FINAL TECHNICAL REPORT

GEOPHYSICAL AND PALEOSEISMIC INVESTIGATION OF THE COMMERCE GEOPHYSICAL LINEAMENT, QULIN, SOUTHEAST MISSOURI.

Recipient:
Fugro Consultants, Inc.,
1777 Botelho Dr., Suite 262, Walnut Creek, CA 94596
(925) 256-6070 (phone); (925)256-6076 (fax);
URL www.fugroconsultants.com

Lettis Consultants International, Inc.
1981 N. Broadway, Suite 330, Walnut Creek, CA 94596
(925) 482-0360 (phone); URL www.lettisci.com

Principal Investigators:
John N. Baldwin, Robert Givler, and Cooper Brossy
Email: baldwin@lettisci.com; givler@lettisci.com; c.brossy@fugro.com

Contributors:

Jamey Harris, Millsaps College, Jackson MS 39210-0001
harrijb@millsaps.edu

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Baldwin, J.N. [1], Givler, R. [1], and, Brossy, C.C.[2], J.D. and Harris, J.[3]

Principal Investigators:

[1] Lettis Consultants International, Inc., 1981 N. Broadway, Suite 330, Walnut Creek, CA 94596
balwin@lettisci.com; givler@lettisci.com; phone: (925) 482-0360

[2]Fugro Consultants, Inc., 1777 Botelho Drive, Suite 262, Walnut Creek, CA 94596
c.brossy@fugro.com; phone: (925) 256-6070, fax: (925) 256-6076

Contributors:

[3]Millsaps College, Jackson MS 39210-0001
harrijb@millsaps.edu; phone: (601) 974-1343, fax: (601) 974-1397

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 that is associated with Quaternary deformation northwest of the New Madrid seismic zone. In southern Missouri, a previous study (Stephenson et al., 1999) imaged deformed Quaternary sediments coincident with the CGL. In addition, numerous Late Pleistocene to Holocene faults associated partly with the CGL have been documented in the Benton Hills, Missouri and in Tamms, Illinois (Harrison et al., 1999; Baldwin et al., 2006; 2010). This geophysical and paleoseismic study was designed to further document Quaternary deformation at the southwest end of the CGL in southern Missouri.

At the Qulin site, in southern Missouri, we conducted geologic mapping, collected geophysical data, and drilled closely spaced boreholes across lineaments coincident with previously interpreted Quaternary faulting at depth (Stephenson et al., 1999). Our geologic mapping identified a series of discontinuous northeast-striking tonal and topographic lineaments across the late Pleistocene surface that forms Qulin Ridge. An approximately 1-km-long east-west oriented shear-wave seismic reflection profile, named Qulin 1, was acquired across these lineaments and across the projection of faulting imaged previously by Stephenson et al. (1999). In this seismic line, we identified four steeply east-dipping faults producing up to 5 meters of down-to-the-east displacement of the base of the Quaternary section across a 400 m-wide-zone of deformation. Along the projection of the faults imaged in the Qulin 1 line, we drilled a transect of closely spaced boreholes across the lineaments to a maximum depth of 10 m. The boreholes encountered late Pleistocene braided stream deposits overlain by the Late Pleistocene Peoria Loess (and possibly Roxanna silt). Stratigraphic interpretations developed from the borehole data identified multiple marker horizons to assess presence or absence of deformation from the surface to depths of 2.5 and 4.9 m. The interpreted stratigraphic and pedologic horizons appear to be relatively horizontal with little conclusive evidence of consistently abrupt or anomalous vertical separations. Several of the interpreted horizons may allow for 0.3 to 1.0 m of east-down separation, suggesting little to no deformation within 4.9 m of the ground surface. While stratigraphic interpretations developed from the borehole data were inconclusive, the seismic

refraction data provide evidence of Quaternary faulting at the Qulin site. Together, this investigation and other studies provide evidence of Quaternary fault activity along a 110-km-long section of the Commerce geophysical lineament from southern Illinois to southwestern Missouri.

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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 (EPRI, 2012; USGS, 2014). 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 report presents the results of a geophysical and paleoseismic investigation in southern Missouri at the Qulin site that coincides with the CGL, a geophysical feature with evidence of late Pleistocene to Holocene deformation along the western margin of the Mississippi embayment.

The CGL is a 600-km-long, 5- to 10-km-wide 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 Qulin site is located along the Commerce section of the CGL within the northwestern Mississippi embayment about 50 to 60 kilometers west of the active New Madrid seismic zone (NMSZ) (Figure 1). Recent geologic, geomorphic and geophysical studies performed along the CGL in southeastern Missouri and southern Illinois 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 (Cox, 1988; Fischer-Boyd and Schumm, 1995); (2) displacement of late-Tertiary and Pleistocene to Holocene deposits along northeast-striking faults (Groshkopf, 1955; Satterfield and Ward, 1978; Thompson, 1981; Harrison et al., 1999; Harrison et al., 2002; Baldwin et al., 2006; 2008); (3) paleoliquefaction features within the Western Lowlands (Figure 1; Vaughn, 1991; 1992; 1994; and Vaughn et al., 2002); (4) diffuse microseismicity (Harrison and Schultz, 1994; Langenheim and Hildenbrand, 1997; Hildenbrand and Ravat, 1997); (5) geophysical evidence suggesting faulting of Paleozoic/Cretaceous and possibly Tertiary-Quaternary deposits (Stephenson et al., 1999); and (6) geologic and geophysical data collected in Illinois and Indiana indicate that structures spatially coincident with the CGL maybe Quaternary active (Odum, et al., 2002, McBride et al., 2002; Baldwin et al. 2010).

Combined, this body of evidence strongly implies that previously mapped northeast-striking faults that overlie the surface projection of the CGL in southeast Missouri, 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 southern end of the Commerce geophysical lineament in Missouri and identifies similar possible reactivated faults in the subsurface characterized by Stephenson et al. (1999) (Figures 1 and 2).

2.0 REGIONAL TECTONIC SETTING

The CGL represents a 600-km-long series of Early Cambrian to possibly Precambrian mafic dike intrusions emplaced along pre-existing 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 is 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 has been reactivated multiple times during varying stress regimes.

The Qulin site lies just west of the Reelfoot rift, southwest of the Fluospar Area Fault Complex, the Rough Creek graben, and the Wabash Valley (Figure 2). The northeast-trending Reelfoot rift includes the active New Madrid seismic zone (NMSZ) that lies approximately 50-km-east 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 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). Similarly, 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 (Figure 2) (Baldwin et al., 2006; 2008; 2010). These northeast-striking faults overlie the CGL, similar to the lineaments identified at the Qulin Site.

2.1 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 previously assessed Commerce and Penitentiary faults, as well as the Qulin 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 2). 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, recently interpreted as Quaternary active (Odum et al., 2002; Baldwin et al., 2008; 2010; 2011) (Figure 2).

Quaternary active faults along the CGL are interpreted as transpressional strike-slip structures using a number of geologic and seismologic observations, including: (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; 2008; 2010); (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.

2.2 Commerce Geophysical Lineament - Contemporary Seismicity

The CGL 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). Investigators have shown that some of the focal mechanisms 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).

2.3 Evidence of Late Quaternary deformation along or near Qulin, Missouri

Several lines of evidence suggest the Qulin site experienced past near-surface deformation (Figures 2, 3, and 4), including: 1) faulting interpreted in seismic lines by Stephenson et al. (1999); 2) nearby paleoliquefaction features, 3) anomalous deflections of the St. Francis and Black rivers; and 4) geomorphic and tonal lineaments at the Qulin site. Each of these lines of evidence are discussed below.

2.3.1 Seismic lines by Stephenson et al. (1999)

Stephenson et al. (1999) acquired a 6-km-long, north-south oriented seismic reflection line (CGL-1) across the surface projection of the CGL, near Qulin, Missouri (Figure 4). The seismic reflection line is located near several paleo-liquefaction sites assessed previously by Vaughn (1991; 1992; and 1994), fluvial geomorphic anomalies of the Black and St. Francis Rivers (Fischer-Boyd and Schumm, 1995), and traverses the northeastern part of Qulin Ridge (Figures 2, 3, 4, and 5). Line CGL-1 provides an excellent image of gently south-dipping Paleozoic, Cretaceous and Tertiary stratigraphy underlying Qulin Ridge (Figure 6a). The overlying Quaternary deposits dip in the opposite direction than the underlying Tertiary stratigraphy and thin over a 0.5-km-wide zone of faulting and warping (Figures 6a and 6b). Deformation is

concentrated along the southern end of seismic profile CGL-1 (stations 750 and 850), where faulting and folding of Paleozoic through Quaternary reflectors is pronounced. This zone of distinct Quaternary faulting lies within the zone of the CGL (Figure 4). Between stations 750 and 850, faults show an apparent north-side up vertical separation, consistent with previously acquired seismic reflection profiles collected elsewhere along the CGL (Anderson, 1997; Palmer et al., 1997; Reid et al., 2002; Baldwin et al., 2006; 2010). Near station 820, the Quaternary/Tertiary reflector displays approximately 20 m of down to the south separation, a similar amount to what is observed across the Paleozoic/Cretaceous and Cretaceous/Tertiary reflectors (Figure 6a). Furthermore, an intra-Quaternary horizon located as much as 25 m deep is relatively continuous along much of the profile, however is absent across the northern part of distinct faulting, suggesting the basal Quaternary reflector is warped or faulted vertically up on the north (Figure 6b). Stephenson et al. (1999) interpret that the absence of the intra-Quaternary reflector may be caused by a buried topographic high resulting from Quaternary faulting. Reconstruction of the reflectors to horizontal, suggest that most, if not all, of the apparent vertical separation across the fault zone occurred after deposition of this intra-Quaternary reflector.

2.3.2 Local Paleoliquefaction Features

Paleo-liquefaction studies performed in the Western Lowlands, several tens of kilometers from the NMSZ and between 8 and 20 km from Qulin Ridge, provide evidence for at least four poorly constrained prehistoric events (individual earthquakes or sequences of earthquakes), some of which may be related to the NMSZ, or structures associated with the CGL (Vaughn; 1994; Tuttle et al., 1998; Tuttle, 1999) (Figures 2 and 5). Evidence of prehistoric earthquakes preserved in sediments in the Western Lowlands is derived from the interpretation of numerous northeast-trending liquefaction-related dikes and surficial and buried sand blow deposits. Vaughn (1994) estimates the timing of at least four prehistoric events occurring between about 23,000-17,000 yr BP, 13,400-9000 yr BP, A.D. 240-1020 and A.D. 1440-1540. The two most recent events of Vaughn (1994) are likely related to paleoearthquakes associated with seismic sources within the New Madrid seismic zone (Tuttle et al., 2002). The two earliest paleoliquefaction events are documented at the Dudley Main Ditch and Mingo Ditch sites, 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 (Tuttle et al., 2002; Tuttle et al., 2006). 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. In summary, the paleoliquefaction timing data from the Western Lowlands provide evidence for about four poorly constrained pre-historic events.

