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Paleoseismic Characterization of the Penitentiary Fault and its Association with the Commerce Geophysical Lineament, Tamms, Southern Illinois

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FINAL TECHNICAL REPORT

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ABSTRACT

The Commerce geophysical lineament (CGL) is a 600-km-long, 5- to 10-km-wide, northeast-trending magnetic and gravity anomaly that extends from northeastern Arkansas to central Indiana. In southern Illinois, geophysical surveys across the CGL and coincident with the Penitentiary fault image folded and faulted Quaternary sediments similar to multiple studies conducted in Missouri along the 120-km-long Commerce section of the CGL. The Penitentiary fault (PF) is coincident with a strikingly linear northeast-trending, east-facing bluff that separates late Quaternary Cache River Valley (CRV) deposits on the east from Paleozoic upland rocks on the west. This geophysical and paleoseismic research study was designed to further document Quaternary deformation along the PF zone and the CGL for a combined distance of about 110 km between Missouri and Illinois.

At the Tamms site in southern Illinois, we collected closely-spaced boreholes across the Penitentiary fault zone to investigate suspected Quaternary deformation inferred from geologic mapping and geophysical profiles. Geomorphic and geologic mapping revealed primarily a distinct linear hillfront, however little evidence of middle to late Holocene surface-fault rupture. Shear-wave seismic reflection profiles intersecting the bluff line of the Shawnee Hills record coherent reflectors that delineate an unconformable contact between Paleozoic bedrock and Quaternary alluvium, warped and faulted Quaternary deposits, as well as a distinct buried east-facing bedrock scarp aligned with the PF. The PF consists of a 0.5-to 0.75-km-wide zone of

high-angle faults offsetting latest Pleistocene Pearl and Henry Formations and comes within about 10 to 20 m of the ground surface. A geologic profile compiled from closely-spaced boreholes intersecting zones suspected of Quaternary faulting defines multiple vertically separated late Quaternary deposits. Deformed deposits include those of the Henry Formation (older than ~20,000 to 25,000 years old), Equality Formation (17,000 to 12,000 years old) and possibly early Holocene Cahokia Formation (approaching 12,000 years old near the base). The geophysical and geologic profiles support transpressive (?) faulting with cumulative vertical separations ranging from 25 to 5 m using bedrock and late Quaternary strain markers. The youngest age of deformation appears to extend into the late Pleistocene to possible early Holocene. Consistent with geologic and geomorphic mapping, middle to late Holocene Cahokia deposits remain undeformed.

The findings from this study, combined with evidence for late Pleistocene deformation along the surface projection of the CGL from multiple sites in southeast Missouri, suggests the CGL represents a potential seismogenic structure that has been active in the Quaternary. Using empirical relationships and initial earthquake timing information between several CGL sites, we speculate that the CGL may be capable of generating moderate to large magnitude earthquakes (>Mw 7.0 to 7.4; Wells and Coppersmith, 1994). The present-day alignment of diffuse contemporary microseismicity with the Commerce section of the CGL further suggests that northeast-trending structures in the central United States may be accommodating a small component of the tectonic strain in the region with very long recurrence intervals. The preponderance of trench and paleoliquefaction data from the CGL shows that this feature has not been active significantly during the middle to late Holocene Epoch.

TABLE OF CONTENTS

ABSTRACT i
1.0 INTRODUCTION 1
2.0 REGIONAL TECTONIC SETTING 3
Commerce Geophysical Lineament 4
Penitentiary Fault Zone 5
Commerce Fault Zone 6
Contemporary Seismicity 7
3.0 LOCAL GEOLOGIC AND GEOMORPHIC SETTING 8
Quaternary Geology 9
Pearl Formation 10
Henry Formation 10
Equality Formation 11
Cahokia Formation 11
Holocene Deposits 12
Regional Geomorphology 12
4.0 METHODOLOGY 14
Quaternary Geologic and Geomorphic Mapping 14
Seismic Reflection Data Acquisition 14
Borehole Transects 15
Magnetic Susceptibility 16
Age Dating 16
5.0 RESULTS 18
Seismic Reflection Profiles 18
Faulting and Folding Interpreted from Seismic Lines 18
Shallow Geologic Cross Sections 19
Stratigraphic Relations - Cross Section B-B' 20
Stratigraphic Relations Cross Section C-C' 23
Near-Surface Structural Relations 24
6.0 DISCUSSION 27
Penitentiary Fault 27
Late Quaternary Fault Activity along the Commerce Section of CGL 30

7.0 SUMMARY OF FINDINGS 34
8.0 ACKNOWLEDGEMENTS 35
9.0 REFERENCES 36

LIST OF TABLES

Table 1. Radiocarbon Data 43

LIST OF FIGURES

Figure 1 Regional map of the southeastern Missouri showing the surface projection of the Commerce geophysical lineament (horizontal hatch pattern). The pre-Quaternary deposits (light gray fill pattern), Quaternary (white), and main rivers (medium gray) are also shown. Sites of paleoliquefaction (Vaughn, 1994) are shown by triangles. Epicenters of recorded seismicity from 1974 to 1995 are shown by black dots. Epicenters of M4.8 are shown by stars. Letter A shows Commerce section of the CGL. Newport and Junction sections are to the southwest and northeast of map edge, respectively. Modified from Stephenson et al. (1999).

Figure 2 Regional location map of the New Madrid seismic zone and the Commerce geophysical lineament based on latitude and longitude coordinates provided by Hildenbrand (personal communication, 2002) and modified partly from Stephenson et al. (1999). IHF = Idalia Hill fault; CF = Commerce fault; PF= Penitentiary fault. WVFZ = Wabash Valley Fault Zone; FAFC = Flourspar Area Fault Complex and hachured area. Arrows in inset map point to the location of the FAFC, NMSZ, and WVFZ. Star (*) = epicenters of M4.8 earthquakes.

Figure 3 Digital elevation model (DEM) of the Cache River Valley, Shawnee Hills, and Benton Hills in Southern Illinois and Missouri. 30-meter DEM downloaded from National Elevation Dataset (January, 2006). Site of paleoliquefaction from Munson et al. (1997) and, Tuttle and Chester (2001).

Figure 4 Quaternary geomorphic and geologic map of the Tamms area, southern Illinois. Note the four small magnitude earthquakes that occur near the step-over between the Commerce and Penitentiary faults. See Plate 1 of Baldwin et al. (2008) for full-scale version of geologic mapping.

Figure 5 Uninterrupted migrated depth-converted seismic-reflection profile of Odum et al. (2002). Odum et al. (2002) interpret the reflective package observed across the profile to be predominantly Paleozoic with small amount of overlying Quaternary deposits. The profile shows substantial folding and faulting. Much of the deformation coincides with the projections of topographic bluff fronts (suspected fault-line scarps) and the projected trace of the Commerce fault. Faults F1 to F4 of Odum et al. (2002) are the focus of this investigation.

Figure 6 Schematic showing stratigraphic relationship between major geologic units in the map area. (See Plate 1 of Baldwin et al., 2008 for detailed map unit descriptions.)

Figure 7 Geologic cross section A-A' across the Penitentiary fault and Shawnee Hills range front. Note the buried east-facing scarp coincident with the Penitentiary fault and imaged Quaternary faulting. At the base of well numbers 7500 and 8300 only chert was noted on driller's logs. These descriptions are either fluvial chert-rich gravels or bedrock chips.

Figure 8 Local geologic map with borehole locations.

Figure 9 Shear-wave seismic reflection survey of Tamms-1 along Old Diswood Road. Interpreted profile shows the top of bedrock (Paleozoic bedrock), Late Pleistocene gravels, and Holocene to Late Pleistocene alluvium, and interpreted faults. Faults are labeled with integers and individual fault splays are labeled with letters.

Figure 10 Shear-wave seismic reflection survey Tamms-2 along Newell Road. Interpreted profile shows bedrock adjacent to an area of poor reflector quality interpreted as faulted bedrock which coincides with a mapped bedrock fault (Figure 4). The bedrock (Unit 1) contact with Late Pleistocene gravels (Unit 2) is not resolvable.

Figure 11 Cross section B-B' across Penitentiary fault zone at edge of Shawnee Hills escarpment.

Figure 12 Cross section C-C' along Old Diswood Road in Tamms, Illinois, in the west central part of the Cache River Valley.

Figure 13 Magnetic susceptibility plots vs. depth with approximate elevations and correlated stratigraphy. Surface elevations are approximate and horizontal distances are schematic.

Figure 14 Preliminary compilation of event timing information for faults aligned with the Commerce geophysical lineament between Missouri and Illinois. Dashed lines are "permissible events".

1.0 INTRODUCTION

Considerable attention over the last two decades has been focused on assessing the recurrence of large magnitude earthquakes and paleoseismic history of the New Madrid seismic zone of the Central United States. This study expands the regional coverage of paleoseismic investigations outside of the New Madrid seismic zone (NMSZ) with the intent to identify and assess other possible seismic sources, such as the Commerce geophysical lineament (CGL), and to evaluate the spatial and temporal characteristics of prehistoric earthquakes along poorly characterized structures in the central United States. This paper presents the results of a recent detailed fault and paleoseismic investigation in southern Illinois of the Penitentiary fault that coincides with the CGL, a geophysical feature with evidence of late Pleistocene to Holocene deformation along the western and northern margin of the Mississippi embayment.

The CGL is a 600-km-long (373 mi), 5- to 10-km-wide (3.1 to 6.2 mi) northeast-trending gravity and aeromagnetic anomaly that trends subparallel to and west of the Reelfoot rift and extends from northeast Arkansas to central Indiana (Figure 1) (Langenheim and Hildenbrand, 1997). The Tamms area is located along the 150-km-long (93 mi) Commerce section of the CGL within the northwestern Mississippi embayment about 75 to 80 kilometers (47 to 48 mi) northwest of the active New Madrid seismic zone (NMSZ) (Figure 1). Recent geologic, geomorphic and geophysical studies performed along the CGL in southeastern Missouri provide direct and indirect evidence indicative of late Quaternary activity along faults coincident with the CGL (Figure 2). This evidence includes: (1) anomalous west-flowing drainages on Crowley's Ridge (Cox, 1988; Fischer-Boyd and Schumm, 1995) and the Bloomfield and Benton Hills; (2) displacement of late-Tertiary and Pleistocene to Holocene deposits (Groshkopf, 1955; Satterfield and Ward, 1978; Thompson, 1981; Harrison et al., 1999; Harrison et al., 2002; Baldwin et al., 2006) along northeast-striking faults that are consistent with the present-day stress field (Zoback, 1992); (3) paleoliquefaction features within the Western Lowlands that overlie the CGL (Figure 1; Vaughn, 1991; 1992; 1994; and Vaughn et al., 2002); (4) presence of diffuse microseismicity consisting of low to moderate magnitude earthquakes spatially associated with the CGL (Harrison and Schultz, 1994; Langenheim and Hildenbrand, 1997; Hildenbrand and Ravat, 1997); (5) geophysical evidence of about 20 meters (65.6 ft) of vertical separation of the Paleozoic/Cretaceous boundary, as well as poorly constrained Tertiary-Quaternary deformation coincident with the surface traces of previously mapped faults in the

Bloomfield and Benton Hills (Stephenson et al., 1999); and (6) a prominent tonal lineament developed in late Wisconsin braided stream deposits that aligns partly with the Commerce and Idalia Hill faults (Heyl and McKeown, 1978). Furthermore, similar geologic, geophysical, seismologic, and paleoliquefaction data collected in Illinois and Indiana provide support for Quaternary active structures spatially coincident with the CGL (Odum, et al., 2002, McBride et al., 2002).

Combined, this body of evidence strongly implies that previously mapped northeast-striking faults that overlie the surface projection of the CGL in southeast Missouri and Illinois, but are outside of the active NMSZ, represent poorly characterized seismogenic structures that are capable of generating moderate to large magnitude earthquakes. This study focuses on the 120-km-long (75 mi) Commerce section of the CGL and develops initial information on earthquake timing, recurrence and earthquake magnitude information on the northern part of this section. Multiple lines of evidence support the interpretation that northeast-striking faults in southeast Missouri and coincident with the CGL were active up to at least the Late Pleistocene and early Holocene (Vaughn, 1994; Baldwin et al., 2006), and possibly into the middle to late Holocene (Harrison et al., 1999). This study shows that late Quaternary faulting along the CGL also can be traced into southern Illinois, north of the NMSZ.

2.0 REGIONAL TECTONIC SETTING

The CGL represents a 600-km-long (373 mi) series of Early Cambrian to possibly Precambrian mafic dike intrusions emplaced along pre-existing or coeval faults (intrusions accompanying origin of the Reelfoot rift) between Arkansas and southern Illinois (Langenheim and Hildenbrand, 1997). The southern part of the CGL coincides with the northwest margin of the Reelfoot rift, as identified by gravity and aeromagnetic data. Faulting along the CGL appears to be complex and long-lived, and includes both dip-slip and strike-slip faulting. Hildenbrand et al., (2002) speculate that the Commerce geophysical lineament evolved in the Mesoproterozic (1.1 to 1.5 Ga) as a major cratonic rheological boundary that was reactivated during varying stress regimes throughout its history.

The Tamms site lies within the northwest margin of the Reelfoot rift, west-southwest of the Fluospar Area Fault Complex and the Rough Creek graben, and south of the Wabash Valley and southernmost part of the Illinois Basin (Figure 2). These major basin structures intersect to the east-northeast of Tamms near Metropolis, Illinois. The northeast-trending Reelfoot rift includes the active New Madrid seismic zone (NMSZ) that lies southeast of the site. Faults within the Wabash Valley fault zone terminate at or near the intersection of the northern margin of the relatively aseismic Rough Creek graben northeast of the Cache Valley, and thus do not comprise this part of the CGL (Hildenbrand and Ravat, 1997; Wheeler, 1997) (Figure 2).

Within the intersection between the Reelfoot rift and Rough Creek graben lies an approximately 40-km-wide (25 mi) zone of steeply dipping, northeast-striking bedrock faults that comprise the Fluorspar Area fault complex (FAFC) (Kolata and Nelson, 1991) (Figure 2). The FAFC was active during the latest Proterozoic to early Cambrian (several hundred million years ago), coincident with the formation of the northeast-striking faults associated with the Reelfoot rift. Northeast-striking faults of the FAFC exhibit evidence of multiple episodes of dip-slip reactivation (e.g., late Pennsylvanian and Permian), as well as strike-slip movement that extended into the late Quaternary (Nelson et al., 1999; Woolery et al., 2009). This fault system lies directly east of Tamms (Figure 2). Northeast-striking faults associated with the CGL, such as the Idalia Hills-Commerce-Penitentiary faults, located directly west to southwest of the FAFC also exhibit late Quaternary deformation. This is consistent with the hypothesis that multiple

structures lying outside of the NMSZ but within ancient rifts have been active in the recent past, and provide potential uncharacterized seismic source zones.

Commerce Geophysical Lineament

The CGL has been differentiated into the Newport, Commerce and Junction sections on the basis of variations in gravity, magnetic and geologic characteristics (Langenheim and Hildenbrand, 1997). The Commerce and Penitentiary faults, as well as the study site, lie along the Commerce section of the CGL in southeastern Missouri and southern Illinois. Of the three sections, the Commerce section exhibits the most prominent gravity and magnetic anomalies. It extends from the Arkansas-Missouri border across Thebes Gap and into southern Illinois (Figures 1 and 3). The northern part of the Commerce section is associated with the mapped trace of the Commerce fault, near Commerce, Missouri, where neotectonic studies provide evidence of Pleistocene and Holocene deformation (Figure 1; Harrison and Schultz, 1994; Harrison et al., 1999; Harrison et al., 2002). The southern part of Commerce section coincides with a well-defined photo-lineament and topographic escarpment along the southeastern margins of the Benton and Bloomfield Hills (Heyl and McKeown, 1978) and the Idalia Hill fault, which offsets late Quaternary deposits (Figure 1; Stephenson et al., 1999; Palmer et al., 1997; Baldwin et al., 2006). Northeast of the Benton Hills, within southern Illinois, the Commerce section of the CGL aligns with both the Commerce fault and Penitentiary fault, which recently have been interpreted as Quaternary active (Odum et al., 2002) (Figure 3).

Quaternary active faults along the CGL are characterized as transpressional strike-slip structures using a number of geologic and seismologic observations: (1) the style and pattern of neotectonic and older deformation collected from trench, mapping, and geophysical studies in the Thebes Gap area is consistent with strike-slip faulting along near-vertical structures (Harrison et al., 1999); (2) near-vertical faults and complex flower-structures are observed in seismic data at multiple locations along the CGL (Stephenson et al., 1999; Harrison et al., 1999; and Baldwin et al., 2006); (3) the regional northeast strike of the faulting is favorably oriented for right lateral transpressive slip in the present north-northeast-directed maximum horizontal stress field (Zoback, 1992); and (4) focal mechanism analysis of a mb 4.7 earthquake (September 26, 1990) near the Commerce fault is consistent with primarily right-lateral strike slip displacement.

Penitentiary Fault Zone

The northeast-striking, southeast-side down Penitentiary fault zone was hypothesized first by Devera and Follmer (in prep) based on the distinct linear eastern range front of the Shawnee Hills, near Tamms, Illinois (Figure 4), and later confirmed by geophysical surveys (Odum et al., 2002; Baldwin et al., 2008). The Penitentiary fault is generally obscured by thick Quaternary sediments that abut the Shawnee Hills and by younger Holocene alluvium derived from east-flowing creeks. From field reconnaissance and review of previous bedrock maps, numerous minor northeast-striking faults are mapped in quarries along the western margin of the Shawnee Hills between Olive Branch and Tatumville as well as in road cuts in the Shawnee Hills. These exposed bedrock faults exhibit tens of feet of minor apparent vertical separation. A single northeast-striking southeast-side down fault offsetting Devonian Clear Creek Formation and St. Laurent/Grand Tower Formations bedrock is coincident with the mapped trace of the Penitentiary fault zone at the northwest end of the Cache Valley, where the valley makes an abrupt change to the east (Figure 4) (Devera et al., 1994).

Odum et al. (2002) previously collected seismic reflection data across the Penitentiary fault zone and the eastern margin of the Shawnee Hills (Figure 4). Odum et al. (2002) imaged numerous faults, including the Commerce and Penitentiary faults, displacing Paleozoic bedrock reflectors, and the Quaternary-Paleozoic interface. Several of the imaged faults (Faults F1 to F3) project upsection to the Quaternary-Paleozoic interface, with Fault F3 vertically displacing the Quaternary-Paleozoic reflector about 5 to 10 meters (16 to 33 ft) along trend with the near-linear N35°E-trending bluff of the Shawnee Hills and the Penitentiary fault (Figure 5). Fault F3 comes within 25 meters (82 ft) of the ground surface and is interpreted as the Penitentiary fault (Odum et al., 2002). Collectively, many of these faults define a broad fault zone with Fault F3 representing the primary fault strand. Fault F2 forms an apparent synform and/or “flower structure” that is consistent with regional topography, and the interpreted “transpressive” pattern of faulting and folding observed elsewhere (Qulin Ridge, Holly Ridge and Benton Hills) on Quaternary active faults aligned with the CGL (Baldwin et al., in 2006) (Figure 2).

