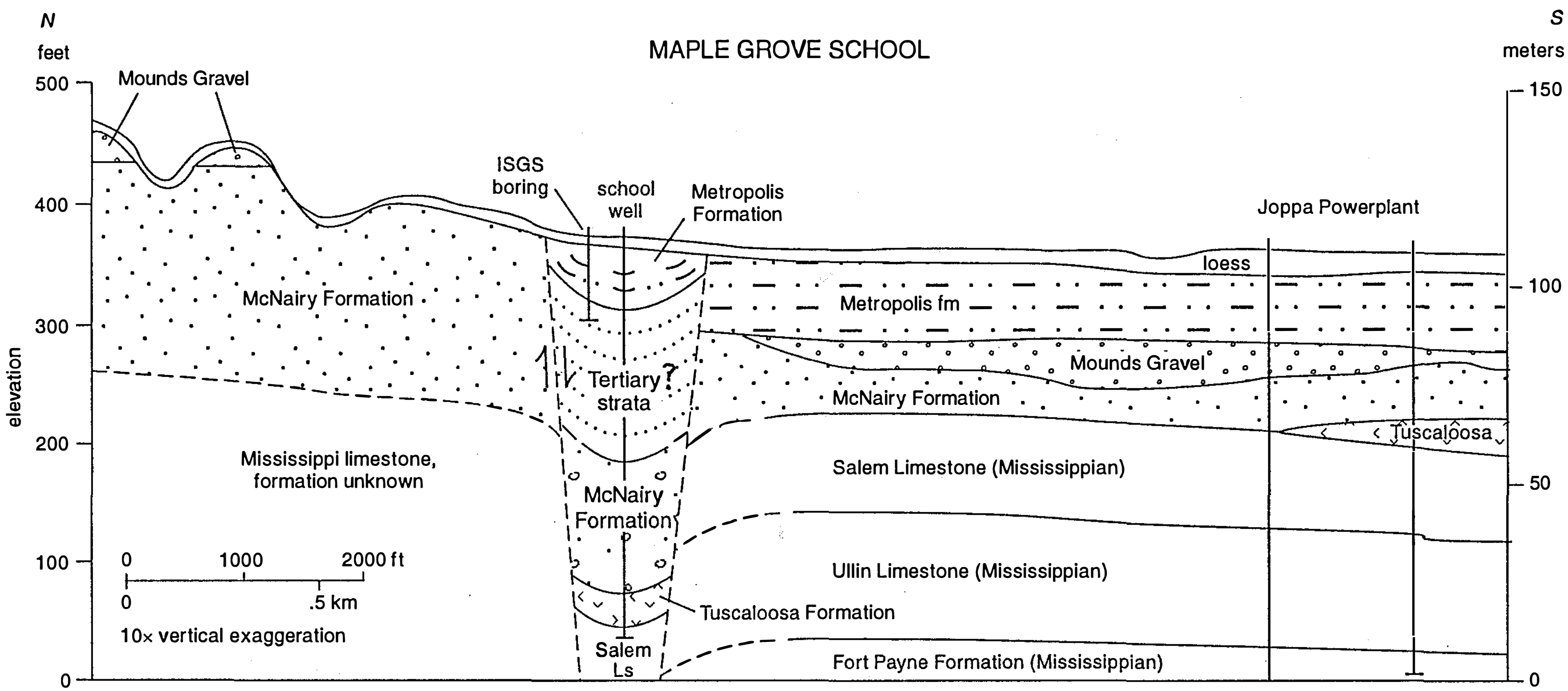


Figure 21. Cross section of graben at Maple Grove School, based on cored ISGS borehole and sample log of school water well.

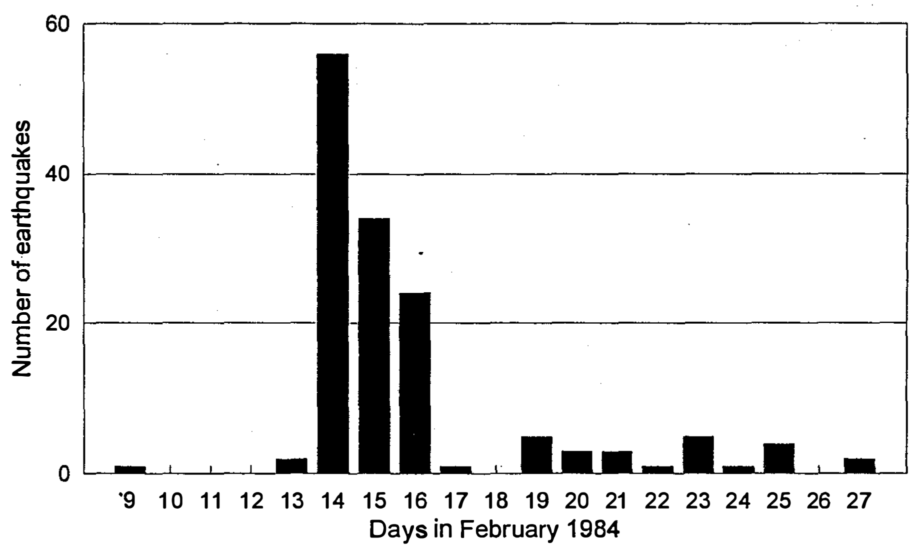
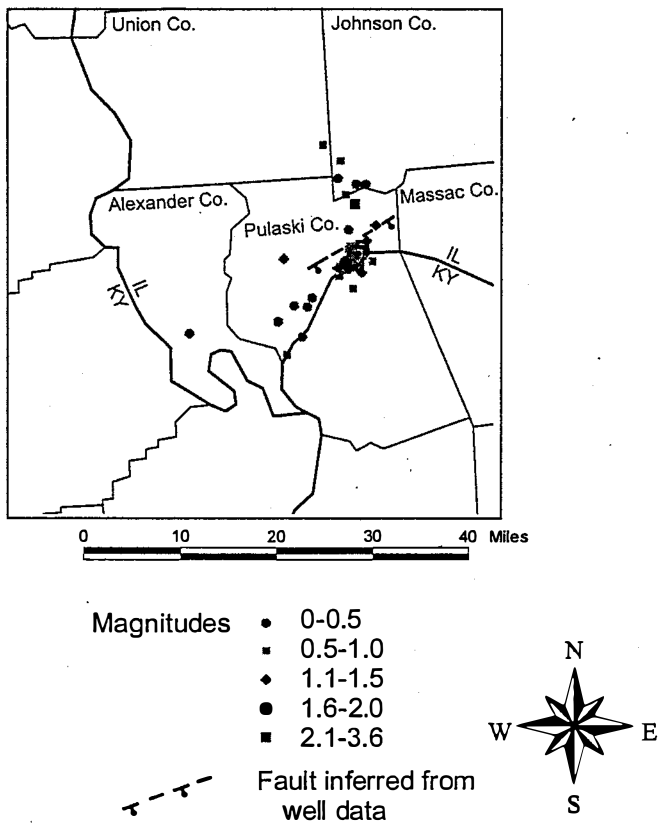


Figure 22. Bar graph (modified from Tim Larson, ISGS) showing number of earthquakes per day for the 1984 earthquake swarm near Olmsted, Illinois.



Figur 23. Map (modified from Tim Larson, ISGS) showing hypocenters (sorted by magnitude) for the 1984 Olmsted earthquake swarm. Fault interpreted from well data also is shown.