2.3.3 Anomalous Deflection of the St. Francis River

Qulin Ridge is bounded on the west by the Black River and the east by the St. Francis River (Figures 1 and 2). Fluvial geomorphic analysis of the St. Francis River by Fischer-Boyd and Schumm (1995) identified an anomalous alteration to the river course directly northeast of Qulin Ridge (Figure 2). For instance, the St. Francis River flows south-southeast across the Western Lowlands after leaving the bluffs of the Ozark Uplands and changes to a southwest flow direction near the intersection with the CGL. The St. Francis River continues southwest and parallel to the orientation of the CGL for approximately 6 to 8 km, where it then abruptly turns south (Figure 2). This sudden change in stream flow direction across the CGL aligns with a 300-m-wide zone of northeast-trending tonal lineaments and faulting interpreted from seismic reflection profile CGL-1 on Qulin Ridge (Figures 4 and 5).

2.3.4 Geomorphic Lineaments

Geomorphic lineaments related to possible Quaternary tectonic and secondary deformation (e.g., earthquake-induced liquefaction) are present at the Qulin Site (Figure 4 and 5). The site is located on the 20-km-long approximately 2- to 2.5-m-high Qulin Ridge (part of Melville Ridge; Figure 3) that is composed of late Wisconsin, or reworked late Wisconsin, glacial outwash deposits. The Quaternary deposits are about 50 m thick (Stephenson et al., 1999). The relative age of the Quaternary material is estimated from regional geomorphic and geologic studies of the evolution of the northern Mississippi embayment (Saucier, 1996; Royall et al., 1991; Blum et al., 2000; Rittenour et al., 2007).

3.0 LOCAL GEOLOGIC AND GEOMORPHIC SETTING

The regional landforms in this part of the central United States are dominated by large fluvial systems within broad alluvial valleys (Cache, Mississippi, Ohio, and St. Francis Rivers) that have flowed 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; Rittenour et al., 2007). The Qulin site is located in the northern part of the lower Mississippi valley just west of Crowley Ridge on a Pleistocene geomorphic surface named Melville Ridge (Figure 3). The Melville Ridge braid belt, a late Pleistocene-age belt of braided Mississippi River channels, lies within the Western Lowlands of the northern lower Mississippi Valley. Herein, we refer to Qulin Ridge as the geographic portion of the Melville Ridge braid belt near the town of Qulin Missouri and on which the study site is located. Melville Ridge at the Qulin site is underlain by Paleozoic bedrock, Paleocene Porter Creek Formation, and Clayton Formation (Stephenson et al., 1999). The ridge is composed either of late Wisconsin, or reworked late Wisconsin, glacial outwash deposits that are about 50 m thick capped by Pleistocene loess (Figure 3; Rittenour et al., 2007). In the area of the study site, the ridge has relatively low relief and stands 2-3 m tall along its northern margin but slopes down to the south and east where it meets the meander belt of the St. Francis River (Figure 4).

Previous regional geomorphic and geologic studies of the northern Lower Mississippi Valley (Saucier, 1996; Royall et al., 1991; Blum et al., 2000) hypothesize that the Western Lowlands consist of ancestral Mississippi River material derived from braided glacial outwash streams present during the Late Illinoian (Isotope Stage 6) to Late Wisconsin time (ca. 11.5 to 10.5 kyrs BP). These studies largely relied on a limited amount of radiocarbon ages and relative age relationships. More recently, Rittenour et al. (2007) refined the age of many of these geomorphic surfaces from extensive optically stimulated luminescence (OSL) dating.

Several units (including the Peoria Loess and Roxanna Silt) and accompanying paleosols (Table 1) are relatively widespread across the lower Mississippi Valley and serve as key stratigraphic markers. The loess units typically consist of several meters of material that overlie channel belt surfaces or overlie bedrock in uplands on the margins of the Mississippi Valley. At the Qulin site, Peoria Loess caps the top of the ridge; whereas Roxanna silt is preserved along Pleistocene surfaces further to the south within the Mississippi River Valley (Rittenour et al.,

2007) and is likely buried at the Qulin site. The Farmdale Geosol is developed within the upper parts or throughout the Roxanna silt and consists of an well-developed argillic horizon with clay coats formed on soil ped faces (Rittenour et al., 2007).

Qulin Site

Three main geologic-geomorphic domains are present within the Qulin Ridge study area: latest Pleistocene alluvium associated with the Melville Ridge braid belt, latest Pleistocene to Holocene alluvium associated with the Ash Hill braid belt, and Holocene alluvium associated with the St. Francis River.

Melville Ridge

In the Qulin area, the Melville Ridge braid belt lies topographically above both the Ash Hill braid belt and above the Holocene alluvium of the St. Francis River (Figure 4). Cores studied by Rittenour et al. (2007) show the Melville Ridge braid belt is overlain by 2 to 5 m of Peoria Loess (thinning to the north), which overlies a paleosol with moderate subangular blocky structure and an argillic horizon that has developed in fluvial sands. The OSL age range of Melville Ridge braid belt deposits from both its northern and southern extent is 42 ± 3 to 35 ± 3 ka (Rittenour et al., 2007). Materials sampled from Melville Ridge deposits near the Qulin study site (2 km southwest of Qulin; Figure 4) have OSL ages of 34.5 ± 2.5 ka and 37.3 ± 2.9 ka.

Ash Hill Braid Belt

Within the study area, the Ash Hill braid belt lies topographically below the Melville braid belt but slightly above the Holocene alluvium of the St. Francis River (Figure 4). The Ash Hill braid belt represents the last major flow of the Mississippi River into the Western Lowlands of the northern lower Mississippi valley (Rittenour et al., 2007). The braid belt is likely contemporaneous with Peoria Loess because as much as 3 m of loess is recognized on this braid belt in the southern Western Lowlands but loess is absent to the north (Rittenour et al., 2007). Sand dunes are common on the Ash Hill braid belt, even persisting in areas of the former braid belt where Holocene surface processes have altered the original Ash Hill deposits. OSL ages suggest the Ash Hill braid belt formed at about 27 ± 2 to 25 ± 2 ka, with ages from sand dunes ranging from 26 ± 2 ka to 19 ± 1 ka. The low relief and relative similarity of the geomorphic surfaces of the area directly to the north of Qulin Ridge and the adjacent meander belt of the Holocene St.

Francis River suggest the portions of the Ash Hill braid belt near the study area were modified by Holocene fluvial processes.

Holocene – St. Francis River Deposits

Qulin Ridge is bounded on the west by the Black River and the east by the St. Francis River (Figure 4). The Holocene meander belt and modern floodplain of the St. Francis River lies topographically below Qulin Ridge (i.e., the Melville Ridge deposits) and subtly below the Ash Hill braid belt. The St. Francis River split from the Black River meander belt and was likely in its present position in the Qulin area by about 12.4 to 12.1 ka, based on paleogeographic reconstructions in Rittenour et al. (2007). Based on the lack of loess on the combined latest Pleistocene Black River – St. Francis River meander belt to the west (which predates the modern St. Francis River), loess deposits are not likely present in areas of Holocene alluvium along the St Francis River.

Table 1. Age of Loess Units in the Lower Mississippi Valley, after Stratigraphy of Rutledge et al. (1996)†

Unit	Age (ka)	Oxygen Isotope Stage	Thickness (m)	Munsell Color	Texture	Other Characteristics
Peoria Loess	25–12‡	OIS 2	0–15	Pale brown to yellowish-brown (10YR 6/3–4, 5/4, 4/6)	Silt loam to silty clay loam	
Farmdale Geosol						well-developed argillic horizon, clay coats
Roxanna Silt	55–27§	OIS 3	0–3	Dark brown to reddish-brown color (10YR 4/4–3, 3/6; 7.5YR 4/4)	Silty clay loam to fine sandy clay loam	
Sangamon Geosol						
Loveland Loess	ca. 190–120*	OIS 6	Variable	Reddish brown to yellowish-brown (5YR 4/4; 7.5YR 4–5/6)	Silty loam to silty clay loam	Present in uplands

† Table modified from information presented in Rittenour et al. (2007).
‡ Based on radiocarbon ages (McKay, 1979; Ruhe, 1983).
§ Based on radiocarbon and luminescence ages (Leigh and Knox, 1993; Rodbell et al., 1997; Markewich et al., 1998).
* Based on luminescence ages (Markewich et al., 1998; Forman and Pierson, 2002). However, thermoluminescence ages suggest that Loveland Loess deposition may have continued into OIS 5 (Rodbell et al., 1997).

4.0 METHODOLOGY

This investigation of the Qulin site 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. The technical approach for each of these tasks is described below.

It is important to note that this study originally proposed paleoseismic trenching. However, the fields in the area have been carefully laser leveled for flood irrigation and landowners were concerned that a trench excavation (even at the margins of fields) could damage their fields sufficiently to prevent proper drainage. As a result, the paleoseismic trenching approach was changed to methods acceptable to the landowners: a series of closely spaced geoprobe samples across the lineaments.

4.1 Quaternary geologic and geomorphic mapping

The Quaternary geologic map developed for the Qulin site region (Plate 1) is based on interpretation of black and white, 1:20,000 scale, stereo-paired aerial photography (from 1955 and 1960) combined with field reconnaissance. The purpose of the mapping was to develop an understanding of the local geology and identify potential tectonically-derived surface features that could provide data on the nature, origin, and timing of surface faulting at the Qulin site.

Development of the surficial geologic-geomorphic map involved interpretation and synthesis of a variety of data, including:

- Black and white 1:20,000 scale stereo aerial photography from 1955 and 1960
- USDA soil maps (Gurley, 1976; Graves, 1983)
- 0.6 m NAIP imagery from 2007 and 2008
- Google Earth imagery
- 1:24,000-scale USGS topographic maps
- 10 meter and 3 meter elevation data from the National Elevation Dataset
- LiDAR-derived elevation data collected in 2012
- Field reconnaissance, and
- Other maps and documents.

The mapping was developed to represent landscape conditions present at the time of the aerial photography (i.e., 1955 and 1960) and relied on interpretations made from the stereo aerial

photography synthesized with soil and 3 m DEM data. The 1955 and 1960 aerial photographs are the primary data set for interpreting surficial geologic deposits because they are the oldest available high-quality, detailed images pre-dating much of the late 20th century cultivation and landscape alteration. Therefore, the map depicts the surficial geology before the late 1950s and significant late 20th Century human alteration. It is important to note that following completion of the mapping, LiDAR data became available for the area. Many significant modifications to the landscape are evident in the modern aerial imagery and the LiDAR data but are not included in the map. For example, the detailed LiDAR data illustrates the precise grading completed in the area to assist with flood irrigation of crops in the area. These data illustrate a checker board pattern coincident with field boundaries, which emphasis the large degree of anthropomorphic landscape alteration in the study area.