Paleo-liquefaction reconnaissances of drainages in the Cache Valley have also identified numerous liquefaction-related features within close proximity to the Commerce geophysical lineament (Tuttle et al., 1998; Tuttle and Chester, 2001; Munson et al., 1997) (Figure 2, 3, and

4). Tuttle and Chester (2001) searched 70 kilometers (43.5 mi) of river and ditch cutbanks, quarries, and terraces mapping earthquake-induced paleoliquefaction features in the Cache River Valley. Along the Cache River south of Tamms, six sheeted clastic dikes were found at four sites ranging from 1 to 9 centimeters (0.39 to 3.5 in) wide occurring within the Cahokia Formation. Tuttle and Chester (2001) consider the possibility that two generations of liquefaction are recorded at these sites, with the youngest occurring after A.D. 1020. The origin of these dikes is unknown, however, they could have formed as a result of earthquakes in the New Madrid seismic zone (Tuttle and Chester, 2001), or an unknown seismic source such as the CGL or other structures in southern Missouri, Illinois and western Kentucky.

Commerce Fault Zone

The Commerce fault is a northeast-striking, Quaternary strike-slip fault coincident with the CGL and merges with the Penitentiary fault (Figure 3). The fault is geomorphically expressed in part as a prominent geomorphic lineament (similar to the Penitentiary fault) along the southern escarpment of the Benton Hills and is roughly parallel with the Idalia fault in Missouri (Harrison and Schultz; 1994; Baldwin et al., 2006). The fault exposures are generally poor, but evidence for Quaternary fault activity is well documented (Stewart and McManamy, 1944; Harrison and Schultz, 1994; Harrison et al., 1999). Geophysical surveys in the Benton Hills (Anderson, 1997), and Bloomfield Hills of the Idalia Hill fault (Stephenson et al., 1999; Baldwin et al., 2006) image extensive faulting aligned with the CGL, and the Commerce-Idalia Hill faults. (Figures 2 and 4). Geophysical profiles by Odum et al. (2002) in southern Illinois also link the Commerce fault to interpreted faults in high-resolution seismic reflection surveys that offset Quaternary deposits.

The Commerce fault is mapped in bedrock along a road cut on Olive Branch Road west of Tamms as a near vertical 5-m-wide zone of brecciated and tilted Paleozoic Grassy Knob Chert. The northeasterly strike of the bedrock shears and minor fault displacement (3-6 meters or 9.8 to 19. 7 ft) interpreted from bedrock marker horizons suggest that this fault: (1) is a secondary trace; (2) is dying out in a northeasterly direction and away from the Benton Hills, and (3) transfers slip easterly to the Penitentiary fault across a narrow (0.75 km wide) right-step in the valleys between Wolf and Sandy Creeks (Figure 4; Devera and Follmer, in-prep).

Contemporary Seismicity

The northernmost arm of northeast-trending contemporary microseismicity associated with the NMSZ is located about 50 km (31 mi) southeast of Tamms. The two weak parallel bands of northeast-trending microseismicity that are aligned with the northern arm of the NMSZ and traverse southern Illinois and western Kentucky lie about 25 km (15.5 mi) east of Tamms, and do not intersect the CGL (Figure 2). The GCL is characterized by a diffuse pattern of contemporary seismicity between Arkansas and southern Illinois (Harrison and Schultz, 1994; Langenheim and Hildenbrand, 1997). Focal mechanisms of 16 earthquakes that occurred between 1963 and 1990 are consistent with predominantly strike-slip and reverse modes of faulting along the entire length of the CGL. At least two M4.8 earthquakes with predominantly strike-slip components have occurred near or on the Commerce section of the CGL within this 17-year period (Figure 1). Locally, historical earthquakes as large as M5.0 are estimated to have occurred in the Tamms, Illinois area. In 1965, a M5.0 earthquake centered near Tamms caused considerable damage to buildings (cracked walls) and toppling of chimneys, and was accompanied by six aftershocks. Investigators have shown that some of the focal mechanisms of the historically instrumented seismicity are consistent with northeast-striking faults (Harrison and Schultz, 1994), and others have indicated that a few of the focal mechanisms are consistent with northwest-trending structures (Zoback, 1992). Further northeast, near Vincennes, Indiana, where it is hypothesized that the CGL forms a restraining left-step, the CGL is believed to be associated with the location of several large prehistoric earthquakes on the basis of a deflection in the Wabash River and a left-step in the CGL magnetic anomaly (McNulty and Obermeier, 1999).

3.0 LOCAL GEOLOGIC AND GEOMORPHIC SETTING

The regional landforms of this part of the central United States are dominated by numerous large fluvial systems within broad alluvial valleys (Ohio, Cache, Obion and Tennessee Rivers) that have been coursing toward the Mississippi embayment throughout much of the Pleistocene Epoch (Saucier, 1996; Frye et al., 1962; Fisk, 1944; Esling et al., 1989; Autin et al., 1991; Blum et al., 2000). Cache River Valley intersects southern Illinois as a 1.5- to 4-mi-wide (2.4 to 6.4 km) valley that extends from the northeast at Ropers Bluff to Cairo, Illinois, in the southwest, where it intersects the Mississippi River (Figure 3). The northern margin of the valley is often steep and bounded by the Shawnee Hills (elevations average about 60 meters above the adjacent alluvial lowlands) composed of Paleozoic rocks. The southern valley margin is defined by low relief slopes and more easily erodible unconsolidated Cretaceous and Tertiary sediments of the upper Mississippi embayment.

The Shawnee Hills are composed of gently northeast dipping Paleozoic bedrock (Devonian and Silurian carbonate and chert) mantled by Pleistocene loess (Devera et al. 1994; Nelson et al, 1999; Devera and Follmer, in prep; Nelson and Williams, 2004) (Figure 4). Near the west side of the valley, multiple road cuts and quarries expose white to very light gray Grassy Knob Chert with gray to orange staining. Mapped bedrock faults within the Shawnee Hills are generally northeast-striking, short lengths (1-2 km), and exhibit relatively minor displacement (10-30 meters). Within the study area, the Commerce and Penitentiary faults are the exceptions with strike-lengths of several to tens of miles based on regional mapping and interpretation of geophysical data (Baldwin et al., 2008; Odum et al. 2002, Devera et al., 1994).

The origin of the Cache Valley has been the focus of many decades of Quaternary research. The valley is believed to have formed when the paleo-Ohio River flowed through the area in the Pleistocene Epoch (during the Illinoin and waning stages of Wisconian glaciations). The ancestral Ohio River flowed west-southwest through the Cache Valley up to about 25,000 years ago transporting coarse- to fine-grained outwash deposits from Wisconsin glaciers located to the north-northeast (Fisk, 1944; Esling et al., 1989) (Figure 1). The maximum extent of the continental glaciers reached southerly to about Carbondale, Illinois located approximately 60 km north of Tamms, Illinois. The present-day Ohio River has occupied its present course since about 14,000 to 17,000 years ago, at or near the time of the Maumee Flood on the Tennessee

River (Wayne and Zumberge, 1965; Olive, 1980; Saucier, 1974; Royall et al., 1991), or possibly slightly later between 11 and 10.5 ka (Blum et al., 2000) based on recent Quaternary analysis in the upper Mississippi Embayment. Thus the lowlands of the Cache Valley consist of Pleistocene braided stream channel deposits derived from the ancestral Ohio River, alluvial fan deposits shed from the adjacent highlands, and Holocene alluvium and slack-water deposits that represent the waning stages of glaciations and migration of the Ohio River (Figure 4; Esling et al., 1989; Nelson et al., 1999; Devera and Follmer, in prep).

Quaternary Geology

The middle Pleistocene and younger geologic history of the Cache Valley is dominated by the effects of the Illinoian and Wisconsinan glacial periods. During these times, the Ohio River flowed through the Cache Valley and deposited coarse-grained glacial outwash as the Pearl and Henry Formations (Esling et al., 1989, Nelson et al., 1999, Nelson and Williams, 2004). During periods of high discharge, the Cache Valley was overwhelmed with sediment and tributary valleys and portions of the main valley often blocked or dammed forming slackwater lakes. Under these quiet-water conditions the finer-grained Equality Formation was deposited (Esling et al., 1989; Lineback, 1979; Shaw, 1911; William and Frye, 1970; Ray, 1963). Loess deposition accompanied each glacial advance and retreat north of Tamms and blankets the uplands surrounding the Cache Valley (Follmer, 1996; Grimley et al., 2003; Nelson and Williams, 2004). Regional models interpret the loess deposits as follows: Loveland Silt (180 to >125 ka), Roxana Silt (55 to 28 ka), and Peoria Loess (25 to 10 ka) (Curry and Follmer, 1992; Leigh, 1994; Follmer, 1996; Forman and Pierson, 2002; Bettis III, et al.; 2003 Grimley et al., 2003). Locally near the site, loess deposits are reworked as fluvial and alluvial deposits filling the Cache Valley, and typically are associated with the Equality and Cahokia Formations. The depth to bedrock in many places of the Cache Valley is about 180 to 200 feet (55 to 61 m) deep with the deepest fluvial deposits consisting of mostly sand and gravel of the Pearl and Henry Formations. A schematic section of the primary geologic units in the study area is provided in Figure 6.

Between 25 ka and 8 ka years ago, the Ohio River abandoned the Cache Valley and established its present course to the east (Esling et al., 1989). Then, local streams and overflow from the Ohio River reworked the glacial outwash and loess, depositing the Cahokia

Formation (Elsing et al., 1989). Holocene-age streams were sometimes controlled by the ridge and swale topography of the glacial outwash and established well-developed meander belts within the swales. Holocene alluvial fans have formed at the mouths of the tributary valleys that join the Cache Valley and intersect the eastern margin of the Shawnee Hills and Penitentiary fault zone. See Figures 6 and 7 for the regional and local stratigraphic relationships. The fundamental stratigraphic sequence and marker units used to assess late Quaternary faulting near Tamms include the formations and deposits described below.

Pearl Formation

The Pearl Formation underlies much of the Cache Valley and is composed of sand, subrounded to well-rounded gravel up to 3 inches (7.6 cm) in diameter, and sandy clay in a single, upward-fining sequence (Nelson et al., 1999). Chert pebbles dominate with exotic quartz, metamorphic, and igneous clasts making up 10-20% of the gravel content and suggesting a distal source from the north. On the basis of driller's logs for the central Cache Valley, the Pearl Formation is up to ~15 meters thick (49 ft) and directly overlies bedrock at significant depths (>30 m/98 ft) (Figure 7). The Pearl Formation was not encountered during this investigation. Nelson and Williams (2004) interpret the Pearl Formation to represent an Illinoian Age (170 to 120 kya) fluvial channel deposit derived from the ancestral Ohio River.

Henry Formation

Sand, gravel, and minor silt and clay comprise the Henry Formation (Nelson et al., 1999) (Figures 4 and 7). The Henry Formation is similar to the underlying Pearl Formation but is finer-grained. The Henry Formation consists of sand with gravel clasts ranging from 0.5 inch to 1.25 inches in diameter. The Henry Formation is at least 37 meters (120 feet) thick and commonly is expressed geomorphically as ridges and small hills along the length of the Cache Valley. The Henry Formation represents fluvial channel, point bar, longitudinal bar, natural levee deposits, and eolian sands largely derived from Wisconsinan (120,000 to 10,000 years ago) glacial outwash and interfingers with the overlying Equality Formation (Esling et al., 1989; Nelson et al., 1999). The Henry Formation contains a distinct clay mineralogy that is suggestive of a northeastern source and transported to the Cache River Valley by the ancestral Ohio River (Esling et al., 1989). About 20 to 25 km (12.4 to 15.5 mi) northeast of the Old Diswood Road site, the top of the Henry Formation was dated previously at 25,343 ± 450 B.P. indicating the

Ohio River occupied the Cache River Valley at this time (Esling et al., 1989). The Henry Formation was encountered in the lowermost part of the borings for this study.

Equality Formation

The Equality Formation consists of silt and clay, with minor sand and gravel derived primarily from a lacustrine source (Esling et al., 1989; Nelson et al., 1999). Limonite concretions and organic matter, such as wood and plant fragments, are common (Nelson and Williams, 2004). The Equality Formation is over 21 to 24 meters (70 to 80 feet) thick and its lower contact is often erosional where resting on Paleozoic bedrock. The upper contact is gradational with the overlying Cahokia Formation (Nelson et al., 1999). The Equality Formation underlies all the major tributary valleys of the Cache Valley and interfingers laterally with the Henry Formation near the margins of the Cache Valley. Within the study area, Equality Formation was grouped with Cahokia Formation in the upland tributary valleys and mapped as Unit Qce (Figure 4). The Equality Formation is interpreted as Wisconsinan interglacial overbank and lacustrine sediments (Esling et al., 1989; Nelson et al., 1999). The Equality Formation is present in all borings drilled as part of this study.

Cahokia Formation

Silt, sand, clay, gravel, and rock debris comprise the Cahokia Formation (Nelson et al., 1999) (Figures 4 and 6). The gravel portion consists primarily of angular to well-rounded chert pebbles with lesser amounts of reworked quartz, igneous and metamorphic clasts (Nelson et al., 1999). In the broad valleys Cahokia Formation is dominated by upland-derived loess silt whereas in the small upland valleys it consists of silt and angular rock fragments derived from the local weathered bedrock. In the broad valleys, surface soils are weakly developed but buried soils are common. Nelson et al., (1999) also recognize an alluvial fan facies (map unit Qcf) and a wetland facies (map unit Qcw). Map unit Qcf is a mixed silt alluvial fan deposit with angular rock fragments and is mapped along the margin of the Shawnee Hills and near the site. Map unit Qcw consists of organic-rich silt and clays deposited in low-lying areas such as abandoned channels, swales, and wetlands. The Cahokia Formation's lower contact may be sharp (erosional), or more commonly gradational with the underlying Equality and Henry Formations. The Cahokia Formation ranges from 1.5 to 10.5 meters (4.9 to 34.4 ft) thick in the Pulaksi 7.5 minute quadrangle (Nelson and Williams, 2004) and up to 14 meters (45.9 ft) thick in the

Tamms 7.5 minute quadrangle (Devera and Follmer, in-prep). In the upper Cache Valley, organics 8.30 meters (27.2 ft) deep in the Cahokia Formation were dated at 8,160 ± 180 B.P. (Graham, 1985). The Cahokia Formation is present in all the borings drilled at the site and commonly is associated with reworked loess and discontinuous alluvial fans, colluvium, and channel deposits.

Holocene Deposits

Younger Holocene landforms and deposits (alluvial fans, terraces, colluvium, and stream channels) were mapped to evaluate the local geomorphic processes and neotectonic activity (Figure 8). For example, map unit Qf is similar to Qcf, but unit Qf describes smaller and steeper alluvial fans that have formed at the mouths of small drainages along the bluff line of the Shawnee Hills. The fans are estimated to be middle to late Holocene because of their steep slopes and position relative to the lower relief Cahokia Formation found in Cache Valley. Map unit Qt (subunits Qt1 and Qt2) denotes the location of small terraces that now lie above the modern floodplain. These landforms are probably Holocene, but their genesis could date to the Late Pleistocene because of their relative topographic position above the modern floodplain, especially those west of the Penitentiary fault (Figure 8). Stream channels active in the Holocene are shown by map unit Hch. Holocene oxbows are included in map unit Hox. These features are abandoned or cut-off channels that may still contain water or could be infilled with fine-grained deposits. See Plate 1 of Baldwin et al. (2008) for a comprehensive description of the Quaternary geologic deposits in the study area.

Regional Geomorphology

The site lies in the west-central part of the Cache Valley near Tamms, Illinois, an area dominated by slackwater to braided fluvial deposits near the base of a 60-m-high (197 ft) northeast-trending topographic escarpment along the eastern margin of the Shawnee Hills (Figure 3). Possible fault-related geomorphic lineaments within the study area include prominent east- and northeast facing-bluffs of the Shawnee Hills, linear drainage patterns, weak and discontinuous slope breaks in fans, multiple terraces(?) near Old Diswood Road, and possible deflected stream drainages along the northern and western margins of Cache Valley.

Previous mapping (Devera and Follmer, in prep.) inferred the Penitentiary Fault existed along the range front based on the strikingly linear N50ºE-oreinted, 7-km-long (4.3 mi) bluff line between Sandy Creek and the northwestern most part of Cache Valley. Within the N50ºE trending segment, the topographic change across the range front is abrupt, especially considering the flat topography that characterizes the lowlands of the Cache Valley. To the north where the valley makes an abrupt change in orientation to the east toward Metropolis, the linear northeast-trending hill front ends, becomes embayed, and is incised with occasional isolated bedrock knobs surrounded by Quaternary deposits (Figures 3 and 4). Similarly, the bluff line south of Sandy Creek trends approximately N20ºE and becomes more arcuate towards the south, where the bluff line appears modified by a meander scroll (i.e. fluvial scarp) of the Mississippi River (Figures 3 and 4).

Close to the eastern bluff line of the Shawnee Hills, several stream valleys trend northeast and subparrallel to the Penitentiary and Commerce faults (Devera et al., 1994). As shown on Figure 4, the east branch of Sandy Creek is strikingly linear, parallel to the Penitentiary fault, and coincident with mapped discontinuous faults to the north (Devera et al., 1994; Nelson et al., 1997). Similarly, the Commerce fault is mapped along the southeastern margin of Wolf Creek. Odum et al. (2002) infer a possible northeast (e.g. right-lateral) deflection of Wolf Creek by the Commerce fault.

These observations collectively suggest that the geomorphology of the drainage basin(s) in this area is controlled partly by underlying bedrock structure. However, no convincing fault-related geomorphic features suggestive of late to middle Holocene activity were mapped along the eastern margin of the Shawnee Hills or within the drainages of Wolf Creek or Sandy Creek (e.g. shutter ridges, tonal lineaments, fault scarps, springs). Only at the research site along Old Diswood Road are one or more possible terrace(?) surfaces inferred at suspicious elevations directly west of the Shawnee Hills range front (Figure 8). In addition, south of this site is a weak break in slope developed in alluvial fan sediments of unknown age. The apparent lack of tectonic geomorphology may be the result of discrete Holocene alluvial fan deposition along the Shawnee Hills, as well as anthropogenic influences (Eaton, 1992; Walters and Merritts, 2008), which may obscure signs of tectonic geomorphology.

4.0 METHODOLOGY

The investigation of the Penitentiary fault and its association with the CGL included interpretation of aerial photography, field reconnaissance and Quaternary geologic mapping, acquisition and interpretation of seismic reflection data, followed by the drilling of closely spaced boreholes across features suspected of late Quaternary deformation.