The surficial geologic-geomorphic map was developed at the nominal scale of historical aerial photography (approximately 1:20,000) and is presented at 1:24,000-scale. The map should not be used or displayed at scales greater than 1:24,000. Solid map unit boundaries shown on the surficial geologic map should be considered approximate, and are accurate to within about 100 feet on either side of the line shown on the map; dashed contacts are accurate to within about 250 feet on either side of the line.

4.2 Seismic Reflection Data Acquisition

As part of this study, shallow seismic reflection imaging was used to characterize the significance of near-surface tectonic deformation associated with the northeast-trending Commerce Geophysical Lineament (CGL) near Qulin (southeastern), Missouri. S-wave (shear wave) methods have proven to be extremely effective for imaging Quaternary deformation (e.g., Cox et al., 2000; 2001; Baldwin et al., 2005; 2006; Harris, 2009; 2010). One of the primary advantages in using S-waves is increased seismic resolution (compared to conventional compressional P-wave methods) in the water-saturated, shallow sediments of the Mississippi River valley; a very important consideration in light of the modest surface deformation in the region.

Two east-west oriented shear-wave seismic reflection profiles (Qulin 1 and Qulin 2) were collected approximately 4 km east of Qulin, Missouri, across a suspected fault zone with the intent to identify the location and style of neotectonic deformation, and help guide the placement

of subsequent subsurface investigations (Figure 5). Unfortunately, due to difficult ground conditions at the time of sampling, Qulin 2 provided no useable data and thus, the following discussion is focused on Qulin 1. Line Qulin 1 was collected along Country Road 212 in an east-west alignment.

The reflection data were collected in SH mode (sensitive to horizontally polarized shear waves) on a 24-channel engineering seismograph (Seistronix RAS-24). The active spread was a portable landstreamer with 12 receivers (14 Hz horizontal geophones oriented perpendicular to the seismic line) spaced at 4-m intervals. The seismic profiles were shot off-end with 2-m source offsets (274 shotpoints were recorded on the Qulin 1 profile for a total length of 1,096 m). Seismic energy was generated by five horizontal impacts of a 1.8-kg sledgehammer on a 10-kg steel I-beam oriented perpendicular to the spread. Acquisition parameters on the seismograph included a 1.0 s record length and 0.5 ms sampling interval. Processing followed a standard sequence for shallow common midpoint (CMP) reflection data (Table 2).

Table 2. Seismic Data Processing Sequence

Reformat Data
Edit Data (kill traces, first-arrival mute)
CMP Sort
Bandpass Filter (10/15-70/110 Hz)
Automatic Gain Control (250ms window)
Velocity Analysis
NMO Correction
CMP Stack (6-fold)

4.3 Borehole Transects

One approximately west-east oriented borehole transect was collected to assess the age and lateral continuity of sediments, and to identify the absence or presence of fault-related vertical displacements of stratigraphic horizons interpreted from the seismic reflection profiles (Photos 1-4 (see below) and Figures 5 and 7). A total of 15 direct push technology (DPT) Geoprobe cores were collected at variable spacings (25 to 100 ft) across several prominent photo-lineaments and along parts of seismic line Qulin 2 to specifically target possible deformation

zones projected along strike from Qulin 1 (red circles in Figure 8). The cores were collected as continuously to a maximum depth of 6 to 9.75 m (20 to 32 ft). A vertically exaggerated detailed cross section of the geoprobe transect is shown on Plate 2.

A Geoprobe is a hydraulically-powered soil probing machine that utilizes static force and percussion to advance a 1 and 11/16-inch-diameter sample tube within 4-foot-long sections at each borehole location (Photos 2 and 3). 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. 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 (Photo 2).

The elevations along the transect ranges from approximately 96 to 97 m (315 to 317 ft) above mean sea level (msl) (Plate 2). The borehole locations were located using a combination of tape measure, compass, and satellite imagery; and the borehole elevations were estimated from available LiDAR data.

Photo 1. Photomosaic looking from east (photo left) to south (photo right) of the Qulin geoprobe site. The location of geoprobe boreholes are marked by the white stakes in the left side of the photo. Note the tonal lineament in the right side of the photo. According to the land owner the dark region in the right part of the photo was graded level to match the lighter colored soil in the central part of the photo (a pre-existing east-facing break-in-slope?). The apparent curvature in the landscape is an artifact of the photomosaicing software. The actual landscape has very sublte relief as shown in the photos below.

Photo 2. Field photo looking west along the borehole alignment. Geoprobe samples were laid out for logging and correlation of key stratigraphic horizons between boreholes. Blue tape across multiple core samples represents a field correlation of similar units.

Photo 3. Field photo looking west at the Geoprobe rig.

Photo 4. Field photo looking east along trend of the borehole alignment. Note the flat landscape and large furrows plowed by the land owner for flood irrigation drainage and 2-3 ft high berm on the left for rice field irrigation.

5.0 RESULTS

The combination of geologic mapping and geophysical information collected along Melville Ridge at the Qulin site provide evidence for late Pleistocene deformation, however little to no evidence of Holocene deformation was identified. Seismic reflection data collected as part of this study provides evidence for late Quaternary deformation coincident with previously identified faulting by Stephenson et al. (1999) along the CGL. Faults imaged in the profiles could be interpreted with relative confidence up to within approximately 15 m of the ground surface. However, relatively closely spaced boreholes placed in areas suspected of late Quaternary deformation (i.e. across photo lineaments and faults identified in geophysics) did not provide compelling evidence for vertical offsets in late Pleistocene loess stratigraphy.

5.1 Geologic Mapping

The Quaternary geologic map developed for the Qulin site region was completed to develop an understanding of the local geology, and to identify potential tectonically-derived surface features that could provide data on the nature, origin, and timing of surface faulting at the Qulin site (Figure 5 and Plate 1). Through this mapping we identified three main geologic-geomorphic domains (or geomorphic surfaces): (1) Holocene alluvium associated with the St. Francis River; (2) latest Pleistocene alluvium associated with the Melville Ridge braid belt; and (3) latest Pleistocene alluvium associated with the Ash Hill braid belt. We have subdivided a variety of eolian and fluvial geomorphic features and related deposits (including anthropogenic features such artificial fill) developed in these domains. In addition to geologic map units, we identified a series of potentially tectonically-related features on the aerial photography, including: sand boils and various lineaments (topographic, tonal and/or vegetation) not attributed to shallow drainages. The three main domains (following Rittenour et al. [2007]) are described below, followed by other mapped geomorphic features and related geologic units.

5.1.1 Latest Pleistocene alluvium of the Melville Ridge braid plain

Latest Pleistocene alluvium of the Melville Ridge braid plain (Map unit Qam) consists of undifferentiated alluvium of Melville Ridge braid belt, which is capped by Peoria Loess and Roxanna silt (southern part of the ridge; Rittenour et al., 2007). The Melville Ridge geomorphic surface lies topographically above the Ash Hill braid belt deposits (map unit Qaa) and Holocene

alluvium of the St. Francis River (map unit Has). A 1.5- to 2.4-m-high northwest to east-west-trending scarp separates the northern margin of Melville Ridge from the Ash Hill braid belt floor. The Melville Ridge geomorphic surface merges topographically with the St. Francis River flood plain in the southeastern portion of the map area. Melville Ridge deposits consist of various braided stream channel (Hf) and eolian deposits (He) which are broken out as individual map units where recognized. Soils associated with alluvium of Melville Ridge include the Calhoun silt loam, Dubbs silt loam, Foley silt loam, Lafe silt loam, and the Crowley silt loam (Gurley, 1976; Graves, 1983). Two OSL ages from materials sampled on Melville Ridge deposits 1.5 miles southwest of Qulin (Figure 4) were 34.5 ± 2.5 ka and 37.3 ± 2.9 ka.

A series of shallow north- to north-northeast-trending curvilinear depressions (interpreted as fluvial channels) are developed in Melville Ridge (map unit Pch). These interpreted channels may include sorted and unsorted mixtures of sands, silts, and clays, with possible rare gravel. We hypothesize these channels developed while the late Pleistocene Ash Hill and Melville Ridge braid plains were active and are relatively wide and/or anastomosing due to their genesis in the braided stream environment. In most cases, these channels have some subtle topographic expression and therefore, may have been reactivated during Holocene time via locally-derived surface waters. The relatively wide and linear Fish Trap Slough bounding the eastern margin of the Qulin Site, and associated channels, appear to connect geomorphically with channels on the Ash Hill surface, suggesting they formed during Ash Hill time. The linearity of Fish Trap Slough is likely man-made, but some have inferred an original linear pattern suggestive of surface deformation (Vaughn personal communication, 2008). The slough also overlies faulting interpreted by Stephenson et al., (1999). We associate the Jackport silty clay loam soil (Gurley, 1976) to the large channel feature mapped along the eastern margin of the map area. In some locations, natural levee deposits (map unit Pnl) may flank the channels as a slightly elevated ridge paralleling the channel.

5.1.2 Latest Pleistocene Alluvium of the Ash Hill braid belt

The Ash Hill Braid Belt (map unit Qaa) consists of various braided stream channel and eolian deposits north of Melville ridge and is topographically below (8-12 ft) the Melville braid belt deposits, but slightly above the Holocene alluvium of the St. Francis River (map unit Has)(Figure 5). As discussed above, loess is not likely present on Ash Hill braid belt in the area

of Qulin (Rittenour et al., 2007). As part of our mapping, we mapped individual geomorphic features such as channels and sand dunes, where possible (see Plate 1 for unit names and descriptions). Soils associated with the alluvium of the Ash Hill braid belt include the Wiville fine sandy loam (occasionally flooded), Wiville fine sand (leveled, occasionally flooded), Tuckerman-Wiville complex (leveled, occasionally flooded), Amazon silt loam (occasionally flooded), and Kobel clay (occasionally flooded) (Gurley, 1976; Graves, 1983).

Within the Ash Hill braid belt, we mapped individual sand dunes, or remnants of sand dunes (Qass) These features are characterized by lighter tones in the black and white aerial photographs and locally may exhibit some relief where not heavily modified by agricultural practices. The Wiville fine sandy loam and Tuckerman-Wiville complex soil series (Graves, 1983) are associated with map unit Qaas. These features are characterized by lighter tones in the black and white aerial photographs and locally may exhibit some relief where not heavily modified by agricultural practices. The Wiville fine sandy loam and Tuckerman-Wiville complex soil series (Graves, 1983) are associated with map unit Qaas.

The Ash Hill braid belt represents the last major flow of the Mississippi River into the Western Lowlands of the northern lower Mississippi valley. The braid belt is likely contemporaneous with Peoria Loess because as much as 3 m of loess is recognized on this braid belt in the southern Western Lowlands but loess is absent to the north (Rittenour et al., 2007). OSL ages suggest the Ash Hill braid belt formed at about 27 ± 2 to 25 ± 2 ka, with ages from sand dunes ranging from 26 ± 2 ka to 19 ± 1 ka.

5.1.3 Holocene-aged Alluvium of the St. Francis River Floodplain

The alluvium of the St. Francis River floodplain (map unit Has) consists of undifferentiated alluvium within the meander belt and modern floodplain of the St. Francis River (Figure 5). The St. Francis River flood plain is inset into and cuts across the Melville Ridge deposits and is topographically lower than the Ash Hill Braid belt. Our mapping separates the flood plain into various stream channel and floodplain deposits. We delineate individual meander scrolls, oxbow lakes, swamps, and terraces where possible (see Plate 1 for unit names and descriptions). Soils associated with the alluvium of the St. Francis River include the Alder silt

loam (occasionally flooded), Falaya silt loam (occasionally flooded), the Collins silt loam (rarely flooded), and locally the Dubbs silt loam (Gurley, 1976; Graves, 1983).

5.1.4 Potential tectonically-derived features

Coincident with the subsurface faulting identified by Stephenson et al. (1999), we identified a series of northeast trending tonal and subtle topographic lineaments parallel to the CGL, as well as a broad zone of circular to oblong light-colored features suggestive of sand blow (or dunes?) origin (Figure 5). The tonal lineaments are southeast trending and extend for more than 3.5 km across a 1.2- to 3.0-km-wide zone. Mapped lineaments consist of subjective interpretations of linear breaks-in-slope (bis), linear tonal contrasts (t), anomalous alignments of vegetation (v), and suspicious linear troughs or ridges (bis). The apparent strength or level of expression of lineaments was scored with values of 1, 2, or 3, where 1 are the most well-expressed and 3 are the least well-expressed features in the historical aerial imagery.

These lineaments intersect Fish Trap Slough, which drains southwest within a broad (200 to 400-m-wide) northeast-trending swale that is at least 7 km long (Figure 4). The linear swale is bordered, in part, by discontinuous subparallel tonal photolineaments and subtle topographic escarpments (Figure 5). Fish Trap Slough also trends parallel to the Cache Creek Slough / Cache River ditch located directly northwest on Qulin Ridge that also falls within the broad surface projection of the CGL (Figure 3). We note that the up dip surface projection of the Quaternary faulting from seismic reflection profile CGL-1 coincides roughly with Fish Trap Slough and the regional trend of the CGL. We interpret the distinct northeast-trending tonal lineaments, subtle topographic scarps and linear swales, and possible paleo-liquefaction features as possible tectonic-related geomorphology associated with the Quaternary faults of CGL-1, and are possibly related to co-seismic rupture of the CGL.

5.2 Seismic Reflection Profiles

Seismic line Qulin 1 was collected for this study along County Road 212 (Co Rd 212) and is oriented east-west across the photo/geomorphic lineaments identified as part of this study and faults imaged previously by Stephenson et al. (1999) in seismic line CGL-1 (Figure 5). At least three distinct units can be interpreted from the geophysical data.

Profile Qulin 1 images Tertiary bedrock (Unit 1) between 50 and 70 m depth (0.6 to 1.0 sec TWTT) that is overlain by faulted Quaternary deposits (Units 2 and 3) (0 to 0.6 sec TWTT) (Figure 7). Based on comparison with available data from the Missouri Division of Geologic Survey and water resources (Borehole number 23187, located 2.5 km to the west of the Qulin Site) Tertiary bedrock is composed of Paleocene Porter Creek (Gravely Clay) and Clayton Formations (Stephenson et al., 1999). Although perhaps present, we are unable to identify the top of the Cretaceous reflector near the base of the Qulin 1 line. Based on correlation with previously acquired P-wave seismic reflection data (Stephenson et al., 1999), a reflection from the Quaternary/Tertiary boundary is visible (purple reflection on Figure 7) around 50 m depth. The Quaternary deposits can be imaged within 10 to 15 m of the ground surface.

Unit 2 appears to be correlative with a series of coarse grained sand and gravel deposits near the base of the Quaternary section (Figure 7). This interpretation agrees with a series of fanning reflectors that may represent paleochannel deposits (i.e. gravels) shaded yellow on Figure 7. Unit 3 appears to roughly correspond with a finer-grained sequence of deposits preserved along Qulin ridge composed of clay, fine sand, and medium sand.

It is important to note that the shallow portions of the line were influenced by low frequency noise (Love wave and refractions). As part of the data processing, it was necessary to complete first arrival muting (FARM) to the data, which mutes out the upper 0.1 to 0.2 sec twtt (10-15 m) of the data. The western most 125 m of Qulin 1 did not contain as much low frequency noise and thus, required less FARM. As a result, the shallow data is not muted 125 m from the west end of the line; however the apparent displaced reflectors are a function of the processing and should not be interpreted as shallow deformation.

Interpretations of faults and folds from the Qulin 1 line were defined by: (1) offset reflectors and (2) changes in reflection amplitude and coherency. Within Qulin 1, faults are labeled F1, F2, F3, and F4 from west to east. These interpreted faults are near vertical (steeply east-dipping) and between 0.2 and 1.0 sec twtt appear to displace a prominent reflector at approximately 0.6 sec twtt. Faults F1 and F2 are interpreted to displace the base of Quaternary reflector (shown in purple) 1-2 m in an east-side-down sense of slip with a very small degree of tilting (<5° towards the west). Similarly, the intra-Quaternary reflector (between Units 2 and 3 marked in orange) is displaced 1-2 m down-to-the-east across F1, but is possibly tilted several degrees towards the

east. Fault F1 is interpreted to extend up to approximately 15 m depth. Fault F2 is not interpreted to displace the intra-Quaternary reflector. Faults F3 and F4 are steeply dipping to vertical faults interpreted to displace the base of Quaternary reflector 1-2 m and 2-3 m, respectively. These faults extend to approximately 20 m depth and are not interpreted as displacing the intra-Quaternary reflector.

The faults interpreted in the Qulin 1 seismic line characterize a fault zone that is approximately 400 m wide, shows down-to-the-east offsets, and correlates very well with a zone of faults imaged by Stephenson et al. (1999) near the southern end of seismic line CGL-1. This correlation suggests a northeast-striking fault zone with down-to-the-southeast offset and deformation extending upward into the shallow subsurface.

5.3 Shallow Geologic Cross Section

The geologic cross section developed from the DPT borehole data lies along a northeasterly projection of the deformation interpreted from seismic profile Qulin 1, and is coincident with suspected tectonic lineaments identified from geologic mapping. All of these features lie above the CGL (Figures 5 and 7). The cross section shows multiple distinct, laterally continuous Quaternary stratigraphic and incipient soil horizons developed in loess deposits that cap braided stream deposits of the Melville braid belt (Plate 2).

5.3.1 Cross Section A-A' - Stratigraphic Relations

Cross-section A-A' is approximately 600 ft long and is oriented roughly east-west in between agriculture fields and across suspected tectonic lineaments identified through aerial photo interpretation (Figure 5 and Plate 2). The 20- to 30-ft-deep probes encountered four primary units, from oldest to youngest material: (1) sand and gravel of the Melville braid belt; (2) Roxanna silt (?); (3) Peoria Loess; and (4) artificial fill. The base of the Quaternary is located below the depth of exploration (> 50 m; Stephenson et al., 1999). Each of these units is described below.

Unit 4 represents an fining-upwards sequence of interfingering sand, coarse sand, clean silt, and sandy silt (from 3.6 to 4 m [12-13 ft] below bgs to the base of the section), which we interpret to be Pleistocene Melville Ridge fluvial sand and braided stream deposits (Rittenour et

al., 2007) (Plate 2). This sequence has several subunits, including a (1) reddish brown fine sand (subunit 4a), (2) gray or olive-brown sand (subunit 4b); (3) clayey silt (subunit 4c), (4) package of mostly reddish brown medium coarse sand (subunit 4d) with interfingering finer-grained lenses (subunit 4e), and (5) gray fine to very coarse sand (4f).

The reddish brown (5YR 5/3 to 5/6) sand (subunit 4a) consists of very fine- to fine-grained sand with silty interbeds, is often saturated, and occurs at the top of the braided stream deposits. A distinctive color change to gray brown fine to medium-grained sand (subunit 4b) is mapped at its base. This package of grayish brown to olive brown (2.5 YR 5/3) sand is traceable across the entire profile and occurs at an elevation of 301 to 300 ft. The base of subunit 4b is marked by a transition to finer-grained materials, often a clayey silt interbed (subunit 4c) that is up to 0.33 m (1 ft) thick at 301 to 298.5 ft elevation. Beneath subunit 4c is a strong brown to reddish brown (7.5YR5/6 to 5YR5/3) fine sand (subunit 4d) with interbeds of silt and clay (subunit 4e). The eastern portion of the profile has a consistent color change from gray to olive brown above to reddish brown colors below (elevation of ~298 ft (~5 m [16 ft] bgs). On the eastern half of the profile this color change occurs near the top of the sequence and coincides with a saturated, reddish brown (5YR5/3) fine sand (subunit 4d). In, the western half of the profile, however, the color change is more difficult to discern and typically occurs deeper in the profile at an elevation of ~295 ft., and crosses a silty interbed (subunit 4e). Another prominent color change from reddish brown to gray to olive brown was present between 289 and 293 ft elevation between subunits 4d and 4f. The base of the profile is defined by a thick sequence of coarsening-downward fine- to medium-grained sand (subunit 4f). The gray (10YR 4/1 to 10YR 6/2) sand is approximately 1.8 m thick [6 ft] in borings B8, B9, and B10.

Unit 3 includes a buried soil (Buried Soil #2) developed in laminated silt interpreted as Roxanna silt, and/or Peoria Loess (Plate 2). Buried Soil #2 is less than 0.7 m thick [2.25 ft] and includes a clay-rich Bt-soil horizon with common manganese nodules and staining. Buried Soil #2 is less developed than Buried Soil #1. Below Buried Soil #2 is typically light brown (7.5YR 6/3) to olive brown (10YR 4/3) distinct clean and laminated silt with sparse clay or sand and has very rare iron and manganese oxide nodules. The basal portion of Unit 3 is a gradational boundary ranging from clay, silt, and sand. In places, the base of Unit 3 contains occasional manganese nodules and a buried soil. It is important to note this boundary was often coincident with the top of a new sampling tube where core tends to be compressed during advancement of the

sampling apparatus. Consequently, this compressed core leads to greater uncertainty in the location of the contact between Units 3 and 4.