Quaternary Geologic and Geomorphic Mapping

The Quaternary geologic map developed for the site region is based on interpretation of black and white, 1:20,000 scale, stereo-paired aerial photography (from September 1956) combined with field reconnaissance. The Quaternary geologic mapping was performed as part of Baldwin et al. (2008). Historical topographic maps (U.S. Geological Survey, 1920; 1923; 1933; 1934; 1947), more modern maps (U.S. Geological Survey, 1966 and 1967), and the Alexander County soil survey (NRCS, 2002) aided in the analyses of landforms and deposits. Geologic units and structural features were adapted mostly from existing geologic maps of the Mill Creek, McClure, Dongola, and Tamms 7.5 minute quadrangles completed by the Illinois State Geological Survey (Devera et al., 1994; Nelson et al., 1999; and Devera and Follmer, in prep) and modified based on our interpretation of the landforms. Field reconnaissance included traverses across and along the base of the Shawnee Hills to verify to the aerial photography interpretations. Much of the reconnaissance was limited to traverses along public roads with more detailed reconnaissance conducted near seismic reflection lines Tamms-1 and Tamms-2.

Seismic Reflection Data Acquisition

As part of the Baldwin et al. (2008) research study in the lower to central part of the Cache River Valley, seismic reflection data for two profiles (Tamms-1 and Tamms-2) were collected in SH mode (sensitive to horizontally polarized shear waves) on a 12-channel engineering seismograph. Seismic line locations are shown on Figure 4. The profiles intersect the Penitentiary fault zone along Old Diswood (Tamms-1) and Newell Roads (Tamms-2). The active spread consisted of 14 receivers (14 Hz horizontal geophones oriented perpendicular to the seismic line) spaced at 4-meter (13.1 ft) intervals. The seismic profiles were shot off-end with 4-meter shotpoint spacings and 2-meter (6.6 ft) source offsets. Seismic energy was

generated by five horizontal impacts of a 4.5-kg sledgehammer on a 5-kg steel I-beam oriented perpendicular to the spread. Processing followed a standard sequence for shallow common midpoint (CMP) reflection data and included: data reformatting and editing, CMP sorting, bandpass filtering (8-80 Hz), automatic gain control (200 ms window), velocity analysis, Normal Moveout (NMO) correction, surface-consistent residual statics, and 6-fold CMP stacking.

Borehole Transects

Two approximately west-east oriented borehole transects across projections of faults identified in the seismic reflection data were prepared to intersect shallow fluvial and colluvial deposits and soil horizons. The transects were used to assess the age and lateral continuity of sediments, and to identify the absence or presence of fault-related vertical displacements of stratigraphic horizons (reflectors) interpreted from the seismic reflection profiles. A total of 18 direct push technology (DPT) Geoprobe cores (boreholes) were collected at variable spacings (6 to 43 ft/1.8 to 13 m) along parts of seismic line Tamms-1 to specifically target possible deformation zones identified in the seismic lines (red circles in Figure 8). In addition, a total of nine (9) detrital charcoal samples were collected from the cores to provide age estimates of the deposits by which to assess the age of faulting and geologic evolution of the western Cache Valley (Table 1). The cores were collected as continuous cores to a maximum depth explored of 52 ft.

A Geoprobe is a hydraulically-powered soil probing machine that utilizes static force and percussion to advance 1- and 11/16-inch-diameter sample tubes within 4-ft-long (1.2 m) sections at each borehole location. The core samplers extended into undisturbed stratigraphy below the base of the sampler by static force from the Geoprobe machine using direct push technology (DPT). Clear, thin-walled plastic liners within the Geoprobe sampler tubes preserved the continuous sediment cores. The sampler tubes were labeled, cut and logged prior to placement in cardboard core boxes delivered to the Illinois Geological Survey core facility in Champaign, Illinois. During logging, the cores from multiple borings were placed side-by-side and in sequential order for detailed characterization and direct correlation of soil and deposit stratigraphy between boreholes.

The elevations along the two transects range from approximately 365 ft (111 m) above mean sea level (msl) at the western end of cross section B-B' to 355 ft (108.2 m) along the eastern end of cross section C-C'. The borehole locations and elevations were located using a combination of tape measure, compass, eye-level, differential GPS surveying, and correlation to the U.S. Geological Survey topographic maps of the site area. All the borehole transects were located along the north shoulder of Old Diswood Road in Tamms, Illinois.

Magnetic Susceptibility

Magnetic susceptibility (MS) of individual units and formations was used to evaluate the interpretation of our borehole correlations. The MS values were used as a crude confirmation of the more definitive sediment to sediment core correlations developed in the field with cores placed adjacent to one another. Variations in magnetic susceptibility in Quaternary sediments of Illinois can be caused by many factors, including sediment provenance, eolian or fluvial sorting into grain size fractions (higher concentrations of magnetite tend to be associated with coarse silt or very fine sand textures for bulk sample), reductive dissolution in waterlogged soils (catalyzed by iron reducing bacteria in the presence of organic matter), or neoformation of ultrafine magnetite in moderate to well drained soil A horizons.

For this study, a Bartington MS2 magnetic susceptibility meter with an MSF attachment was used on selected sediment samples to aid in correlating different stratigraphic units. Sediment samples from five boreholes (B-5 to B-9) were measured at 2-foot (0.6 m) depth increments to a maximum depth of 50 ft (15.2 m) below ground surface. MS analysis was performed on cores where the sediment was relatively uniform and unfractured. The core surface was smoothed and flattened with a clean knife prior to measurement with the MSF probe. Two readings were taken at each selected depth (within a couple inches of each other) and then averaged. Values of magnetic susceptibility are reported in 10^{-5} dimensionless SI units.

Age Dating

The ages of the sedimentary deposits at the site were estimated from radiocarbon dates and pedologic development. Nine detrital charcoal samples to wooden debris were collected from the boreholes and submitted for radiocarbon analysis to Beta Analytic Inc., in Miami, Florida. The radiocarbon dates were dendrochronologically corrected to calibrated years according to

the latest procedure of Stuiver and Reimer and IntCal04 (2004). The radiocarbon results are presented in Table 1.

5.0 RESULTS

The compilation of geologic mapping with geophysical and borehole information collected from the Penitentiary fault zone provide evidence for late Pleistocene and possible early Holocene faulting. Seismic reflection data intersecting the hill front between Sandy Creek and Old Diswood Road provide evidence for late Quaternary deformation coincident with the Penitentiary fault. Closely spaced boreholes placed in areas suspected of late Quaternary deformation are suggestive of late Pleistocene to early Holocene faulting along the margin of the steep range front, however middle to late Holocene deformation does not seem permissible based on the available stratigraphic evidence. The deformation interpreted from the borehole data is based on displaced basal contacts of major stratigraphic units and interbeds of coarse-grained alluvium and colluvium.

Seismic Reflection Profiles

Seismic lines Tamms-1 and Tamms-2 collected for this study along Old Diswood and Newell Roads, respectively, cross the surface projection of the Penitentiary fault of Odum et al. (2002), and image offset reflectors and changes in reflection amplitude and coherency consistent with high-angle bedrock faults extending into Quaternary alluvium (Figure 4). Profile Tamms-1 images Paleozoic bedrock (Unit 1) between 10 and 40 meters (32.8 to 131.2 ft) that forms a steep 10-m-high (32.8 ft) buried, east-facing bedrock step unconformably overlain by faulted and folded late Pleistocene sand and gravel (Henry Formation or Unit 2) (Figure 9). Smaller amounts of vertical deformation within the younger overlying late Pleistocene Equality and Holocene Cahokia Formations (Unit 3) also are interpreted. The seismic stratigraphy imaged in the Tamms-2 seismic line is of poor resolution in comparison to Tamms-1 but overall images an unconformity between bedrock (Unit 1) and Late Pleistocene sand and gravel (Unit 2), and possible deformation where disrupted incoherent reflectors occur in the center of the profile (stations 400 to 600 meters)(Figure 10).

<u>Faulting and Folding Interpreted from Seismic Lines</u>

Faulting and folding interpretations from Tamms-1 and Tamms-2 were defined by: (1) offset reflectors, (2) abrupt termination of strong reflections, (3) residual diffraction patterns, (4) abrupt

change in reflection dips, and (5) associated folds. Within Tamms-1, faults are labeled with a number and fault splays are labeled with a letter (e.g. fault 1a) (Figure 9). The faults coincident with Shawnee Hills range front (faults 1 and 2) consist of near vertical faults that mark a buried east-facing scarp with at least 20 m (65.6 ft) of apparent east-side-down vertical separation and west-tilted stratigraphy. Faults interpreted in the eastern portion of the profile (Faults 3 and 4) offset both the prominent bedrock reflector and Henry Formation. Bedrock offsets along Faults 3 and 4 vary between <2 and 6 m (6.6 to 19.7 ft) and commonly exhibit apparent reverse displacement. Displacements of the Henry Formation reflectors (Unit 2) vary between 2 and 3 m (6.6 to 9.8 ft). As interpreted these faults dip west toward the main mountain front faults along the east side of Shawnee Hills. The poor reflector quality in the youngest geologic units prevents us from confidently projecting faults upward into the youngest overlying deposits. The eastern fault zone is interpreted as possibly a 'flower structure' associated with transpressive deformation similar to the observations of Odum et al. (2002) along the Sandy Creek geophysical profile (Figure 5).

Individual faults are difficult to identify within the Tamms-2 profile (Figure 10). One fault zone is interpreted in profile Tamms-2 as a highly-disrupted zone near the central part of the profile. This zone includes coherent reflectors on either side and is coincident with a mapped bedrock fault trace within the Penitentiary fault zone directly north of the profile (Figure 4). We hypothesize that this disrupted zone is caused by deformation along the Penitentiary fault zone. The overall poor quality of the reflectors within the fault zone does not permit the delineation of individual fault offsets, or Holocene fault activity.

The complex near-surface pattern of faulting interpreted from profiles Tamms-1 and Tamms-2 aligns with the broad, complex faulting previously observed in seismic lines to the south along Sandy Creek (Odum et al., 2002). This latest study demonstrates faulting at or near the margin of the Shawnee Hills with steep west-dipping faults. Faulted Pleistocene and possibly Holocene deposits imaged in the seismic profiles are best explained as transpressive dextral deformation.

Shallow Geologic Cross Sections

Geologic cross sections developed from the borehole data are coincident and overlap with regions highly suggestive of deformation interpreted from seismic profile Tamms-1 and

Quaternary landforms that appear vertically displaced across the Penitentiary fault zone (Figure 8). The cross sections show multiple distinct, laterally continuous Quaternary stratigraphy and incipient soil horizons (Figures 11 and 12). These strata and paleosols are used as strain gauges to assess zones of deformation (e.g., warping, folding and faulting) interpreted from seismic reflection line Tamms-1, as well as deformation zones projected northeast of Sandy Creek where Odum et al. (2002) interpret similar faults. The vertical exaggeration for the cross sections ranges from 2x (B-B') to 4x (C-C') in order to display thin stratigraphic and pedogenic horizons, as well as identifying subtle changes in stratigraphy that may be representative of faulting or folding, or original perturbations in the paleotopography. Cross section B-B' allows for the interpretation of an east-facing buried bedrock scarp with possibly truncated fluvial deposits; whereas C-C' suggests relatively flat-lying stratigraphy and little to no evidence for faulting or folding.

Stratigraphic Relations - Cross Section B-B'

Cross-section B-B' is approximately 240-ft-long (73.1 m) and is oriented roughly northwest-southeast along Old Diswood Road and subparallel to an unnamed drainage flowing southeast out of the Shawnee Hills. The profile intersects Holocene alluvial fan deposits shed eastward by the unnamed creek and extends easterly across an east-facing topographic break in slope coincident with the bluff line of the Shawnee Hills. The probes along this alignment encountered six primary units that from oldest to youngest include: bedrock; colluvium and in places, bedrock residuum with a Sangamon Geosol; Henry Formation and colluvium; Equality Formation; Cahokia Formation; and artificial fill.

The borings delineate a shallow (27 to 30 ft below ground surface [bgs]/8.2 to 9.1 m) bedrock bench dipping westerly in the west part of the profile. The bedrock is comprised of Paleozoic chert that rapidly deepens to greater than 50 ft (15.2 m) bgs in the east part of the section. Bedrock west of borehole B-13 is overlain by angular, coarse-grained colluvium or residuum comprised entirely of angular chert clasts within a clay-rich matrix. Further west the colluvium/residuum is interbedded with a stiff dark red to reddish brown clay consistent with Sagamon Geosol development. East of borehole B-13, the bedrock surface forms a 20-to 30-ft-high (6.0 to 9.1 m) east-facing buried bedrock escarpment aligned with the present-day Shawnee Hills eastern slope. Along the eastern side of the bedrock step varying amounts of

weathered chert and coarse-grained colluvium overlies bedrock but lacks the Sangamon Geosol typically present in similar colluvial deposits in the western part of the profile.

MS values from the chert and limestone clasts in the colluvium indicate a locally derived source and yield very low magnetite content. This is in contrast to the younger overlying colluvium mixed with the Equality Formation. The low MS values are associated with the local sedimentary Paleozoic bedrock that tends to have a low MS (<15 x 10^{-5} SI units), whereas glacial materials comprised of minor clasts derived from igneous/metamorphic terrains in the northern United States and Canada often have slightly higher MS values (Figure 13)(Grimley, 1998).

A bright-red to orange, clay-rich paleosol developed in the western colluvium is attributed to the Sangamon Geosol that developed during the Sangamon-time interval from about 65 to 125 ka (Forman and Pierson, 2002; Grimley et al., 2003). The Sangamon Geosol is characterized by a relatively thick solum, an increase in illuviated clay with increasing depth derived from a previous parent material, clay films, red hue (7.5YR to 5YR hues), prominent clay seams along prismatic and angular blocky peds, calcium carbonate development, and well-developed zones of manganese oxidation. The Sangamon Geosol can be traced easterly from borings B-5 to B-13 where it abruptly terminates at the bedrock step (Figure 11). The absence of the Sangamon Geosol in the eastern part of the section may be due to fluvial erosion or faulting.

The Henry Formation overlies bedrock and the basal colluvium, and is composed of laminated to bedded, gray sand and gravel with laterally continuous beds of silt and clay (Figure 11). The coarse-grained fluvial deposits contain rounded to subrounded fine gravel of granitic, metamorphic and sedimentary affinity derived from northern sources, and transported by the paleo-Ohio River. Moderate MS values yielded by the coarse-grained deposits are consistent with the hypothesis that the highly variable clast compositions originate from sources in the north-northeast. Fluvial deposits directly overly and interfinger with the chert-rich basal colluvium or bedrock residuum. The basal colluvium is unlike the bedrock residuum encountered west of the escarpment in that it lacks the stiff reddish to orange-brown clay matrix typical of the Sangamon Geosol. The colluvium east of the escarpment is less clay rich and lacks strong reddish hues suggesting it is younger than the Sangamon Geosol colluvium west of the bedrock step. The Henry Formation ranges from 15 ft (4.6 m) thick in the eastern part of the

section to perhaps as much as 3 ft (0.91 m) thick in the western part of the section. A radiocarbon sample (Sample B-18-RC-1) from Borehole B-18 at about 40 ft (12. 1 m) bgs provides a radiocarbon age of 20,810 ± 90 yrs BP for the upper part of the Henry Formation (Table 1). Esling et al. (1989) report a slightly older radiocarbon age of 25,343 ±450 yrs BP age for the upper part of the Henry Formation in northeastern Cache River Valley about 20 to 25 km to the northeast of the Old Diswood Road site.

The Equality Formation conformably overlies the Henry Formation as a well-bedded to thinly laminated gray, dark grayish-brown to black, stiff silt and clay that ranges in thickness from 5 to 15 ft (1.5 to 4.6 m) (Figure 11). To the west, the Equality Formation contains discontinuous coarse-grained colluvium composed entirely of white to gray, angular chert clasts derived from the adjacent bedrock escarpment. Down-section the Equality Formation coarsens slightly as it approaches the Henry Formation as noted by an increase in very fine sand and silt laminations, or minor concentrations of rare, randomly distributed coarse clasts. A rare purple mineral with "cauliflower form" called vivianite occurs within the deposit and was encountered in borehole B-18 at about 28 ft (8.5 m) in depth. The Equality Formation can be tracked to as far west as borehole B-13 where it thins abruptly above the bedrock escarpment. Further west it is inferred based on stiffness and textural variations, and MS values. Generally low magnetic susceptibility values characterize the clay-rich zones of the Equality Formation, however a weak, laterally continuous moderate MS value ranging from 20 to 40 x 10^{-5} SI units occurs at about 30 and 35 ft (9.1 to 10.7 m) in depth in boreholes B-8 and B-9 and provide an approximate lateral correlation (Figure 13). The primary magnetite content of the Equality Formation probably was originally low and has undergone significant dissolution since deposition. The fine-grained texture, presence of organic material including sticks and twigs, coupled with dark gray reduction discoloration, indicate this deposit likely formed in slack water, lake or swamp-like conditions following the abandonment of the paleo-Ohio River course through the Cache River Valley. Six woody debris and charcoal samples (e.g., B-13-RC-3; B-15-RC-2; B-8-RC-1; B-8-RC-2; B-10-RC-1 and B-2-RC-2) selected for AMS dating yield calibrated (2σ) ages of 17,410 to 12,650 yrs BP (Table 1) indicating the deposit overlaps with Peoria Loess deposition.

Directly overlying the Equality Formation is the Cahokia Formation often noted by an abrupt and thin oxidized fine-grained sand to silt basal contact, and a clear textural change from soft silt (Cahokia Formation) to stiff silty clay (Equality Formation) between approximately 18 to 20 ft

(5.5 to 6.1 m) bgs (Figure 11). In section B-B', the Cahokia Formation consists of massive reworked loess interbedded with a few discontinuous, thin layers of fine angular chert gravel in a silt matrix. Multiple weak and incipient palesols defined by a concentration of either one or more of the following - dark brown to grayish brown hue, concentration of manganese nodules and staining, and weak clay development – are present throughout the section, some with lateral continuities approaching 100 ft (30.5 m). In the western section, Cahokia Formation directly overlies a thinned Equality Formation. The abundant massive silt and occasional coarse-grained packages of angular chert gravel are indicative of denudation of the Peoria Loess cover in the Shawnee Hills and eventual exposure of the Paleozoic chert bedrock in post early to middle Holocene. Two charcoal samples (B-15-RC-1 and B-13-RC-2) collected near the base of and top of the Cahokia Formation provide ages of 12,610 to 12,110 cal yr BP and 260 to 0 cal yr BP, respectively (Table 1).

The magnetic susceptibility (MS) values from cores B-5 and B-7 at about 15 and 25 ft (4.6 to 7.6 m) bgs range between 40 and 80 x 10^{-5} SI units consistent with unaltered loess deposits in Illinois (Grimley et al., 1998) (Figure 13). The brighter colors, and less iron and manganese staining, may represent rapid depositional conditions associated with an alluvial fan forming at the base of the hills during a receding and filling slackwater swamp or lake. MS values within the Cahokia Formation east of the escarpment contain jagged peaks and valleys ranging between about 10 and 40 x 10^{-5} SI units (Figure 13). These lower MS values, coupled with the observations of pervasive iron and manganese mottling and persistent pale colors, suggest poorly drained soils and reworked loess deposited within a wetland or saturated floodplain environment (Grimley and Arruda, 2007). The distinct east-west variation in MS values also is coincident with the buried bedrock escarpment and supports a distinct change in environmental or depositional conditions across the escarpment.

Stratigraphic Relations Cross Section C-C'

Shallow stratigraphic relations in the upper and eastern part of geophysical profile Tamms-1 are summarized graphically in the 540-ft-long (165 m), east-west oriented cross-section C-C' along Old Diswood Road (Figure 12). The geologic profile is preferentially oriented to intersect Faults 3 and 4 where the imaged bedrock unconformity with the Henry Formation appears vertically displaced, and overlying late Quaternary sediments of the Henry Formation define a west-

dipping transpressive structure. Cross section C-C' consists of six boreholes (B-1 to B-4, B-10 and B-11) ranging in depth from 40 to 52 ft (12.2 to 15.8 m) bgs and having spacings of about 65 to 150 ft (19.8 to 45.7 m). The boreholes extend within or close to the upper part of the diffuse, discontinuous, and incoherent reflectors of seismic reflection profile Tamms-1.

The boreholes encountered gently dipping bedded to flat-lying stratigraphy of the Henry, Equality and Cahokia Formations (Figure 12). The lithologic and textural differences used to differentiate formational deposits in section B-B' hold true in section C-C'. From a review of seismic reflection profiles and nearby water well logs bedrock exists at depths greater than 100 ft (30.5 m) (Figure 7). Bedrock was not encountered in any of the borings. The borings encountered multiple stratigraphic horizons (subtle and distinct) and weakly developed paleosols that collectively provided excellent strain markers to assess the presence or absence of deformation within the Henry, Equality and Cahokia Formations. Two radiocarbon samples (B-2-RC-2 and B-10-RC-1) from the fine-grained silt and clay interbeds of the Equality Formation at depths near 34 to 37 ft (10.4 to 11.3) bgs provide calibrated ages ranging from 16,540 to 17,410 cal yrs BP (Table 1). These ages and depths are consistent with the deepest-most calibrated ages yielded by charcoal samples collected from the Equality Formation to the west and depicted and in section B-B'.

Near-Surface Structural Relations

The genesis of the Shawnee Hills bluff line and its coincidence with the Penitentiary fault zone remains enigmatic but can be explained as either a fluvial, tectonic, or a fault-line scarp. Lacking direct geologic evidence (e.g. trench exposure) it is difficult to eliminate the uncertainty regarding the origin of the escarpment; however, given the available geophysical and geologic data, we argue that it is not unreasonable to interpret the escarpment as partly tectonically-controlled. The Tamms-1 seismic reflection profile and geologic cross section B-B' confirm a buried steep east-facing scarp at or near the northeasterly projection of the Shawnee Hills bluff line that is bounded by bedded fluvial and alluvial Quaternary deposits and coincides with faults imaged in geophysical profiles.

The buried topographic relief imaged in seismic reflection profiles across the east margin of the Shawnee Hills could have been generated by the scouring of the Cache River or paleo-Ohio

River prior to the deposition of the Pearl (170 to 120 ka) and Henry Formations (>20.8 ka) during Illinoian time (Masters and Reinertsen, 1987). Available radiocarbon dates and pedogenic age estimates of the late Pleistocene material encountered in the boreholes indicate that the oldest deposits occur west of the buried escarpment as a coarse-grained colluvium (Unit Qc) overprinted with a Sangamon Geosol (80 to 70 ka). These timing relations suggest the bedrock surface west of the fault could have formed during or shortly after the deposition of the Pearl Formation (170 to 120 ka). Bedded coarse-grained fluvial sediments of the Henry Formation (Unit Qa_3) directly overlie chert-rich coarse-grained colluvium along the east side of the escarpment (Unit Qc/Qal) suggesting there also may have been a later scouring event. Both the Henry Formation and younger overlying deposits exhibit a down-to-the-east vertical separation that decrease upsection and across the buried bedrock high all of which strongly suggest recurrent late Pleistocene deformation along the Penitentiary fault. Furthermore, a slight (5 degree) westerly dip of the Equality Formation (e.g., away from the Cache River Valley) support local tilting within the zone of deformation. Given the available subsurface structural data, a plausible explanation of the origin of the Shawnee Hills range front at Old Diswood Road is a combination of a fault-line scarp (e.g. more erodible deposits on the southeastern side) and reactivation of an old Paleozoic fault (e.g., Penitentiary Fault) during the Quaternary.

We use the finely-bedded alluvium and weak inferred paleosols as marker horizons in borehole profiles B-B' and C-C' to assess the presence or absence of late Pleistocene to Holocene faulting or folding coincident with the Penitentiary fault zone. The borehole data for section C-C' intersect Faults 3 and 4 in the central Cache River valley and suggest very little, if any, near-surface late Pleistocene to Holocene deformation, whereas section B-B' that intersects Faults 1 and 2 strongly supports Pleistocene deformation at the edge of the Shawnee Hills (Figure 8). Geologic cross section B-B' delineates a bedrock step at the escarpment that is coincident with an apparent truncation of a Sangamon Geosol and several younger geologic deposits associated with the Henry and Equality Formations. The Henry Formation (>20.8 ka) has no equivalent deposit west of the bedrock step and exhibits a vertical separation ranging from 19 to 25 ft (5.8 to 7.6 m) across Faults 1 and 2 (Figure 9). The Equality Formation lies west of the fault zone and directly above the Sangamon Geosol, and exhibits a vertical separation ranging from 10 to 17 ft (3 to 5.2 m) across the entire section. Discontinuous colluvial deposits interfingering with the upper (?) part of the Equality Formation east and west of the fault zone that also directly overlie the Sangamon Geosol, provide a minimum apparent vertical separation

of about 5 to 6 ft (1.5 to 1.8 m). Assuming the vertical separation(s) across these units is in part tectonically-controlled cumulative displacements range from 5 to 17 ft (1.5 to 5.2 m) between 20,900 and 12,600 cal yrs BP. Furthermore, the Sangamon Geosol equivalent has not been encountered east of the escarpment suggesting significant displacement and possibly erosion. It is unknown how much of the vertical separation is tectonically-controlled vs. fluvially-modified, and how many earthquake events could have accommodated this apparent deformation.

The basal contact of the Cahokia Formation, if faulted and not a product of "filling" a previous scarp face exhibits about 4 to 5 ft (1.2 to 1.5 m) of down-to-the-east vertical separation and a thickening east of the escarpment. Upsection, multiple coarse-grained alluvial gravel lenses and incipient paleosols project across the buried bedrock escarpment with little or no deflection suggesting the middle to upper parts of the Cahokia Formation are undeformed. These relations suggest the middle to upper part of the Cahokia Formation may have abutted a fault-line scarp, whereas the basal section of the Cahokia Formation may be deformed. If so, the youngest age of deformation is late Pleistocene (post 12,365 255 cal yrs BP) to possibly early Holocene as implied from depositional rates (0.6 mm/yr) within the Cahokia Formation using available radiocarbon information.

Borehole transect C-C' generally shows very flat-lying late Pleistocene to Holocene stratigraphy with no abrupt vertical elevation changes across Faults 3 and 4 imaged in seismic reflection profile Tamms 1. The basal contacts between the Henry and Equality Formations, as well as between the Equality and Cahokia Formations, are generally subhorizonal with minor perturbations along the length of the contact; there are no clear vertical elevation changes suggestive of deformation. A broad and low relief inflection is discernable across the Henry-Equality Formation contact near the base of the profile and is permissible upsection within the lower part of the Equality Formation. Overlying contacts within the Equality and Cahokia Formation do not exhibit distinct vertical elevation changes consistent with youthful and significant deformation. It should be noted that based on the large spacing between borings it is permissible that a fault with displacement values of less than about 3.2 ft (1 m) are not discernable; however, the likelihood of faulting being missed is increasingly more difficult upsection based on the consistent flat-lying stratigraphy. Faults interpreted in Tamms-1 may exist at depths greater than those explored by the boreholes.

6.0 DISCUSSION

Review of aerial photography, combined with Quaternary geologic mapping and field reconnaissance, followed by geophysical acquisition and interpretation, and multiple continuous sediment cores allow us to develop timing constraints on the activity of the Penitentiary fault. Geophysical profiles image late Quaternary faulting and folding across an approximately 0.5-to 0.7-km-wide (0.3 to 0.4 mi) fault zone along the western margin of the Cache River valley (Figure 3). Lithologic correlations from multiple boreholes drilled across suspected fault zones adjacent to the hill front escarpment reflect late Pleistocene to possible early Holocene faulting and tilting. The findings from the Tamms study, coupled with multiple previous paleoseismic investigations in southwest Missouri, indicate a 110-km-long (68 mi) section of the Commerce geophysical lineament has had recurrent episodes of faulting between the late Pleistocene and early Holocene.

Penitentiary Fault

The compilation of previous existing information in the valley, combined with our recent geophysical surveys extending across suspected tectonic-related features, indicate faults interpreted in the subsurface reflect late Quaternary transpressional deformation. Faults have been mapped at or near the mountain front in the Paleozoic bedrock as discrete, steeply west dipping northeast-striking faults. Evidence for faulting includes bedrock exposures of the Commerce fault to the southwest in the Shawnee Hills and to the northeast where the Penitentiary fault is exposed and Cache Valley makes a bend to the east. The bedrock fault exposures in the Shawnee Hills are typically of relatively narrow fault zones whereas the interpreted geophysical profiles near the western valley edge image a wide (0.5 to 0.7km/0.3 to 0.4 mi) fault zone that branches and flowers upsection. The upward branching, steeply dipping fault zones are similar to geophysical images collected across the CGL near Commerce and Idalia, Missouri (Stephenson et al., 1999; Baldwin et al., 2006). Although no kinematic indicators have been measured along the fault zone, evidence for dextral transpression includes: 1) faulting and folding consistent with transpressional ‘flower structures’ (Figures 3 and 9) (Odum et al., 2002); 2) dextral strike-slip focal mechanisms of historical seismicity (Harrison and Schultz, 1994; Harrison et al., 1999); 3) strike-slip kinematic indicators along the Commerce fault at Olive Branch Road (Devera and Follmer, in-prep); and 4) the alignment of the

Penitentiary fault with present day east-northeast-directed stress-field consistent with dextral transpression (Harrison and Schultz, 1994; Odum et al., 2002).

Transpressive Quaternary faulting is identified along the entire 7-km-long (4.3 mi) Penitentiary fault using the findings of the three geophysical profiles. The Penitentiary fault is interpreted to merge in the southeast with the Commerce fault across a right step-over as well as continue to the northeast of the Cache River valley. Near Sandy Creek, southwest of the Old Diswood Road site, strain is likely transferred onto the late Quaternary active Commerce fault to the southwest across a complex right-step (Figures 3 and 4). Quaternary faulting along the Commerce fault has been documented through previous geophysical and geologic investigations (Harrison and Schultz, 1994; Harrison et al., 1999). The northeast continuity of faulting beyond seismic profile Tamms-2 in the northern Cache River valley is less certain. The geomorphic expression of the Shawnee Hills range front at Tamms-2 intersects the east-west trending Cache Valley and loses the prominent northeast-trending hill front and broad alluvial fans crossing the fault zone (Figure 3). East-flowing drainages crossing the CGL tend to become embayed and drowned with alluvial sediment. Nelson et al. (1997) speculate that Quaternary faulting continues northeast of the Cache River valley as a series of small and discontinuous, northeast-striking faults that define a right-stepping, en echelon pattern. Nelson et al. (1997) continue to suggest that a 4.2 Mb earthquake near Dongola, Illinois, located 15 km (9.3 mi) northeast of the Tamms study area, may be associated with these faults and the northeastern extension of the CGL.

The borehole data collected during this investigation suggest very little, if any, late Pleistocene to Holocene deformation outboard of the valley margin, but are strongly suggestive of Pleistocene deformation at the edge of the Shawnee Hills. Geologic cross section B-B' provides evidence for a buried bedrock step coincident with the eastern margin of the Shawnee Hills and an apparent truncation of a Sangamon Geosol and several younger geologic deposits associated with the Henry and Equality Formations. For instance, the Henry Formation has no equivalent deposit west of the fault with the base exhibiting a range in apparent vertical separation of between 19 and 25 ft (5.8 to 7.6 m) (Figure 11). The oldest deposit that can be traced across the bedrock step is the Equality Formation. The basal contact of this deposit exhibits an apparent vertical separation ranging from 10 to 17 ft (3 to 5.2 m). Discontinuous colluvial stringers that interfinger with the Equality Formation east and west of the fault zone,

and that lie directly above the Sangamon Geosol, appear to be vertically offset about 5 to 6 ft (1.5 to 1.8 m). Assuming the vertical separations are in part tectonic, these units collectively provide long term cumulative displacements ranging from ranging from 25 to 5 ft (5.8 to 1.5 m) between approximately 20,900 and 12,650 cal yrs BP.

The basal contact of the Cahokia Formation changes inclination and thickness across the imaged fault zone. If the inflection and elevation change from west to east is unrelated to "filling" a previous scarp face developed in the Equality Formation, then the remaining cumulative vertical separation of the basal Cahokia contact is about 5 to 6 ft (1.5 to 1.8 m). Upsection multiple coarse-grained alluvial gravel lenses and incipient palesols intersect and continue across the buried bedrock escarpment as flat-lying horizons suggesting the middle to upper parts of the Cahokia Formation are undeformed. The apparent disruption of the basal contact of the Cahokia is constrained between late Pleistocene and possibly early Holocene based on a single radiocarbon sample (B-15-RC-1) that yields a calibrated age of 12,620 to 12,110 cal yrs BP (Table 1). The overlying coarse-grained lenses of alluvium and younger Cahokia Formation are not displaced across the same inflection suggesting that the fault has been inactive since the middle to late Holocene.

The geomorphic signature of the Penitentiary fault is consistent with a low slip rate Quaternary active fault. Prominent or distinct tectonic-related geomorphology is lacking along much of the Penitentiary fault, with the exception of the 60-m-high (196 ft) Shawnee Hills range front that is partly fluvially controlled, minor discontinuous escarpments developed in older fans, and rare uplifted (?) alluvial terraces west of the inferred fault zone and bluff line. The apparent lack of tectonic geomorphology in the Tamms study area can be explained by the absence of surface faulting during the middle and late Holocene, as well as significant late Holocene alluvial fan deposition burying evidence of pre-historic ground ruptures. If the Penitentiary fault last ruptured the ground surface in the latest Pleistocene to possibly early Holocene, as suggested by the seismic line profiles and borehole data, signs of deformation likely are buried and/or eroded by the Cahokia Formation and younger alluvial fan deposits (Figure 4). This is especially true if the return period for large earthquakes is long (>5,000 years) and the deformation is dominantly dextral transpression across a broad fault zone. Another possible explanation for the subdued tectonic geomorphology may be anthropogenic landscape modification caused by logging and farming (Eaton, 1992; Walters and Merrits, 2008). This may

have caused the latest deposition of alluvial fans (Unit Qf1) obscuring evidence of surface rupture. In summary, the absence of recent and prominent features from geomorphic and geologic mapping appears to suggest latest Pleistocene to early Holocene deformation consistent with the seismic profiles and inferred from the borehole data.

Late Quaternary Fault Activity along the Commerce Section of CGL

Available geologic data along the CGL between Illinois and Missouri indicate that a large portion of the Commerce section ruptured in late Quaternary time. Constraints on earthquake timing are poorly constrained, but previous paleoseismic studies support the occurrence of several large pre-historic earthquakes in the Pleistocene and early Holocene (Vaughn, 1994; Harrison et al., 1999; Baldwin et al., 2006) between southeastern Missouri and southern Illinois over a distance of about 110 km (68 km). These data also suggest different fault segments of the Commerce section to be active only in the late Pleistocene whereas others may have experienced multiple episodes of Holocene activity (Figure 14). A summary of the poorly constrained age data for past large earthquakes interpreted from stratigraphic and structural relations observed in trenches and streambank liquefaction features is shown in Figure 14. The vertical colored bars in Figure 14 show preliminary late Quaternary rupture scenarios from event timing data collected at multiple paleoseismic sites along the CGL. A summary of the paleoseismic findings and earthquake timing information from each site are described below from southwest to northeast along the CGL. Refer to Figure 2 for the site locations.

In the Western Lowlands near Quilin, Missouri, paleoliquefaction studies provide evidence of four poorly constrained prehistoric earthquakes, some of which are related to the NMSZ and/or structures associated with the CGL (Vaughn, 1994; Tuttle et al., 1998; Tuttle et al., 2002) (Figure 14). Vaughn (1994) estimates the timing of four prehistoric events that, from oldest to youngest, occurred at about (1) 23,000-17,000 yr B.P.; (2) 13,400-9,000 yr B.P., (3) A.D. 240-1020; and (4) A.D. 1440-1540. The two earliest paleoliquefaction events are documented at the Dudley Main Ditch and Mingo Ditch sites along the St. Francis River, and may correlate with CGL structures based on their apparent older age and greater size (i.e., close proximity to the source). In addition, no similar older sandblows are attributed to NMSZ sources in this area (Tuttle et al., 2002; Tuttle et al., 2005). Additional evidence of pre-1811-1812 paleoliquefaction

events are documented at the St. Francis River, Clodfelter Ditch and Wilhelmina Cutoff Ditch sites, but age control on the deposits is lacking.

The oldest paleoliquefaction features of the Western Lowlands of Vaughn (1994) may be correlative with late Pleistocene to early Holocene deformation interpreted from trench exposures at the South Holly Ridge site along the Idalia fault located approximately 40 km (24.8 mi) to the northeast of Quilin (Baldwin et al., 2006)(Figure 14). Interpretation of stratigraphic and structural relations at the South Holly Ridge site from borehole, ground penetrating radar and trenches provide evidence for at least two poorly constrained faulting events: the oldest occurring in the late Pleistocene (predates 23.6 to 18.9 ka), and the youngest in the late Pleistocene to early Holocene (18.5 to 7.6 ka; or pre-7.6 ka). These two events generally overlap with the two oldest events recorded in the Western Lowlands by Vaughn (1994).