Unit 2 includes an upper buried soil (Buried Soil #1) developed in silt and interpreted as Peoria Loess (Plate 2). The loess package is roughly 2-2.5 m [7-9 ft] thick and is encountered at depths of less than a meter [~2-3 ft]. Buried Soil #1 is up to 2 m [3 ft] thick and includes an A-horizon, consisting of dark grayish brown to light yellowish brown (10YR 4/2 to 10YR 6/4) moist silt with grayish white skeltans near the base. The A horizon is underlain by a clay-rich Bt-horizon characterized by brown (10YR6/4 to 10YR 5/3) clayey silt. Buried Soil #1 also includes prominent manganese nodules and iron oxide mottling. Underlying the clay-rich soil is a yellowish brown to brown (10YR 5/6 to 10YR 4/3) loess and sandy silt that reaches a maximum thickness of 1 m (3 ft). The silt is often saturated with variable textures, including clay and fairly clean sand. Based on previous regional mapping and nearby OSL dates of Rittenour et al. (2007), we interpret the upper silt-rich unit as Peoria Loess, and the soil as the Farmdale Geosol.

Unit 1 is a mixture of fill and the modern plow zone material, which is up to 0.6 m [~2 ft] thick. The fill consists of yellowish brown to red brown (10YR 5/6 to 10YR 4/3) very fine to fine sand with silt (Plate 1). Modern roots and organic soils are typically encountered within this unit. Fill is thicker on the western half of the boring profile (boring B8 and west), where soil has been added during grading and field levelling for flood irrigation.

5.3.2 Cross Section A-A' - Structural Relations

The geoprobe transect was collected across the projection of several tonal lineaments that align with inferred subsurface Quaternary deformation imaged in the CGL-1 (Figure 6) and Qulin 1 (Figure 7) seismic lines. The fluvial deposits and paleosols interpreted from the geoprobe data provide late Pleistocene-aged strain gauges to assess the presence or absence of deformation (e.g., warping, folding and faulting) along projection with faults imaged in seismic profiles and lineaments from geologic mapping.

The stratigraphy in the geoprobe transect (Plate 2) is broadly undulatory and generally flat (even at high vertical exaggeration) with little compelling evidence of tectonic deformation. The upper

loess and silt packages and buried soils (Units 2 and 3) as a whole are generally flat with possible a weak indication that these units are 1-2 ft higher on the western side of the profile. However, both the upper and lower boundaries of these units generally vary in elevation on the order of 0.5 to 2 ft between boreholes. This variation is likely due to the natural variability of these deposits and artificial elevation changes due to variable amounts of compression to the samples due to the geoprobe sampling method.

There are some subtle stratigraphic changes that could be speculatively interpreted as fault related. Subunit 4c (on Plate 2) is a fine-grained clayey interbed within the Melville Ridge Braid belt that is generally flat. However, between boreholes B7 and B10 the fine-grained clayey interbeds appear to be 1 to 3.2 ft [0.3 to 1.0 m] higher on the western portion of the section. This area also corresponds to a systematic change in the elevation of the base of Unit 3. These elevation changes in stratigraphy between boreholes B7 and B10 are broadly coincident with the northwest-projection of photo lineaments and deformation imaged in the Qulin 1 seismic line (Figure 5). In addition, these elevation changes are consistent with a west-side-up or east-side-down sense of displacement, which is consistent with the inferred deformation imaged in the seismic lines (Figures 6 and 7). If this 1 to 3.2 ft [0.3 to 1.0 m] elevation change is the result of tectonic deformation on the CGL, there appears to be very little resolvable vertical deformation in latest Pleistocene time. It is important to note, that (1) the boundary between Units 3 and 4 is a gradational boundary (causing additional uncertainty in the location of this boundary) and (2) that this vertical elevation change could be entirely related to the natural variability of the Pleistocene braided stream deposits and not the result of tectonic deformation.

Lastly, the borings may not have penetrated the full sequence of deformed stratigraphy. Tthe Quaternary deformation interpreted in the Qulin 1 seismic line extended up to 14-15 m depth, which is below the maximum depth of the geoprobes (~10 m). Thus, a larger magnitude of deformation may be preserved below the depth explored by this study.

6.0 DISCUSSION

Review of aerial photography, combined with Quaternary geologic mapping and field reconnaissance, followed by geophysical data acquisition and interpretation, allow us to interpret the presence of a northeast-striking fault zone that displaces Quaternary deposits at the Qulin site (Figure 3). A geoprobe transect across the eastern part of the Melville Ridge encountered primarily subhorizontal Late Pleistocene strata that do not support large amounts of Holocene deformation, if any. We acknowledge that the geoprobe methodology is not ideal for assessing subtle features, especially those with little vertical separation; however, geophysics and geologic mapping provide compelling evidence for late Quaternary deformation. The findings from the Qulin study, coupled with multiple previous paleoseismic investigations in southwest Missouri, indicate a 110-km-long section of the Commerce geophysical lineament has evidence for Quaternary fault activity.

6.1 Geophysical Profiles of Qulin Ridge

Both the CGL-1 and Qulin 1 seismic lines image Quaternary deformation that appears to be coincident with a northeast-striking east-side-down fault zone (Figures 5, 6, and 7). However, there are significant differences in the amount of vertical deformation interpreted between these two seismic lines. Stephenson et al. (1999) interpret 20 m of down to the south separation across the Quaternary/Tertiary reflector (Figure 6). Conversely, the Qulin 1 seismic line images up to 5 m of total vertical separation across the Quaternary/Tertiary reflector (Figure 7). This discrepancy in the amount of vertical separation at the Quaternary/Tertiary reflector could be related to several factors. For example, the fault zone may be stepping northeast and the Qulin 1 seismic line images a transfer zone between major fault strands, or the primary fault strand is located west of the Qulin 1 seismic line. Alternatively, the projection of the faults between the seismic lines along a northeast strike parallel to the CGL may be incorrect. The limited number of seismic lines (which do not intersect) and wide spacing between lines hampers our ability to further evaluate the possible geometry of the imaged faults. Lastly, Stephenson et al. (1999) imaged 20 m of south-side-down deformation across a relatively wide (400 m) zone. Because the Qulin 1 seismic line is not oriented perpendicular to strike (due to access constraints), the Qulin 1 line may be imaging just a portion of the folding and faulting imaged by Stephenson et

al. (1999). Without additional seismic data in the area, it is difficult to decipher which of these possible explanations is correct.

7.0 SUMMARY OF FINDINGS

This geologic and paleoseismic investigation at the Qulin Site improves our understanding of the continuity of faulting associated with the CGL in southern Missouri and confirms previously identified evidence of Pleistocene deformation in the region. The Qulin Site provides additional direct evidence for linking observed late Pleistocene deformation with the CGL. The direct evidence for late Pleistocene deformation includes (1) additional imaging of faulting and folding of late Quaternary reflectors in the Qulin 1 seismic line (Figures 4, 5, and 7), which is consistent with previous interpretations of deformation in seismic line CGL-1 of Stephenson et al. (1999); and (2) weak evidence for 1 to 3.2 ft [0.3 to 1 m] of east-side down deformation identified near the middle portion of the transect of geoprobe cores (Plate 2). This direct evidence is supported by indirect evidence of Quaternary deformation identified by previous researchers, including: (1) paleoliquefaction features in the Western Lowlands (Vaughn, 1994) and (2) anomalous deflection of the St. Francis River. These indirect lines of evidence suggest significantly large earthquakes have occurred in the vicinity of Qulin that cannot be associated with New Madrid events and therefore, may be associated with the CGL.

This study, coupled with multiple previous paleoseismic investigations in southwest Missouri (Baldwin et al., 2006) and southern Illinois (Baldwin et al., 2010), provides evidence for Quaternary fault activity along a 110-km-long section of the Commerce geophysical lineament. However, our ability to date paleoseismic events at the Qulin site was limited by the geoprobe technique. Additional event timing information is needed to ascertain the possibility of middle to late Holocene earthquakes along structures aligned with the CGL.

8.0 ACKNOWLEDGEMENTS

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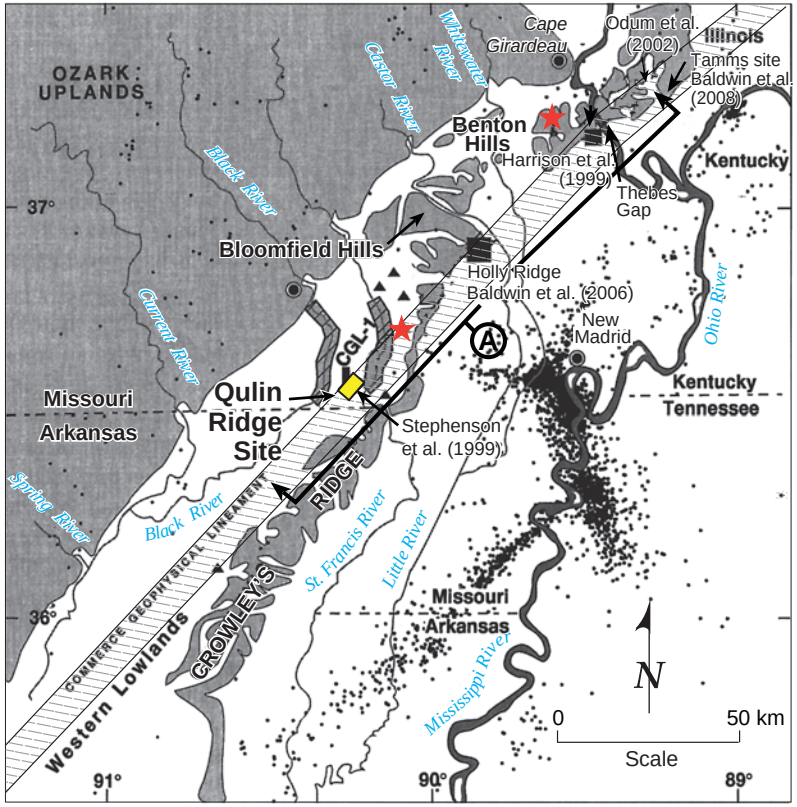


Figure 1. Regional map of the southeastern Missouri showing the surface projection of the Commerce geophysical lineament (horizontal hatch pattern). The pre-Quaternary deposits (light gray fill pattern), Quaternary (white), and main rivers (medium gray) are also shown. Sites of paleoliquefaction (Vaughn, 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).

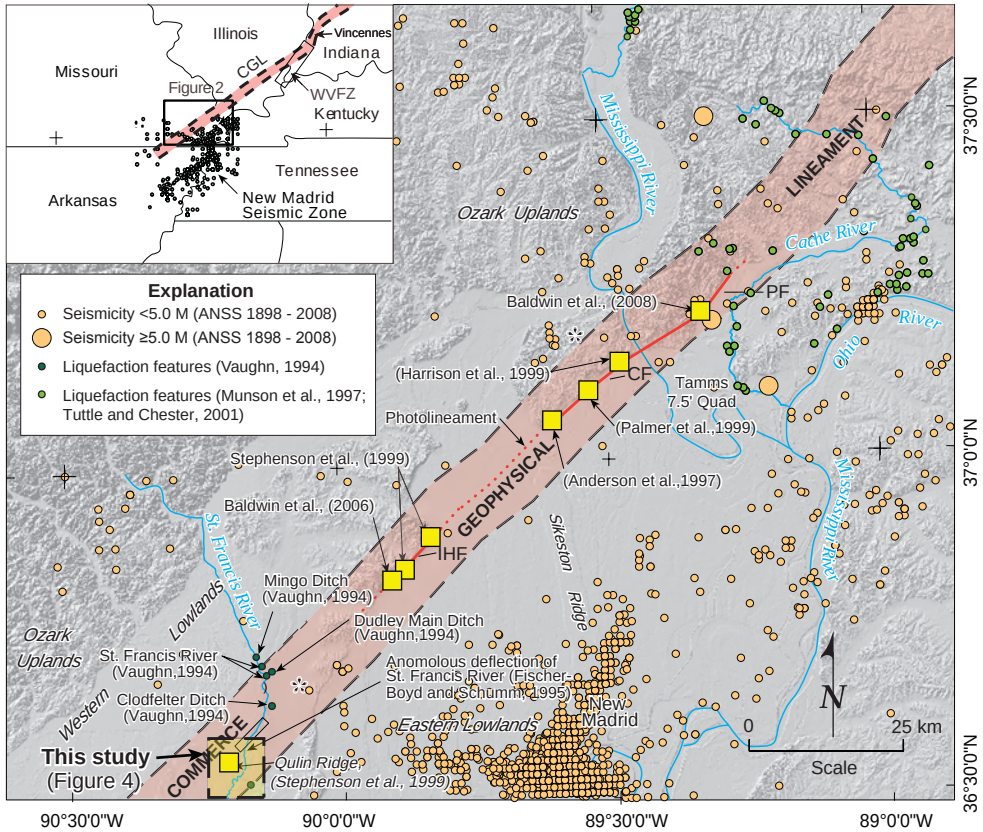


Figure 2. Regional location map of the New Madrid seismic zone and the Commerce geophysical lineament based on latitude and longitude coordinates provided by Hildenbrand (personal communication, 2002) and modified partly from Stephenson et al. (1999). IHF = Idalia Hill fault; CF = Commerce fault; PF=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

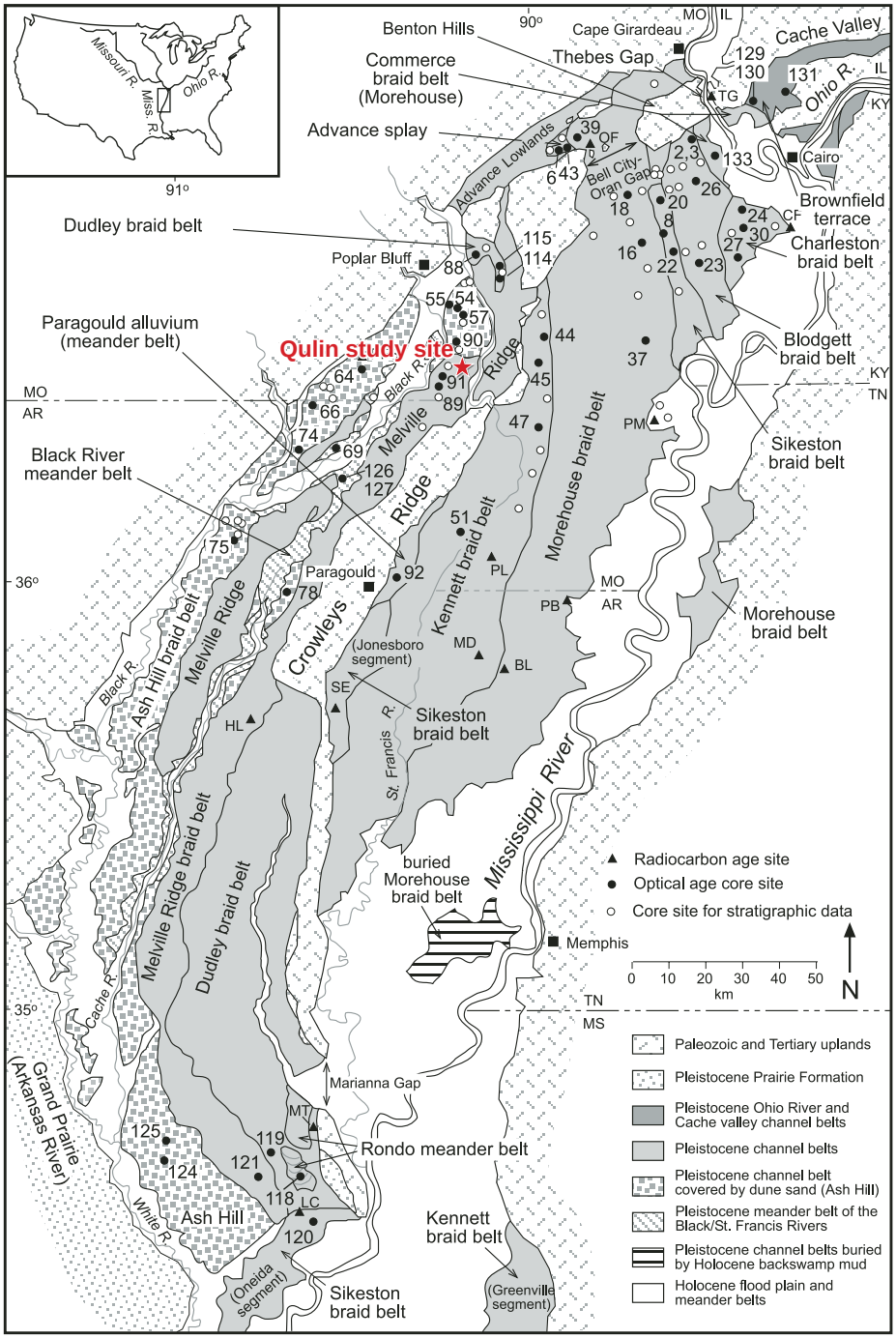
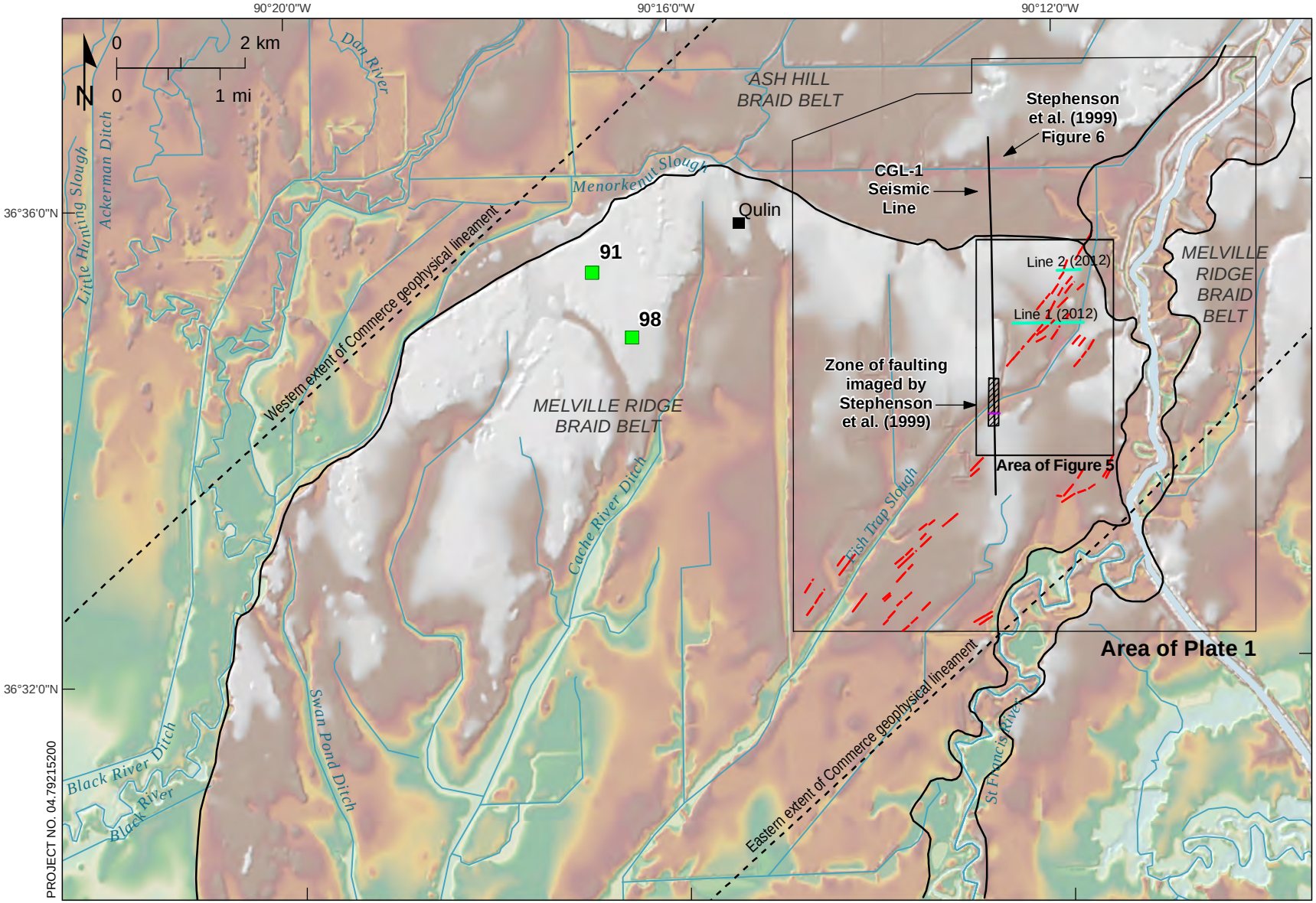


Figure 3. Generalized map of the Lower Mississippi Valley channel braid belts, modified from Rittenour et al., 2007.