Further northeast (approximately 50 km [31 mi]) of the South Holly Ridge site of Baldwin et al. (2006), geophysical and trench data provide evidence of Quaternary and possible Holocene deformation involving near-surface faults in the Benton Hills and Thebes Gap areas as documented by Harrison and Schultz (1994), Harrison et al. (1999), Palmer et al. (1997), and Stephenson et al. (1999) (Figure 14). Detailed trenching studies by Harrison et al. (1999) report evidence of multiple episodes of Quaternary faulting that are broadly constrained: one in late- to post-Sangamon (post 70 to 80 ka), pre- to early Roxana Silt time (between approximately 60 and 50 ka), one in syn-or post-Roxana Silt or pre-Peoria Loess time (between approximately 35 and 25 ka), and at least two episodes of Holocene faulting (4,860 ± 120 yr BP and 1,260 ± 50 yr BP). The late Pleistocene events are compatible with poorly constrained earthquake timing data at the Quilin liquefaction sites, South Holly Ridge site, and Old Diswood Road site (Figure 14). Holly Ridge provides evidence for the absence of faulting since at least 7.6 ka and does not record evidence of the late Holocene events interpreted in the Benton Hills. Harrison et al. (1999) note that the youngest events in the Benton Hills may represent secondary tectonic deformation correlative with a NMSZ event. This would be consistent with one of the older Holocene liquefaction features interpreted by Vaughn (1994) (Figure 14).

Northeast of Commerce, in Tamms, Illinois, the Old Diswood Road site provides evidence of late Pleistocene to possibly early Holocene faulting coincident with the Penitentiary fault zone (Figures 2 and 14). Evidence for late Pleistocene events on the Penitentiary fault zone includes

apparent elevation changes across the fault and truncation of bedding within the Henry and Equality Formations. In addition, the overlying vertical elevation change across the basal section of the Cahokia Formation can be interpreted, although speculative, as latest Pleistocene to possible early Holocene deformation. Middle to late Holocene deposits (Cahokia Formation) encountered in the boreholes, as well as geomorphic landforms intersecting the CGL, indicate the absence of younger Holocene faulting consistent with the South Holly Ridge and Quilin sites. The age of faulting at the Old Diswood Road site overlaps with the late Pleistocene events observed in Missouri, strongly suggesting multiple episodes of faulting along the CGL during the late Pleistocene with apparently long recurrence intervals, and possible sporadic activity during the Holocene Epoch (Figure 14).

Interpreted collectively, the data suggest that the Commerce section of the CGL ruptured between southeast Missouri and southern Illinois between 17,000 and 35,000 yr B.P. (Figure 14). This older event (shown in pink on Figure 14) can be interpreted at the Old Diswood Road site, and intersects the broad time interval for a similar event observed in the Benton Hills (Harrison et al., 1999) and the South Holly Ridge site (Baldwin et al., 2006), and the Western Lowlands near Quilin (Vaughn, 1994). The timing data do not preclude multiple smaller individual ruptures versus a larger continuous rupture of the Commerce section of the CGL, as well as multiple events during this long time interval.

The available timing information also permit the possibility of an event involving one or more parts of the southern and northern portions of the Commerce section of the CGL in the latest Pleistocene. For instance, an event observed at the South Holly Ridge site (18.5 to 7.6 kyr B.P.) broadly overlaps with the age of paleoliquefaction features in the Western Lowlands (Vaughn, 1994) and the faulting that displaces the Equality Formation at the Old Diswood Road site (post 12,600 cal yrs BP but pre-middle Holocene)(shown in orange on Figure 14). The middle to late Holocene deformation events observed in the Benton Hills (shown in yellow and green on Figure 14), however, are not evident along the easternmost fault strands of the Idalia Hills fault at the South Holly Ridge site, nor the Tamms site. Thus, it is unclear if the middle to late Holocene events interpreted in the Benton Hills by Harrison et al. (1999) and the Western Lowlands near Quilin of Vaughn (1994) are related to an earthquake rupturing only part of the Commerce fault, or occur on some other nearby seismic source.

Combined, this body of evidence implies that northeast-striking faults overlying the surface projection of the CGL in southeast Missouri and southern Illinois represent possible seismogenic structure(s) that have been active in the Quaternary, and may be capable of generating moderate to large magnitude earthquakes (> Mw 7.0 to 7.4; Wells and Coppersmith, 1994). The alignment of diffuse contemporary microseismicity with the Commerce section of the CGL suggests that northeast-trending structures may be accommodating a small component of the central U.S. tectonic stress. However, available trench and paleoliquefaction data indicate the CGL has not been active significantly during the Holocene Epoch.

7.0 SUMMARY OF FINDINGS

Our investigation of the Penitentiary fault and its inferred connectivity with the Commerce geophysical lineament provides additional direct and indirect evidence for linking observed late Pleistocene to possibly early Holocene deformation with previously mapped faults directly overlying the CGL. The seismic reflection data acquired across the Penitentiary fault image steeply dipping faults offsetting reflectors correlative with late Pleistocene to possibly Holocene alluvial deposits from the ancestral Ohio River and younger drainages. The pattern of faulting captured in the seismic lines indicates a broad fault zone that likely has accommodated late Quaternary dextral transpression along and directly outside of the western margin of the Reelfoot rift. Geologic transects intersecting regions suspected of late Quaternary faulting imaged in geophysical surveys support an interpretation in which the late Pleistocene Henry and Equality Formations are truncated and displaced across the western part of the Penitentiary fault zone. It is permissible, but speculative, to infer a decrease in displacement upsection across the Equality-Cahokia Formation during the early Holocene.

This geologic and paleoseismic investigation of the eastern margin of the Shawnee Hills and Cache River valley improves our understanding of potentially active, albeit older, seismogenic sources lying outside of the NMSZ and within the mid-continental United States. The existing paleoseismic and paleoliquefaction event timing data for pre-historic large magnitude earthquakes in the Western Lowlands is sparse and poorly constrained, but collectively, the data indicate that future earthquakes on northeast-striking faults aligned with the CGL-Penitentiary-Commerce and Idalia faults- should be considered in probabilistic seismic hazard studies for critical structures sighted in the central United States. Additional event timing information are needed along the Commerce section of the CGL to (1) ascertain the possibility of middle to late Holocene earthquakes along structures aligned with the CGL, (2) assess temporal clustering of large earthquakes in the upper Mississippi embayment between the NMSZ and CGL structures, and (3) refine the initial Late Pleistocene to early Holocene event chronology for the Commerce section of the CGL.

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9.0 REFERENCES

Anderson, N.L., 1997, Subsurface structure of the Commerce English Hill and related faults in the Benton Hills of southeastern Missouri: collaborative research, University of Missouri-Rolla, Department of Geology and Geophysics, and Missouri Department of Natural Resources Division of Geology and Land Survey, U.S. Geological Survey Award No. 1434-HQ-97-GR-03038, Project Summary, 4 p.

Autin, W.J., Burns, S.F., Miller, B.J., Saucier, R.T., and Snead, J.L., 1991, Quaternary geology of the Lower Mississippi River Valley, *in* Morrison, R.B., ed., Quaternary nonglacial geology; Conterminous U.S.: Geological Society of America, The Geology of North America, Boulder, Colorado, v. K-2, p. 547-582.

Baldwin, J.N., Witter, R.C., Vaughn, J.D., Harris, J.B., Sexton, J., Lake, M., and Forman, S.L., 2006, Geological characterization of the Idalia Hill fault zone and its structural association with the Commerce geophysical lineament, Idalia, Missouri: Bulletin Seismological Society of America, Vol. 96, No. 6, p 2281-2303.

Baldwin, J.N., Givler, R., and Brossy, C., 2008, Geophysical and paleoseismic evaluation of the Penitentiary fault and its association with the Commerce geophysical lineament, Tamms, southern Illinois, Final Technical Report, U.S. Geological Survey N.E.H.R.P Award No. 06-HQ-GR0138.

Bettis III, E.A., Muhs, D.R., Roberts, H.M., and Wintle A.G., 2003, Last glacial loess in the conterminous USA: Quaternary Science Review, 22, p. 1907-1946.

Blum, M.D. Guccione, M.J., Wysocki, D.A., Dobret, P.C., and Rutledge, E.M., 2000, Late Pleistocene evolution of the lower Mississippi River Valley, southern Missouri to Arkansas: GSA Bulletin, v. 112, no. 2, p. 221-235.

Cox, R.T., 1988, Evidence of Quaternary ground tilting associated with the Reelfoot rift zone, northeast Arkansas: Southeastern Geology, v. 28, no. 4, p. 211-224.

Curry, B.B., and Follmer, L.R., 1992, The last interglacial-glacial transition in Illinois: 123-25 ka; *in* Clark, P.U. and Lea, P.D. (*eds*) The Last Interglacial-Glacial Transition in North America, Geological Society of America Special Paper 270, pp. 71-88.

Devera, J.A., and Follmer, W.J., in preparation, Geologic map of the Tamms Quadrangle, Alexander County, Illinois: Illinois State Geological Survey, IGQ (7.5 minute) Series.

Devera, J.A., Nelson, W.J., and Masters, J.M., 1994, Geologic Map of the Mill Creek and McClure Quadrangles, Alexander and Union Counties, Illinois: Illinois State Geological Survey IGQ-15, scale 1:24,000, 1 sheet.

Eaton, S., 1992, Complex response of a channelized stream, Alexander County, Illinois, Virginia Journal of Science, Vol. 43, Issue 2, p. 263.

Esling, S. P., Hughes, B.W., and Graham, R.C., 1989, Analysis of the Cache Valley deposits in Illinois and implications regarding the late Pleistocene-Holocene development of the Ohio River Valley: Geology, V. 17, p. 434-437.

Fischer-Boyd, K.F., and Schumm, S.A., 1995, Geomorphic evidence of deformation in the northern part of the New Madrid seismic zone: U.S. Geological Survey Professional Paper 1538-R, 35 p.

Fisk, H.N., 1944, Geological investigation of the alluvial valley of the lower Mississippi River; Vicksburg, Mississippi River Commission, War Department, U.S. Corps of Engineers, p. 39-40.

Follmer, L.R., 1996, Loess studies in central United States: Evolution of concepts, Engineering Geology, 45 Fisk Symposium Volume, p. 287-304.

Forman S.L. and Pierson, J., 2002, Late Pleistocene luminescence chronology of loess deposition in the Missouri and Mississippi river valleys, United States: Paleogeography, Palaeoclimatology, Palaeoecology 186, p. 25-46.

Graham, R.C., 1985, The Quaternary history of the upper Cache River Valley, southern Illinois [Masters Thesis]: Carbondale, Southern Illinois University, 123 p.

Grimley DA, and NK Arruda. 2007. Observations of magnetite dissolution in poorly drained soils, Soil Science, 1 72, pp 968-982.

Grimley, D.A., Follmer, L.R., Hughes, R.E., and Solheid, P.A., 2003, Modern, Sangamon, and Yarmouth soil development in loess of unglaciated southwestern Illinois: Quaternary Science Reviews, v. 22, p. 225-244.

Grimley, D.A., Follmer, L.R., and McKay, E.D., 1998, Magnetic susceptibility and mineral zonations con trolled by provenance in loess along the Illinois and central Mississippi River valleys, Quaternary Research 49, pp 24-36.

Hansel, A.K., and Johnson, W.H., 1996, Wedron and Mason Groups: Lithostratigraphic reclassification of deposits of the Wisconsin Episode, Lake Michigan Lobe Area: Illinois State Geological Survey Bulletin 104, 116 p.

Harrison, R.W., Palmer, J.R., Hoffman, D., Vaughn, J.D., Repetski, J.E., Frederiksen, N.O., and Forman, S.L., 2002, Geologic map of the Scott City 7.5 minute Quadrangle, Scott and Cape Giradeale Counties, Missouri: U.S. Geological Survey, Geological Investigations Series Map I-2744.

Harrison, R.W., Hoffman, D., Vaughn, J.D., Palmer, J.R., Wiscombe, C.L., McGeehin, Stephenson, W.J., Odum, J.K., Williams, R.A., and Forman, S.L., 1999, An example of neotectonism in a continental interior-Thebes Gap, Midcontinent, United States.

Harrison, R.W. and Schultz, A., 1994, Strike-slip faulting at Thebes Gap, Missouri and Illinois: Implications for New Madrid tectonism: Tectonics, v.13, no. 2, p. 246-257.

Heyl, A.V., and McKeown, F.A., 1978, Preliminary seismotectonic map of central Mississippi Valley and environs: U.S. Geological Survey Miscellaneous Investigations Map MF-1011, scale 1:250,000, 2 sheets.

Hildenbrand, T. G., J. H. McBride, and D. Ravat (2002). The Commerce geophysical lineament and its possible relation to Mesoproterozoic igneous Complexes and large earthquakes in the central Illinois Basin, Seism. Res. Lett. 73, no. 5, 640–659.

Langenheim, V.E., and Hildenbrand, T.G., 1997, Commerce geophysical lineament-Its source, geometry, and relation to the Reelfoot rift and New Madrid seismic zone: GSA Bulletin, v. 109, no. 5, p 580-595.

Leigh, D.S., 1994, Roxana silt of the Upper Mississippi Valley: Lithology, source and paleoenvironment. Geological Society of America Bulletin 106, pages 430-442.

Lineback, J.A., 1966, Deep-Water Sediments Adjacent to the Borden Siltstone (Mississippian) Delta in Southern Illinois: Illinois State Geological Survey, Circular 401, 48 p.

Masters, J.M. and Reinertsen, D.L., 1987, The Cache Valley of southern Illinois, *in* Biggs, D. ed., Geological Society of America Centennial Field Guide- North-Central Section, v.. 3, p. 257-262.

McBride, J.H., Nelson, W.J., and Stephenson, W.J., 2002, Integrated Geological and Geophysical Study of Neogene and Quaternary-age Deformation in the Northern Mississippi Embayment: Seismological Research Letters, v 73, no. 5, P. 597-627.

McNulty, W.E., and Obermeier, S.F., 1999, Liquefaction evidence for at least two strong Holocene paleo-earthquakes in central and southwestern Illinois, USA: Environmental and Engineering Geoscience, v. 5, p. 133-136.

Munson, P.J., Obermeier, S.F., Munson, C.A., and Hajic, E.R., 1997, Liquefaction evidence for Holocene and latest Pleistocene in the southern halves of Indiana and Illinois-A preliminary overview: Seismological Research Letters, Vol. 68, No. 4, p. 521-536.

Natural Resources Conservation Service (NRCS), 2002, Soil Survey of Alexander County, Illinois: United States Department of Agriculture, 634 p.

Nelson, W.J., Denny, F.B., Devera, J.A., Follmer, L.R., Masters, J.M., 1997, Tertiary and Quaternary tectonic faulting in southernmost Illinois: Engineering Geology, v. 46, p. 235-258.

Nelson, W.J., Follmer, L.R., and Masters, J.M., 1999, Geologic Map of the Dongola Quadrangle Alexander, Pulaski, and Union Counties, Illinois: Illinois State Geological Survey IGQ-19, scale 1:24,000, 1 sheet.

Nelson, W.J. and L. Williams, 2004, Geology of Pulaski Quadrangle, Pulaski County, Illinois: Illinois State Geological Survey, Illinois Preliminary Geologic Map, IPGM Pulaski-G, scale 1:24,000, 2 sheets.

Odum, J.K., Stephenson, W.J., Williams, R.A., Devera, J.A., and Staub, J.R., 2002, Near-surface Faulting and Deformation Overlying the Commerce Geophysical Lineament in Southern Illinois: Seismological Research Letters, v. 73, no. 5, p. 687-697.

Palmer, J.R., Hoffman, D., Stephenson, W.J., Odum, J.K., and Williams, R.A.., 1997, Shallow seismic reflection profiles and geological structure in the Benton Hills, southeast Missouri: Engineering Geology, v. 46, p. 217-233.

Ray, L.L., 1963, Quaternary events along the unglaciated Lower Ohio River Valley: U.S. Geological Survey Professional Paper 475-B, P. B125-B128.

Royall, P.D., Delcourt, P.A., and Delcourt, H.R., 1991, Late Quaternary paleoecology and paleoenvironments of the Central Mississippi alluvial valley: Geological Society of America Bulletin, v. 103, p. 157-170.

Satterfield, I.R., and Ward, R.A., 1978, Structural geologic study of southeast Missouri: Summary of Annual Progress Report-Phase 1-Fiscal Year 1978, Contract No. NRC-04078-206; *in*, New Madrid Seismotectonic Study-Activities during Fiscal Year 1978, ed. Buschbach, T.C., Illinois State Geological Survey, p. 53-63.

Saucier, R.T., 1974, Quaternary geology of the Lower Mississippi Valley: Arkansas Arch. Survey Res. Series 6, 26 p.

Shaw, E.W., 1911, Preliminary statements concerning a new system of Quaternary lakes in the Mississippi Basin: Journal of Geology, v. 19, p. 481-491.

Stephenson, W.J., Odum, J.K., Williams, R.A., Pratt, T.L., Harrison, R.W., and Hoffman, D., 1999, Deformation and Quaternary faulting in southeast Missouri across the Commerce Geophysical Lineament: Bulletin of Seismological Society of America, v. 89, no. 1, p. 140-155.

Stewart, D.R., and McManamy, L., 1944, Early Quaternary or late Tertiary folding in the vicinity of commerce, Scott County, southeastern Missouri. Internal report, Mo. Acad. Of Sci., Rolla, Mo.

Thompson, T.L., 1981, Structural geologic study of southeastern Missouri: Division of Reactor Safety Research, Nuclear Regulatory Commission, Contract No. NRC-04-78-206, 25 p.

Tuttle, M., Chester, J., Laferty, R., Dyer-Williams, K., Hyanes, M., Cande, R., and Sierzchula, M., 1998, Liquefaction features in southwestern Illinois and southeastern Missouri and their implications for paleoseismicity [abs.]: American Geophysical Union (Eos) Spring Meeting.

Tuttle, M., and Chester, J.S., 2001, Paleoseismology Study in the Cache River Valley, Southern Illinois: Collaborative Research, Texas A&M University and M. Tuttle & Associates: U.S. Geological Survey Award No. 1434-HQ-98GR-00013 and 1434-HQ-98-GR-00015, Final Technical Report, 14 p.

Tuttle, M. P., Schweig, E.S., Sims, J.D., Lafferty, R.H., Wolf, L.W. and Haynes, M.L. (2002), The earthquake potential of the New Madrid seismic zone, Seism. Soc. Am. Bull. 92, 6, 2080–2089.

Tuttle, M.P., Schweig, E.S., Campbell, J., Thomas, P.M., Sims, J.D., and Lafferty, R.H.,2005; Evidence for New Madrid Earthquakes in A.D. 300 and 2350 B.C., Seismological Research Letters, v. 76, no. 4, p. 489-501.

Tuttle, M.P., Al-Shukri, H., and Mahdi, H., 2006, Very large earthquakes centered southwest of the New Madrid seismic zone 5,000-7,000 years ago: Seismological Research Letters, v. 77, no. 6, pp. 664-678.

U.S. Geological Survey, 1920, Jonesboro Quadrangle, Illinois, scale 1:62500, 1 sheet.