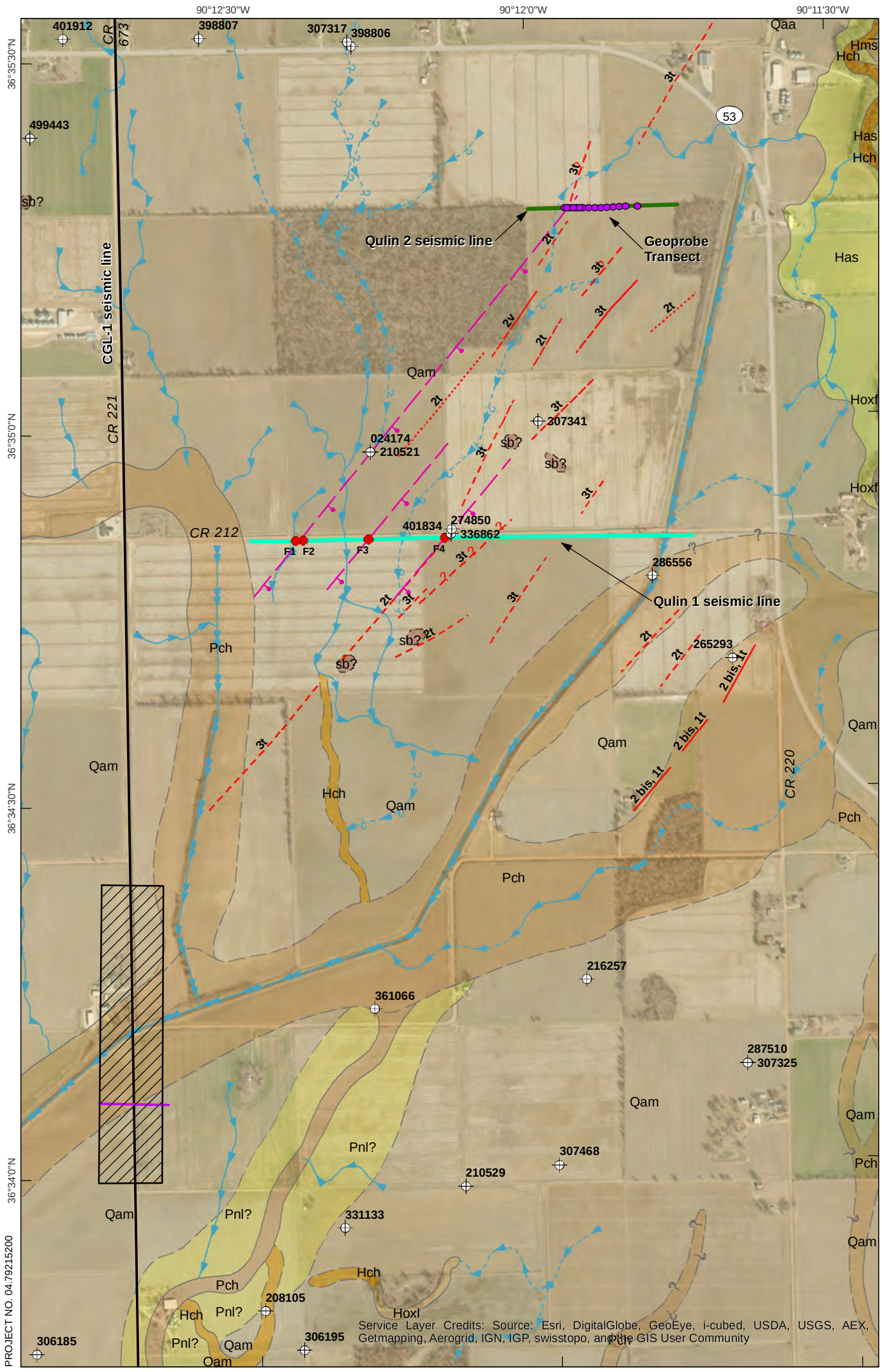
PROJECT NO. 04.79215200

Elevation data from USGS NED 1/3 arc second.

Explanation

- Boundary between geomorphic domains
- Seismic lines (this study)
- CGL-1 seismic line (Stephenson et al., 1999)
- Updip projection of faults imaged by Stephenson et al. (1999)
- Approximate surface projection of southern fault zone of seismic line CGL-1
- Photolineaments; solid where well located, dashed where approximately located, dotted where inferred, queried where existence uncertain
- OSL sample from Rittenour et al, 2007

Figure 4. Color shaded relief map illustrating regional geomorphic features along the Melville Ridge and the eastern and western extent of the CGL.



Explanation

- Geoprobe borehole (this study)
- Well from Missouri Division of Geology and Land Survey
- Fault interpreted in 2012 geophysical data
- Fault, projection inferred from geophysical data and extrapolated along strike
- Approximate surface projection of southern fault zone of seismic line CGL-1
- CGL-1 seismic line (Stephenson et al., 1999)
- Updip projection of faults imaged by Stephenson et al. (1999)
- Lineament mapped from this study; solid where well located, dashed where approximate, and queried where poorly located
- Qulin Line 1 (2012)
- Qulin Line 2 (2012)
- Channel, ditch, or canal

N

0 200 m

0 1,000 ft

See Plate1 and accompanying report text for explanation of geologic units

Figure 5. Geologic map of the Qulin site illustrating interpreted photo lineaments, seismic lines, water wells, and the location of the 2014 geoprobe transect.

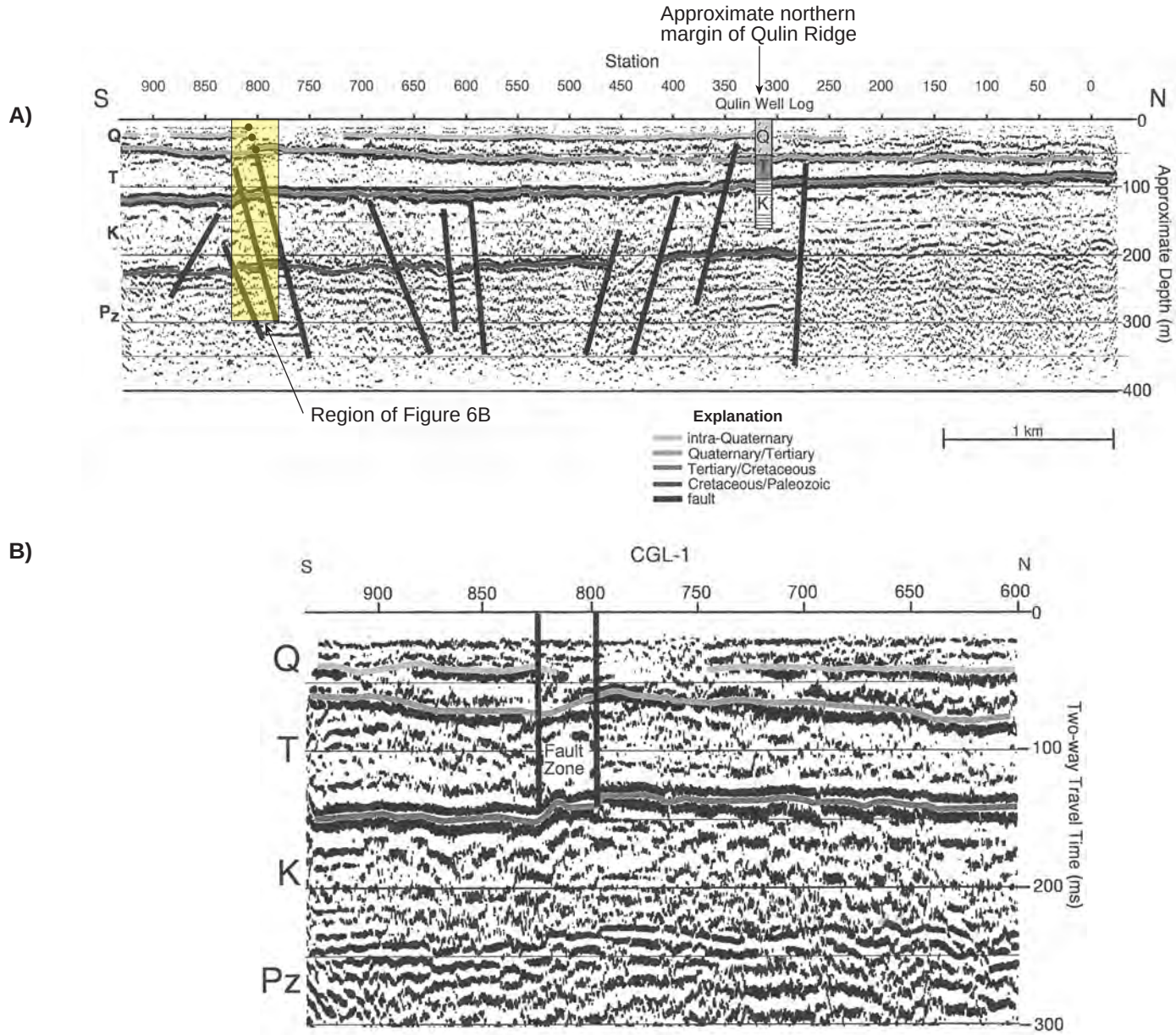


Figure 6. Seismic profile CGL-1 of Stephenson et al. (1999). Quaternary (Q), Tertiary (T). Cretaceous (K), and Paleozoic (P_z). Interpreted faults shown by heavy black lines. Figure 6a shows entire depth-converted seismic reflection profile. Figure 6b represents a portion of seismic reflection CGL-1 showing detail of intra-Quaternary fault zone between Stations 795 and 825 (modified from Stephenson).