U.S. Geological Survey, 1923, Dongola Quadrangle, Illinois, scale 1:62500, 1 sheet.

U.S. Geological Survey, 1933, Cairo Quadrangle, Illinois-Kentucky-Missouri, scale 1:62500, 1 sheet.

U.S. Geological Survey, 1934, Thebes Quadrangle, Illinois-Missouri, scale 1:62500, 1 sheet.

U.S. Geological Survey, 1947 (Photorevised 1990), McClure Quadrangle, scale 1:24000, 1 sheet.

U.S. Geological Survey, 1947 (Photorevised 1990), Mill Creek Quadrangle, scale 1:24000, 1 sheet.

U.S. Geological Survey, 1966 (Photorevised 1990), Dongola Quadrangle, scale 1:24000, 1 sheet.

U.S. Geological Survey, 1967, Tamms Quadrangle, scale 1:24000, 1 sheet.

Vaughn, J.D., 1991, Evidence for multiple generations of seismically induced liquefaction features in the Western Lowlands, southeast Missouri [abs.]: Seismological Research Letters, v. 62, p. 189.

Vaughn, J.D., 1992, Active tectonics in the Western Lowlands of southeast Missouri: An initial assessment; *in*, Missouri Department Natural Resources Special Publication No. 8, 54-59.

Vaughn, J.D., 1994, Paleoseismological studies in the western lowlands of southeast Missouri: Report to NEHRP Annual External Program, contract no. 14-08-0001-G1931, 27 pp.

Vaughn, J.D., Baldwin, J.N., and Barron, A.D., 2002, Recurrent Late-Quaternary deformation within the Dexter Tectonic Zone, upper Mississippi embayment [abs.]: International Basement Tectonics Association 16th Annual Conference, Rolla, MO, May 19 to 24, 2002.

Walters, R.C., and Merritts, D.J., 2008, Natural Streams and the Legacy of Water-Powered Mills, Science, v. 319, p. 299-304.

Wells, D.L and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Bulletin of the Seismological Society of America, v. 84, p. 974-1,002.

William, H.B., and Frye, J.C., 1970, Pleistocene stratigraphy of Illinois, Illinois State Geological Survey Bulletin 94, 204 p.

Zoback, M.L., 1992, Stress field constraints on intraplate seismicity in eastern North America: Journal Geophysical Resources, v. 97, p. 11,761-11,782.

TABLES

Table 1. Summary of Radiocarbon Analyses, Tamms, Illinois, Penitentiary Fault

Sample Name	Lab No.	Depth (ft bgs[1])	Stratigraphic Unit	Sample Description	^{14}C Age, yr B.P.	+/-	95.4% (2σ) cal age total range[#]
B-13-RC-2	Beta 281068	6.5	Cahokia	charred material	90	40	Cal BP 260 to 0
B-15-RC-1	Beta 281070	24.8	Cahokia	charcoal	10,430	50	Cal BP 12,620 to 12,110
B-13-RC-3	Beta 281069	20.3	Equality	orangic material	10,940	50	Cal BP 12,940 to 12,850
B-15-RC-2	Beta 281071	26.5	Equality	charred material	10,640	50	Cal BP 12,820 to 12,650
B-8-RC-1	Beta 269600	24.8	Equality	wood	13,820	70	Cal BP 16,600 to 16,240
B-8-RC-2	Beta 269601	34	Equality	wood	13,660	70	Cal BP 16,410 to 16,050
B-10-RC-1	Beta 269602	35. 0	Equality	wood	14,370	70	Cal BP 17,410 to 16,930
B-2-RC-2	Beta 269599	37.8	Equality	wood	14,070	70	Cal BP 16,890 to 16,540
B-18-RC-1	Beta 281072	40.3	Henry	orangic material	20,810	90	Outside Calibration Range

Samples are listed in stratigraphic order, with stratigraphically highest samples placed at the top.

[1] ft bgs - feet below ground surface

FIGURES

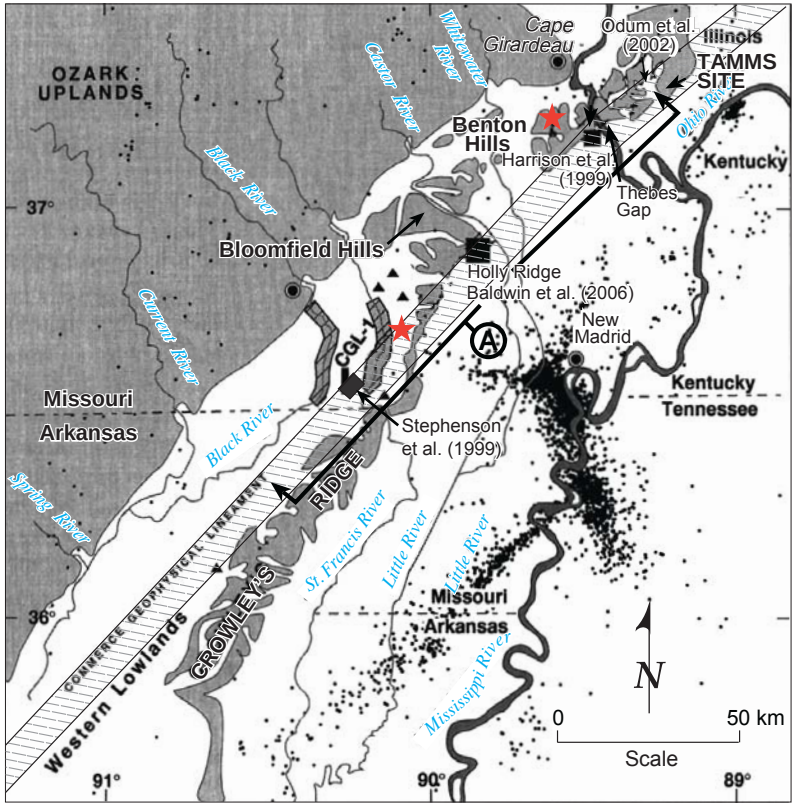


Figure 1. Regional map of the southeastern Missouri showing the surface projection of the Commerce geophysical lineament (horizontal hatch pattern). The pre-Quaternary deposits (light gray fill pattern), Quaternary (white), and main rivers (medium gray) are also shown. Sites of paleoliquefaction (Vaughn, 1994) are shown by triangles. Epicenters of recorded seismicity from 1974 to 1995 are shown by black dots. Epicenters of M4.8 are shown by stars. Letter Ⓐ shows Commerce section of the CGL. Newport and Junction sections are to the southwest and northeast of map edge, respectively. Modified from Stephenson et al. (1999).

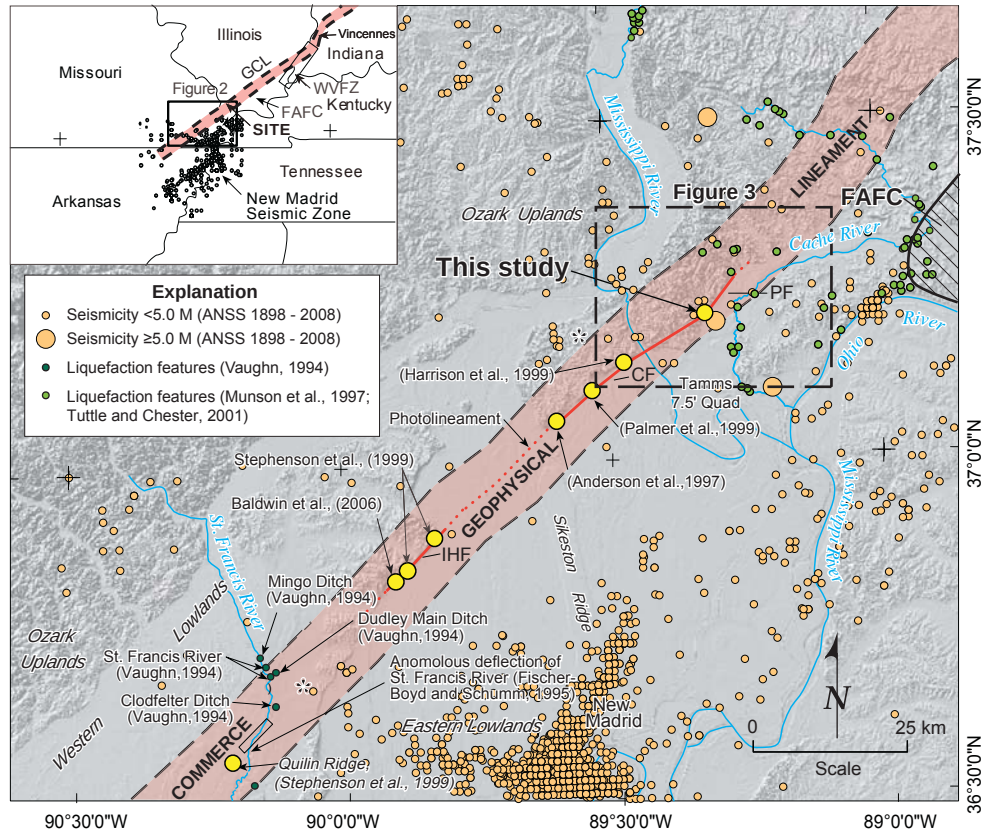


Figure 2. Regional location map of the New Madrid seismic zone and the Commerce geophysical lineament based on latitude and longitude coordinates provided by Hildenbrand (personal communication, 2002) and modified partly from Stephenson et al. (1999). IHF = Idalia Hill fault; CF = Commerce fault; PF= Penitentiary fault; WVFZ = Wabash Valley Fault Zone; FAFC = Fluorspar area fault complex and hachured zone. Star (*) = epicenters of M4.8 earthquakes. Arrows in inset map point to location of FAFC, NMSZ, and WVFZ.

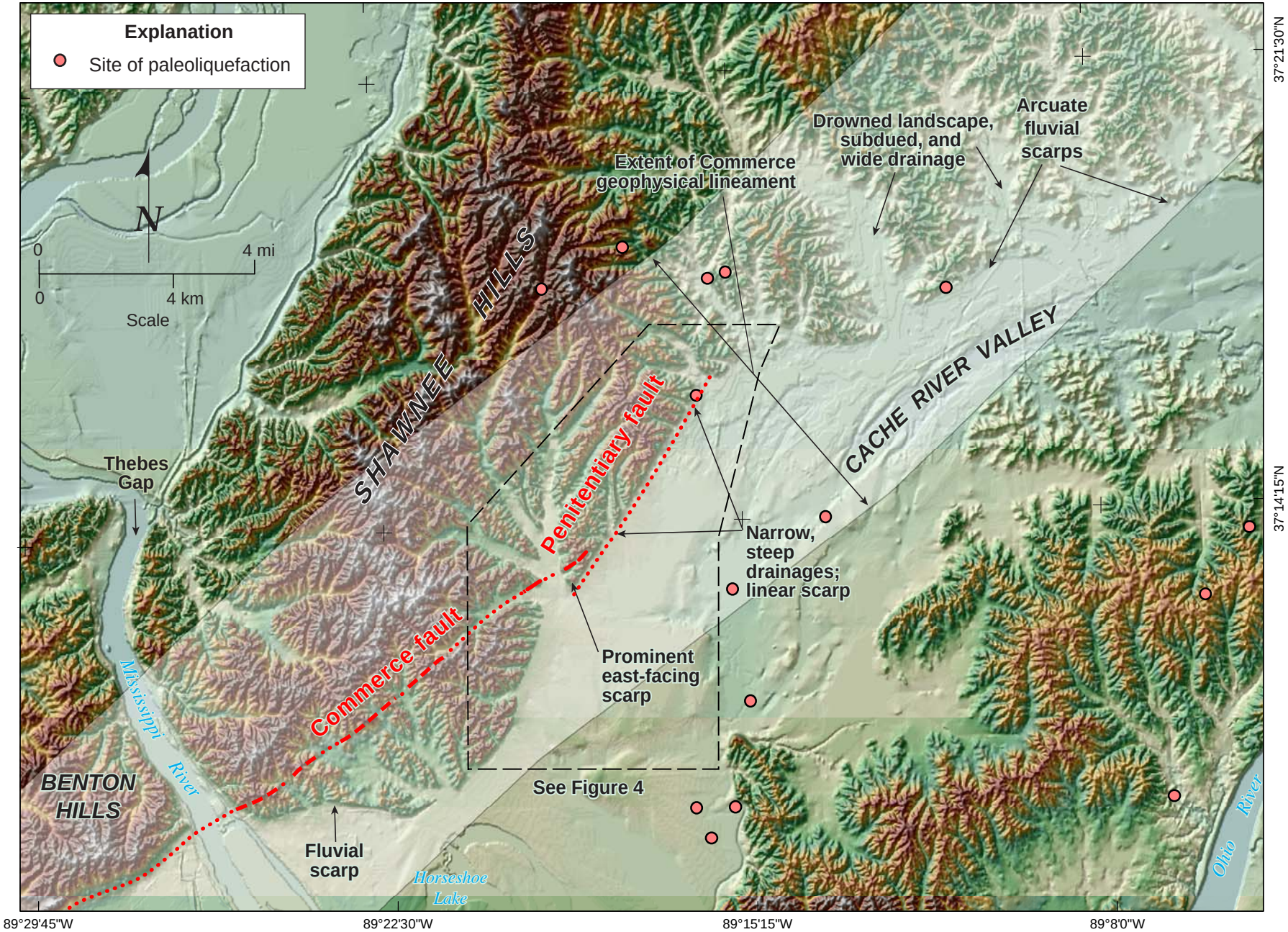


Figure 3. Digital elevation model (DEM) of the Cache River Valley, Shawnee Hills, and Benton Hills in southern Illinois and Missouri. 30-meter DEM downloaded from National Elevation Dataset (January, 2006). Site of paleoliquefaction from Munson et al. (1997) and, Tuttle and Chester (2001). Shaded region is extent of Commerce geophysical lineament.

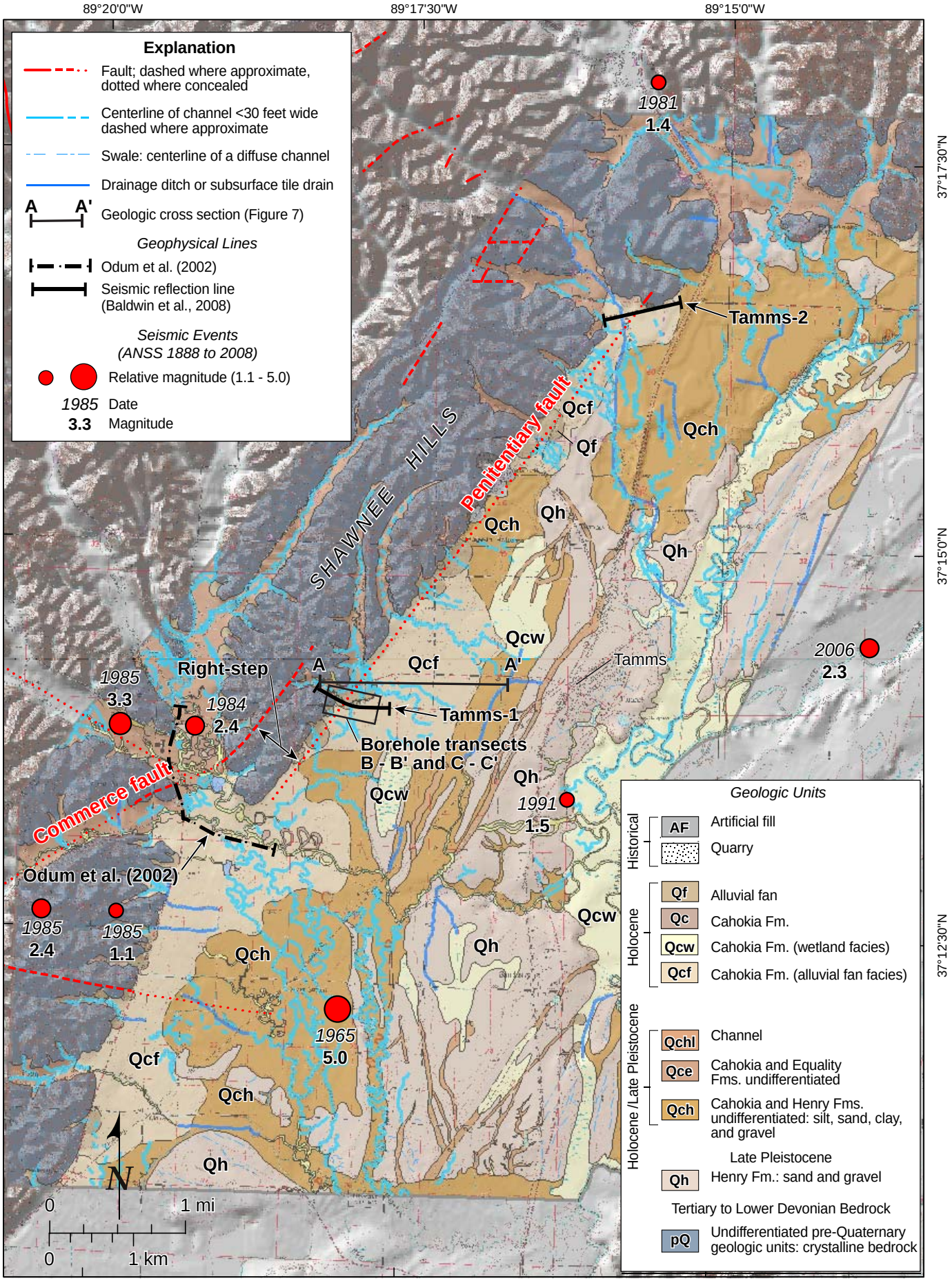


Figure 4. Quaternary geomorphic and geologic map of the Tamms area, southern Illinois. Note the four small magnitude earthquakes that occur near the step-over between the Commerce and Penitentiary faults. See Plate 1 of Baldwin et al. (2008) for full-scale version of geologic mapping.

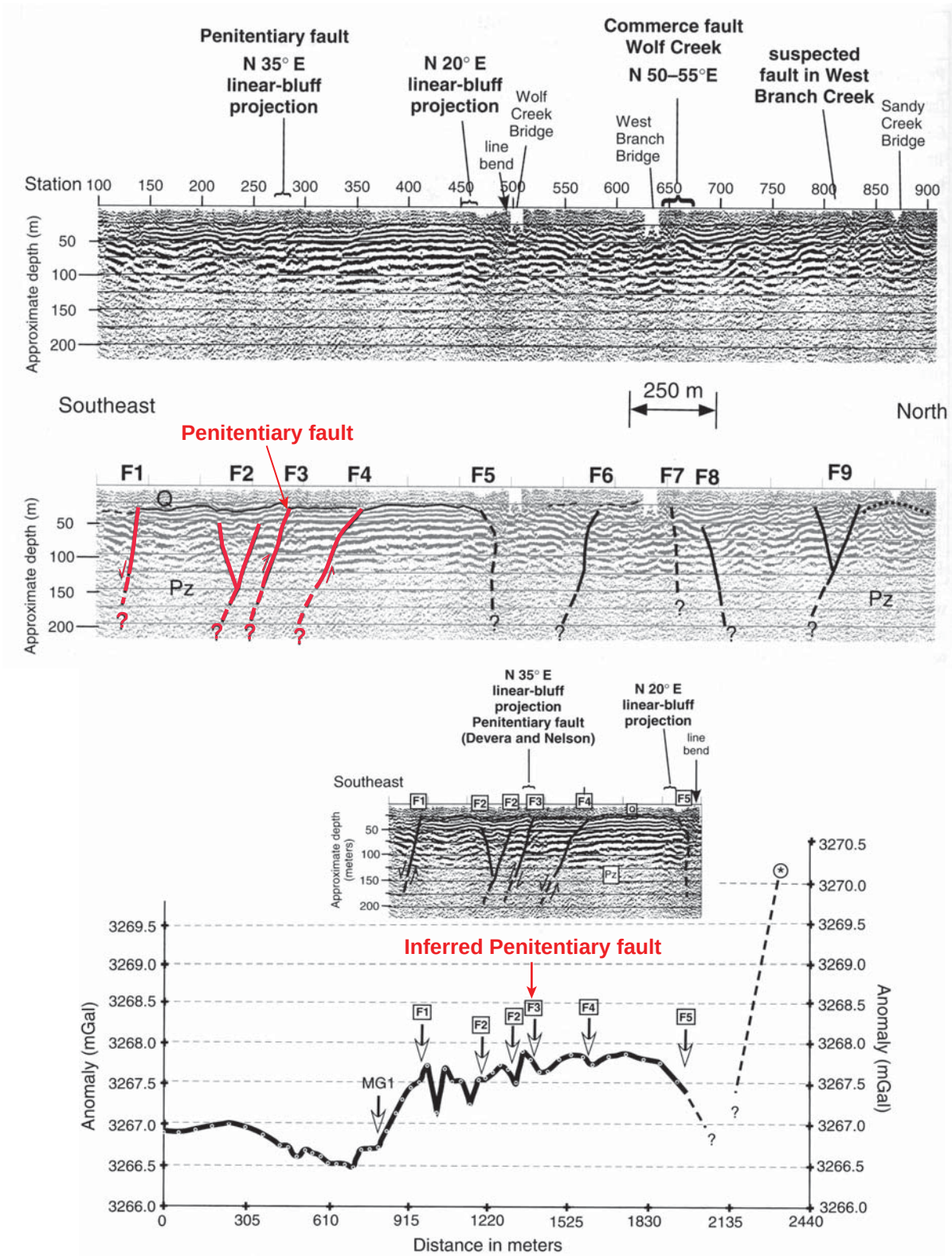
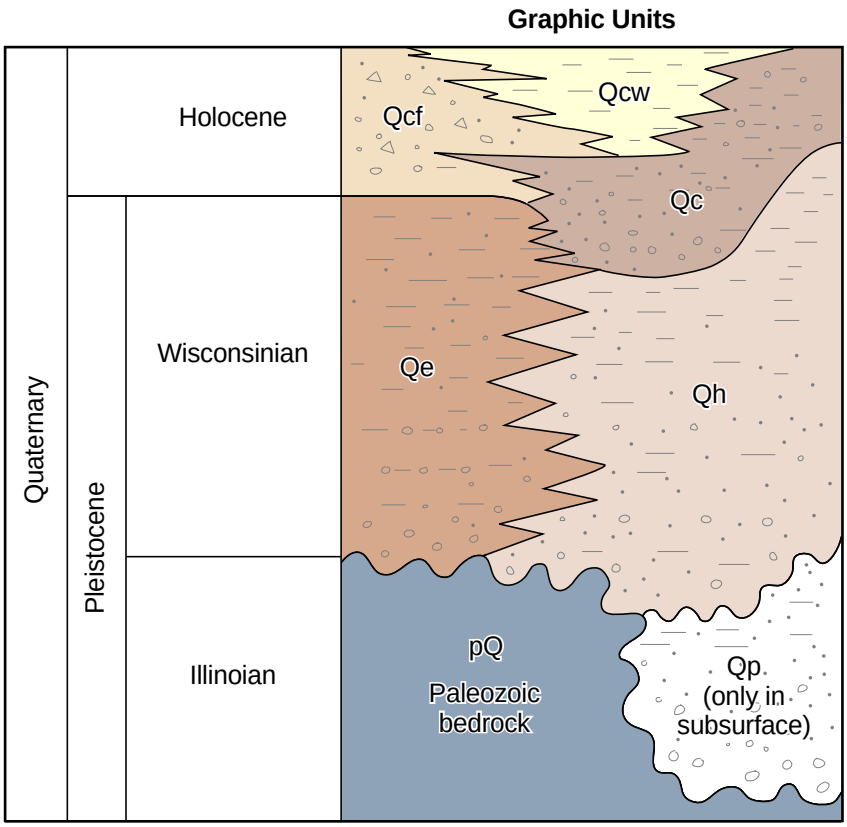


Figure 5. Uninterrupted migrated depth-converted seismic-reflection profile of Odum et al. (2002). Odum et al. (2002) interpret the reflective package observed across the profile to be predominantly Paleozoic with small amount of overlying Quaternary deposits. The profile shows substantial folding and faulting. Much of the deformation coincides with the projections of topographic bluff fronts (suspected fault-line scarps) and the projected trace of the Commerce fault. Faults F1 to F4 of Odum et al. (2002) are the focus of the Old Diswood Road investigation.



Note: Peoria silt not shown, covers bedrock in upland areas. Modified from Devera and Follmer (in prep.).

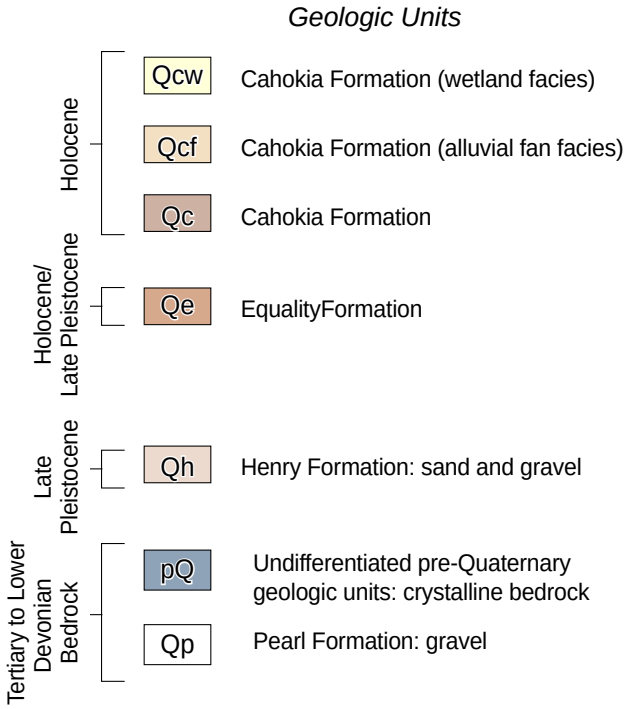


Figure 6. Schematic showing stratigraphic relationship between major geologic units in the map area (see Plate 1 of Baldwin et al., 2008 for detailed map units).

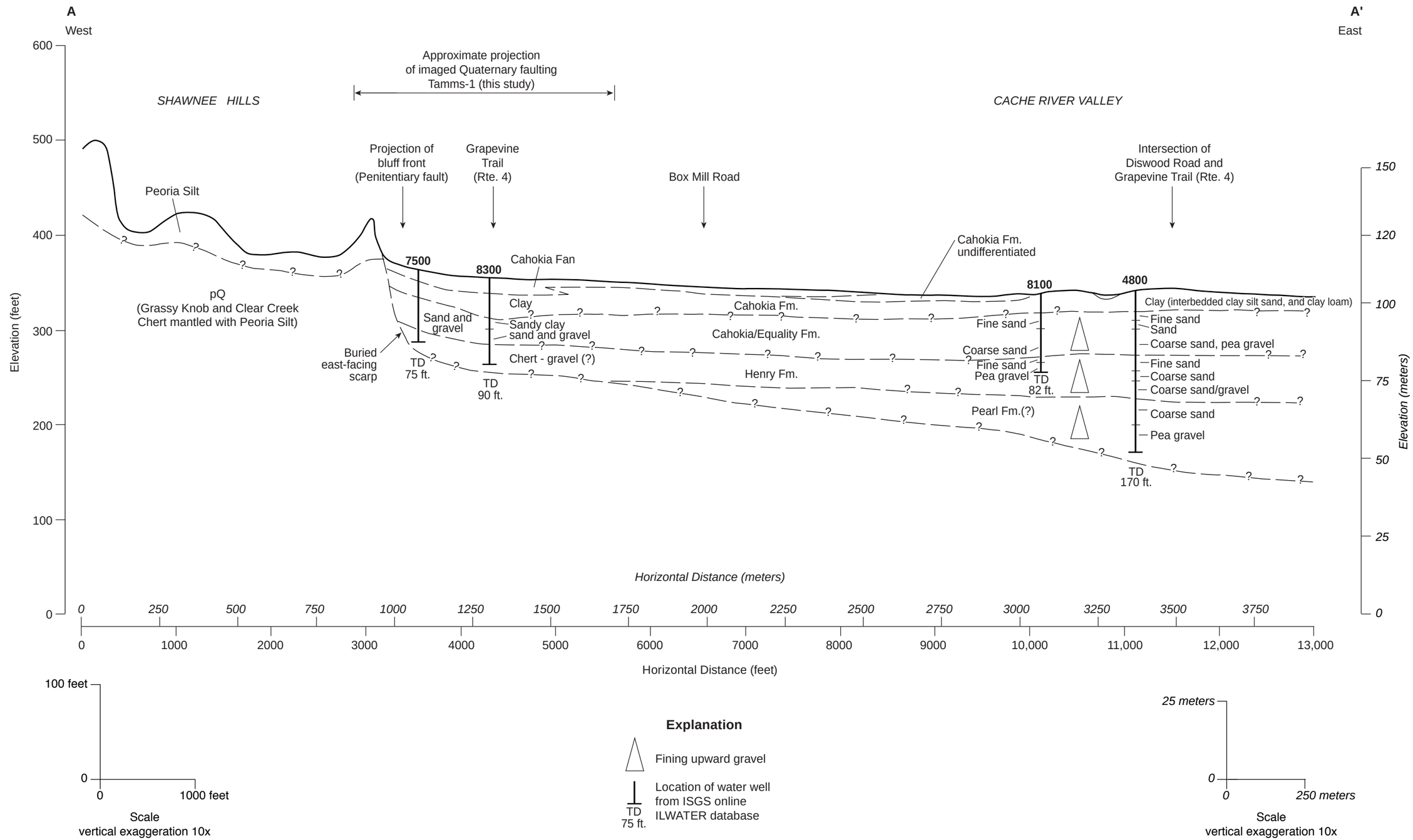


Figure 7. Generalized geologic cross section A - A' across the Penitentiary fault and Shawnee Hills range front. Note the buried east-facing scarp coincident with the Penitentiary fault and imaged Quaternary faulting. At the base of well numbers 7500 and 8300 only chert was noted on driller's logs. These descriptions are either fluvial chert-rich gravels or bedrock chips.

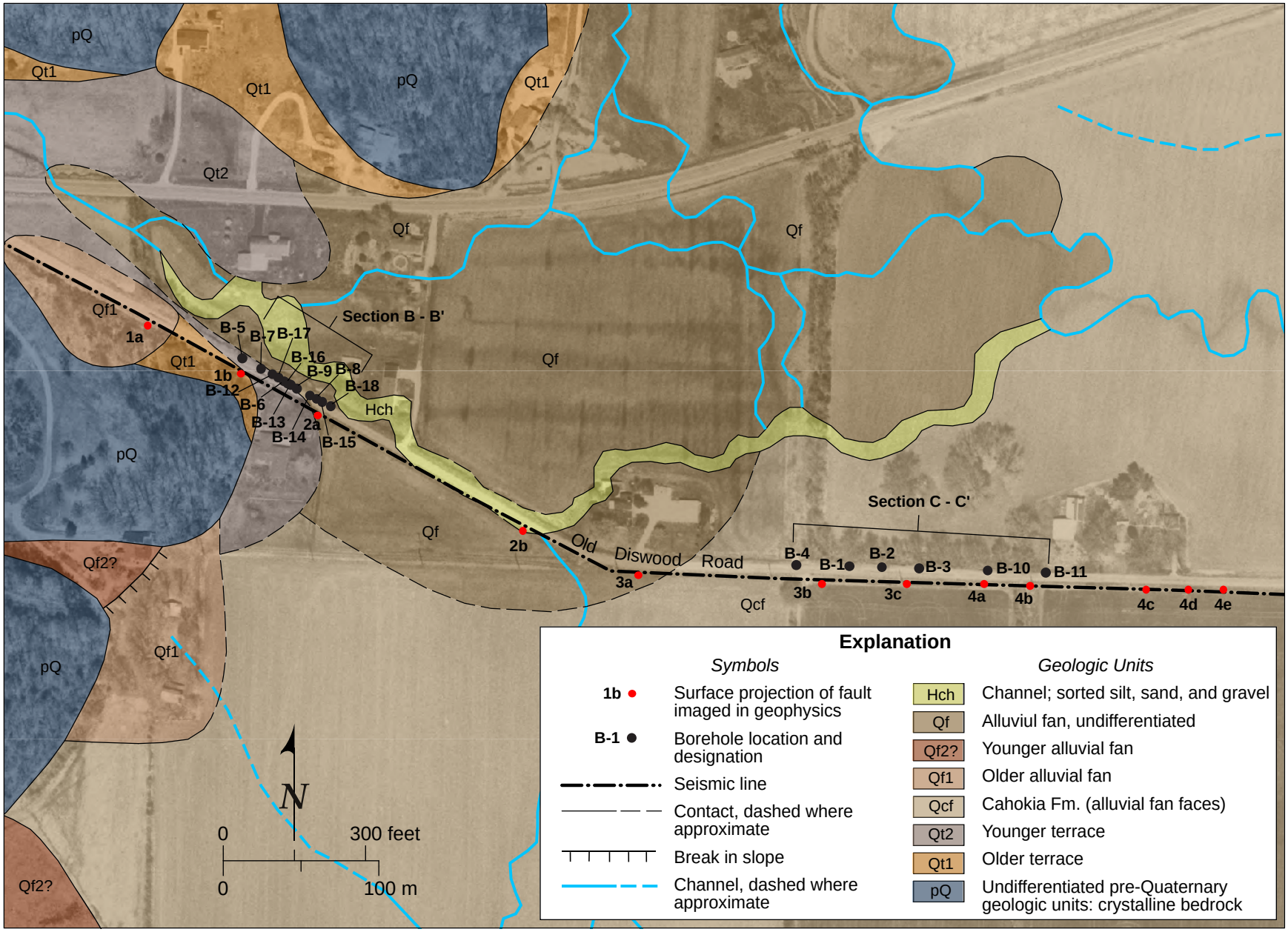


Figure 8. Local geologic map with borehole locations.

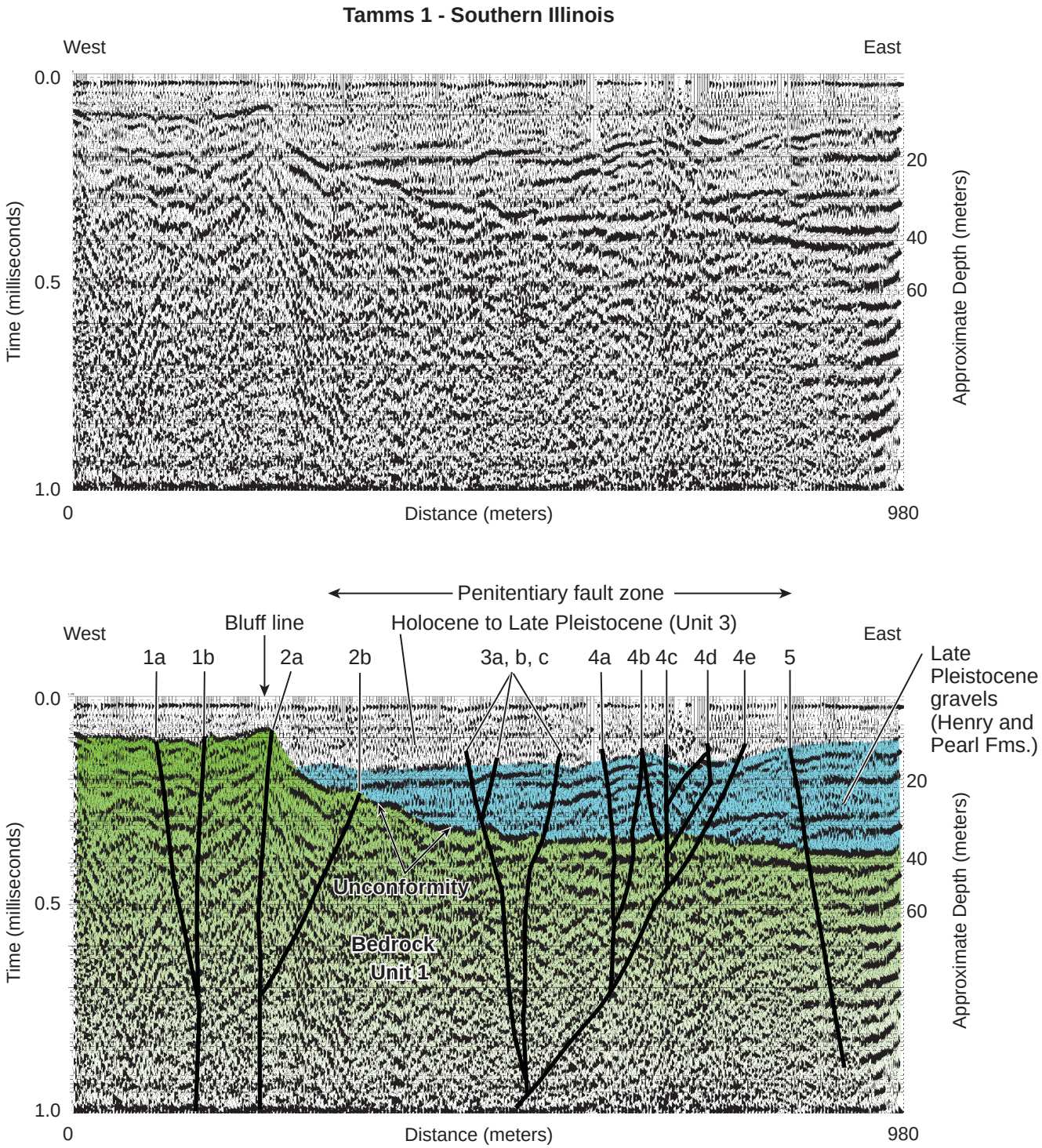


Figure 9. Shear-wave seismic reflection survey of Tamms-1 along Old Diswood Road. Interpreted profile shows the top of bedrock (Paleozoic bedrock), Late Pleistocene gravels (blue color), and Holocene to Late Pleistocene alluvium (poor reflectors shown in white), and interpreted faults. Faults are labeled with integers and individual fault splays are labeled with letters.

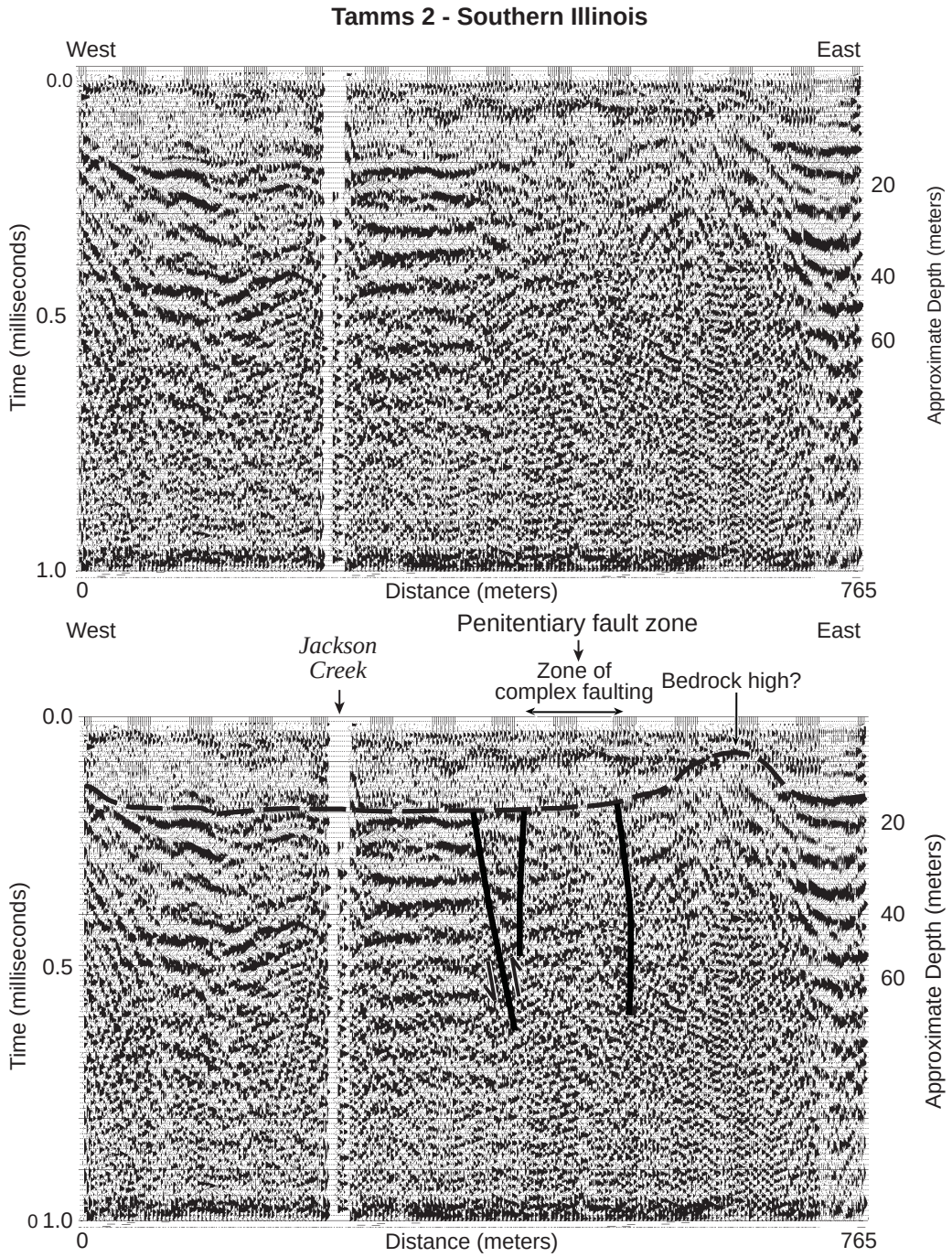
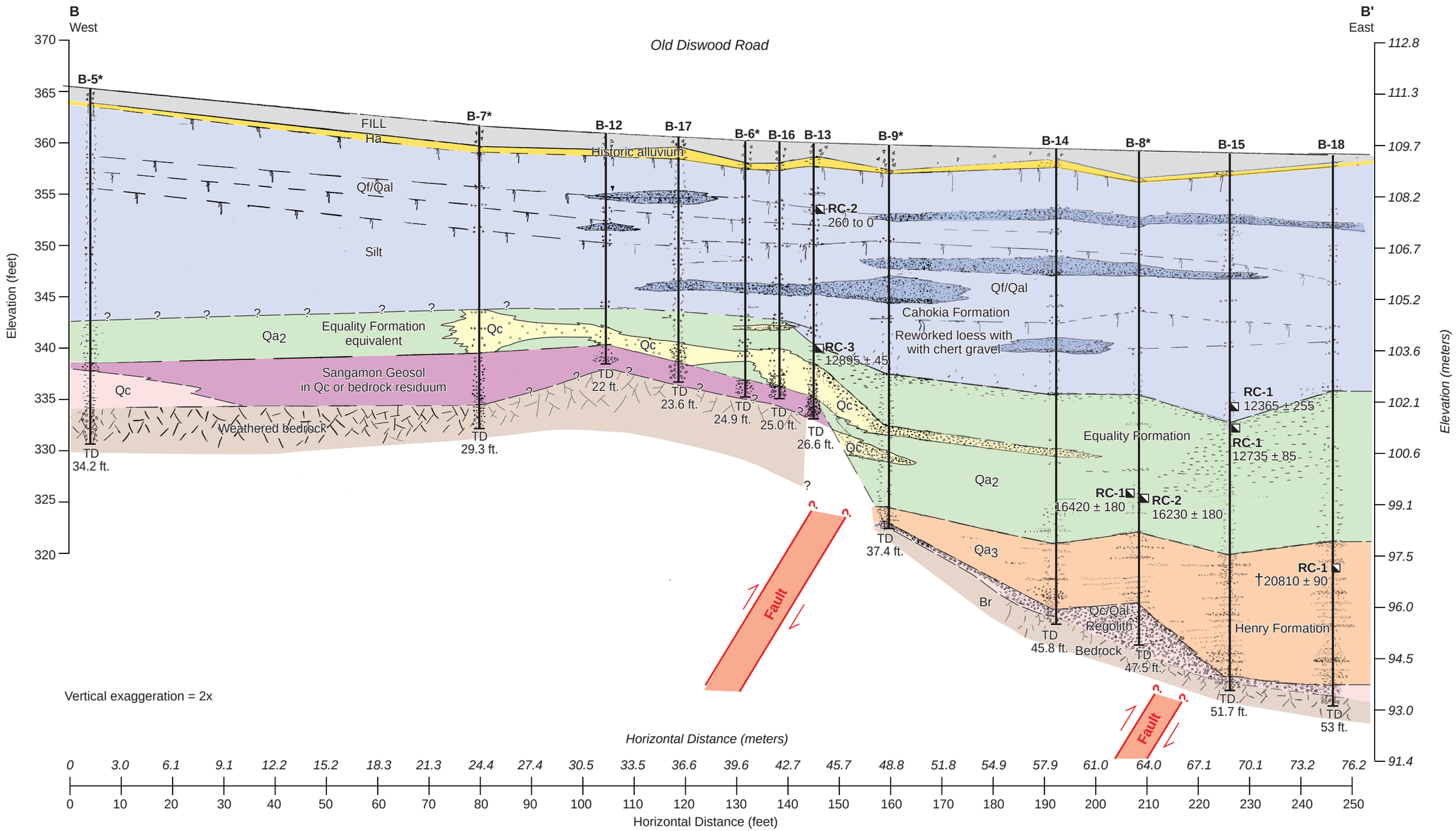


Figure 10. Shear-wave seismic reflection survey Tamms-2 along Newell Road. Interpreted profile shows bedrock adjacent to an area of poor reflector quality interpreted as faulted bedrock which coincides with a mapped bedrock fault (Figure 4). The bedrock (Unit 1) contact with Late Pleistocene gravels (Unit 2) is not readily resolvable.



Explanation

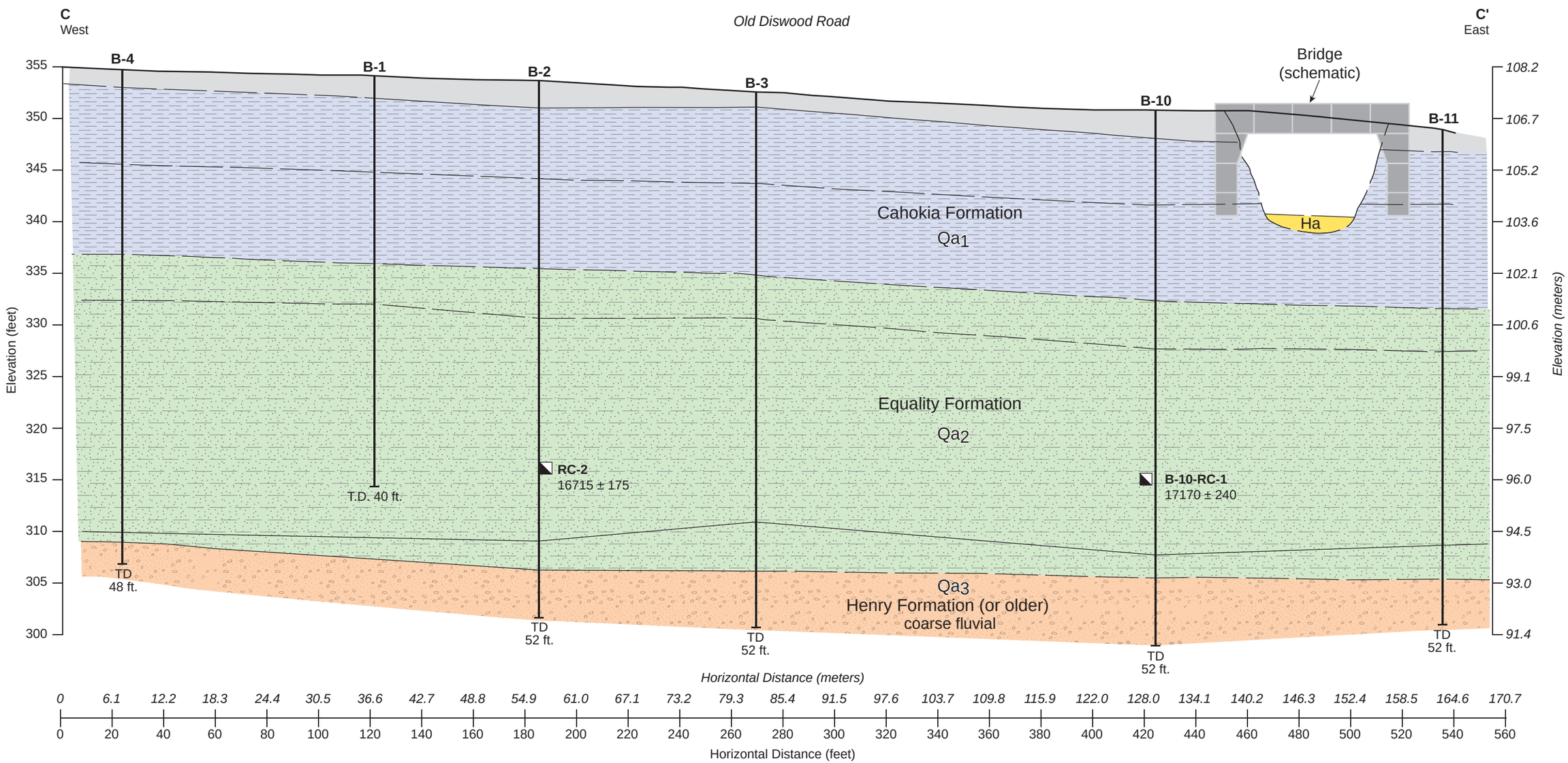
Geologic Units

FILL	Road base fill in shoulder
Ha	Historic alluvium
Qf/Qal	Reworked loess and discontinuous gravels (Cahokia Formation)
Qc	Quaternary colluvium (Equality Formation)
Qa_2	Quaternary alluvium (Equality Formation)
Qa_3	Quaternary alluvium (Henry Formation)
Qc	Sangamon Geosol (Pearl Formation or later)
Qc/Qal	Quaternary colluvium/regolith (pre-Henry Formation)
Br	Bedrock

Symbols

RC-1 ◥ 16420 ± 180	Radiocarbon location and designation; 2σ age is cal yrs. BP (see Table 1)
†	Too old for 2σ age
*	Core with magnetic susceptibility test
	Soil horizon

Figure 11. Cross section B - B' across Penitentiary fault zone at edge of Shawnee Hills escarpment.



Explanation

Geologic Units

- FILL — Road base fill
- Ha — Historic alluvium
- Qa_1 — Reworked loess (Cahokia Formation)
- Qa_2 — Quaternary alluvium (Equality Formation)
- Qa_3 — Quaternary alluvium (Henry Formation)

Symbol

RC-2 16715 ± 175 — Radiocarbon location and designation; 2σ age is cal yrs. BP; (see Table 1)

Figure 12. Cross section C - C' along Old Diswood Road, Tamms, Illinois, in the west-central part of the Cache River Valley.

2043 Penitentiary fault

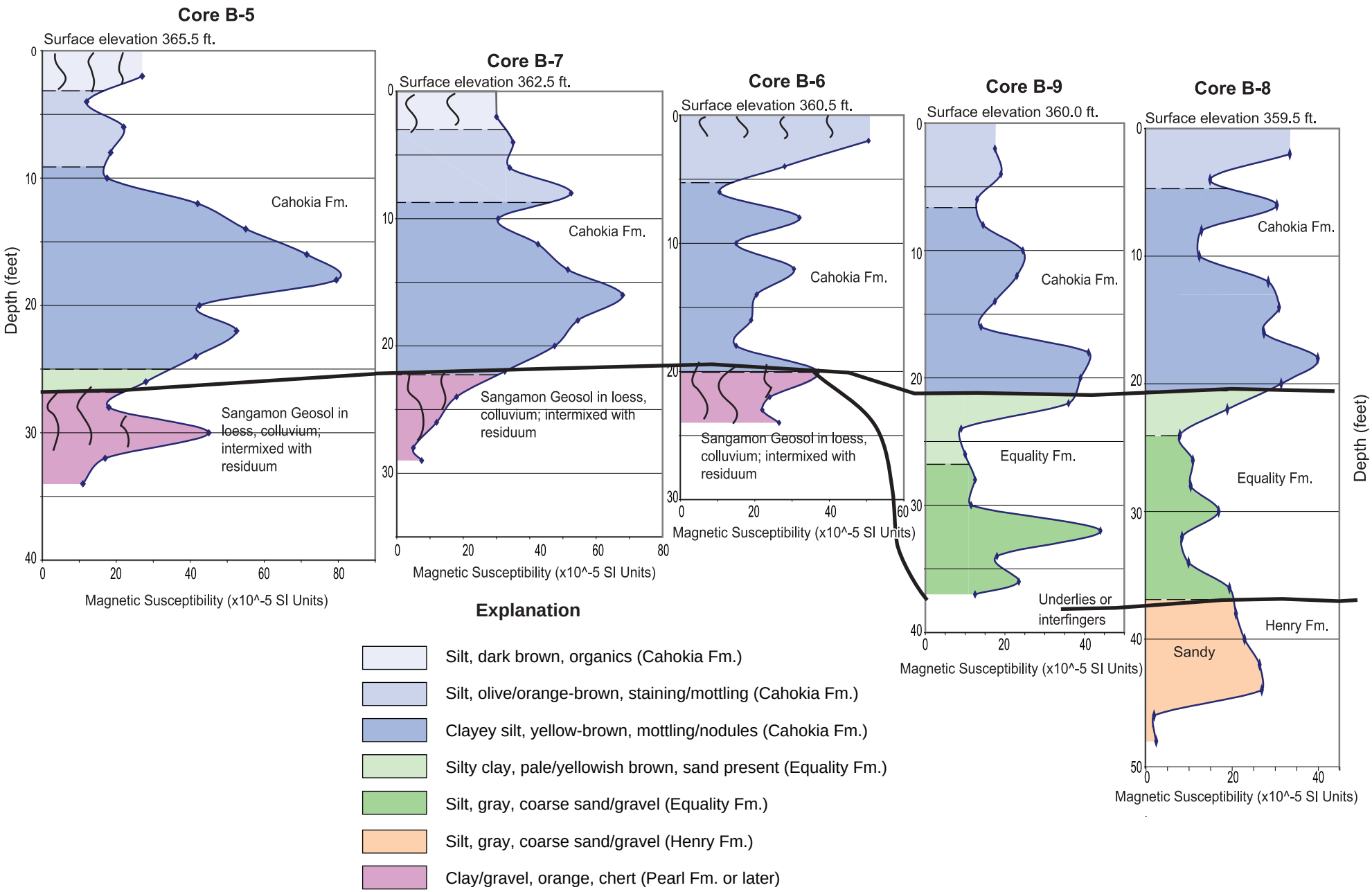


Figure 13. Magnetic susceptibility plots vs. depth with approximate elevations and correlated stratigraphy. Surface elevations are approximate and horizontal distance is schematic.

2043 Penitentiary fault

Distance* along Commerce Section	Paleoseismic Sites (reference)	Possible Rupture Scenarios						
		HOLOCENE					PLEISTOCENE	
		Late Holocene			Middle Holocene	Early Holocene	Pre 17,000 yrs BP	Pre 50,000 yrs BP
0 km	Old Diswood Road, Tamms, IL (this study)					Post 12,600 but pre middle Holocene	Henry Formation	Pearl Formation
19 km	Benton Hills, MO (Harrison et al., 2002)		1260 ± 50 yr BP		4860 ± 120 yr BP		Pre-Peoria (35 to 25 ka)	Pre- to early Roxana time (60 to 50 ka)
65 km	South Holly Ridge Site, MO (Stephenson et al. 1999; Baldwin et al., 2006)					18,500 to 7,600 yr ka	Predates 23,600 to 18,900 ka	
108 km	Qulin liquefaction site, MO (Vaughn, 1994)	AD 1440 to 1540 (attributed to NMSZ)		AD 240 to 1020 (attributed to NMSZ)		13,400 to 9,000 yr BP	23,000 to 17,000 BP	

*Measured from northeast to southwest along the Commerce Section of the CGL.

Figure 14. Preliminary compilation of event timing information for faults aligned with the Commerce geophysical lineament between Missouri and Illinois. Dashed zones refer to "permissable events."