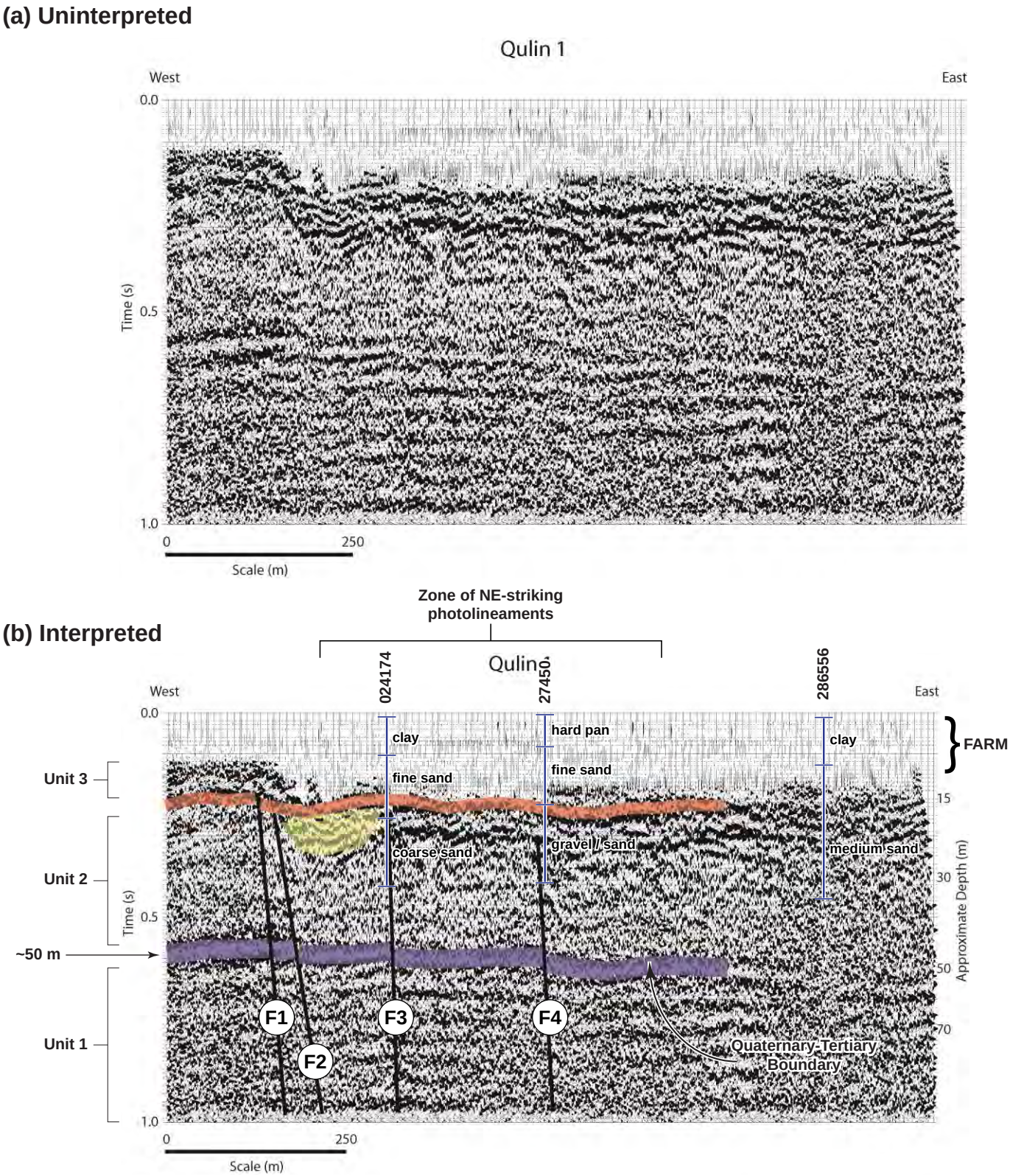
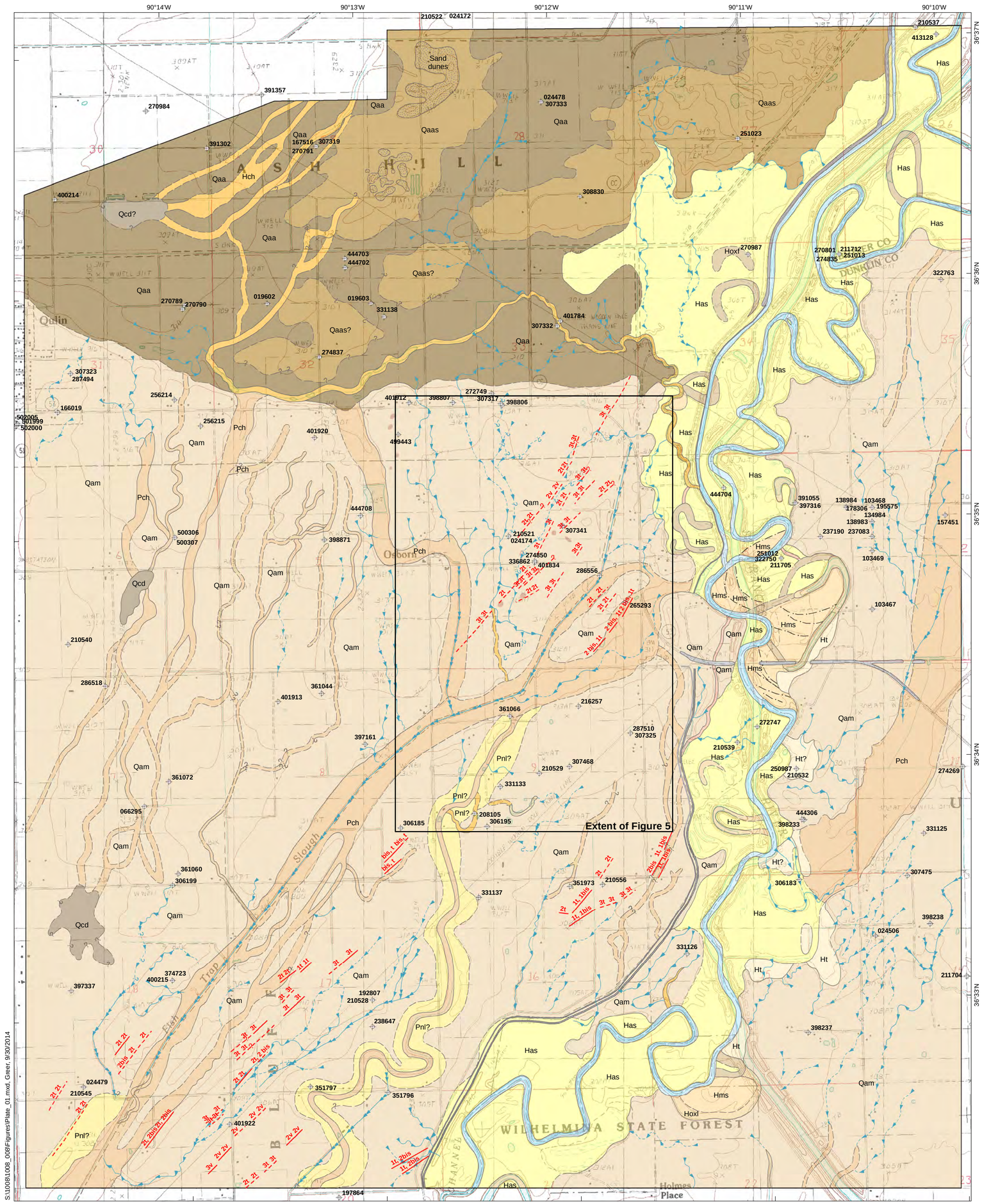
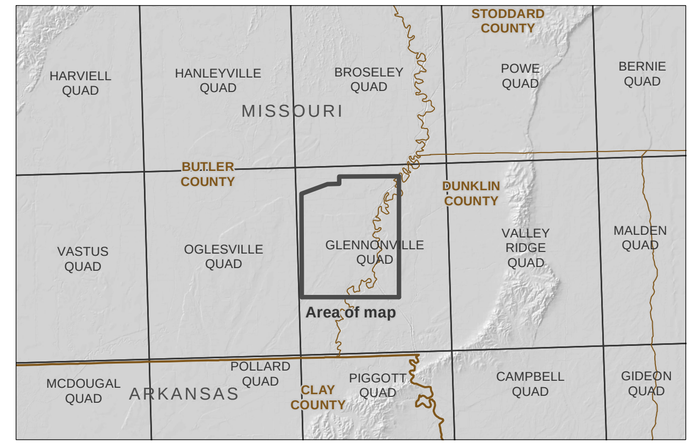


Figure 7. Qulin 1 sheer-wave seismic reflection profile (this study) illustrating a) uninterpreted and b) interpreted lines with east-side-down faults (shown as black lines). The location of the profile is shown on Figure 5. Preliminary estimates suggest the prominent reflector at 550 to 600 ms is the top of Tertiary. Note the shallow reflections on the western side of the seismic line are muted as a result of First Arrival Muting (FARM) due to low frequency noise (Love wave and refractions).



Topographic map: USGS Glennonville 7.5' quadrangle



Explanation

- Well from Missouri Div. of Geol. and Land Survey
- Artificial fill
- Levee fill
- Borrow pit
- Channel
- Channel, approximate
- Channel, approximate queried
- Ditch or canal
- Geologic contact
- Geologic contact, approximate
- Geologic contact, approximate queried
- Lineament
- Lineament, approximate
- Lineament, queried
- Swale within meander scroll complex

Geologic Units

W	Water
AF	Artificial fill
L	Levee Fill; *Levee fill consists of engineered and non-engineered materials placed adjacent to stream courses to control flood waters.*
sb?	Sand Boil; *Small mounds of generally sand-sized particles derived from liquefaction of subsurface water-saturated sediment.*
Has	Alluvium of the St. Francis River; *Undifferentiated alluvium within the meander belt and modern floodplain of the St. Francis River.*
Hch	Stream Channel; *A curvilinear depression where fluvial deposits were transported and accumulated.*
Hofc	Overflow Channel; *A curvilinear depression where fluvial deposits were transported and accumulated during high-stage flood events.*
Hms	Meander Scroll; *Stream channel deposits that were emplaced as channel bends (meanders) sequentially migrated across the floodplain and left behind successive point bars on the inside of the channel bends.*
Hoxl	Oxbow Lake, water filled; *A former channel that is now an area of standing or slack water that was cut off from the active channel due to meander migration and/or meander neck formation.*
Hoxf	Oxbow Lake, mostly filled; *An oxbow lake that is now largely filled with sediment with little to no standing water.*
Ht	Terrace, queried where uncertain; *Fragments of former floodplains that lie elevated above the modern stream due to stream channel incision.*
Pch	Stream Channel; *A curvilinear depression where fluvial deposits were transported and accumulated.*
Pnl?	Natural Levee; *A slightly elevated ridge located on the floodplain adjacent to and parallel to a stream channel.*
Qaa	Alluvium of the Ash Hill braid belt; *Undifferentiated alluvium within the Ash Hill braid belt.*
	Sand dunes of the Ash Hill braid belt
Qaas	Undifferentiated aeolian sands of the Ash Hill braid belt, queried where approximate; *Individual sand dunes, or remnants of sand dunes, of the Ash Hill braid belt.*
Qam	Alluvium of the Melville Ridge braid plain; *Undifferentiated alluvium of Melville Ridge braid belt.*
Qcd	Closed Depression, queries where uncertain; *An apparently low-lying, poorly drained area interpreted from dark tonal contrasts on aerial photography.*

N

0 2,000 feet

0 500 meters

Notes: Scale is 1:20,000 when printed on 20" x 25" plate.
See accompanying text for full explanation of map.

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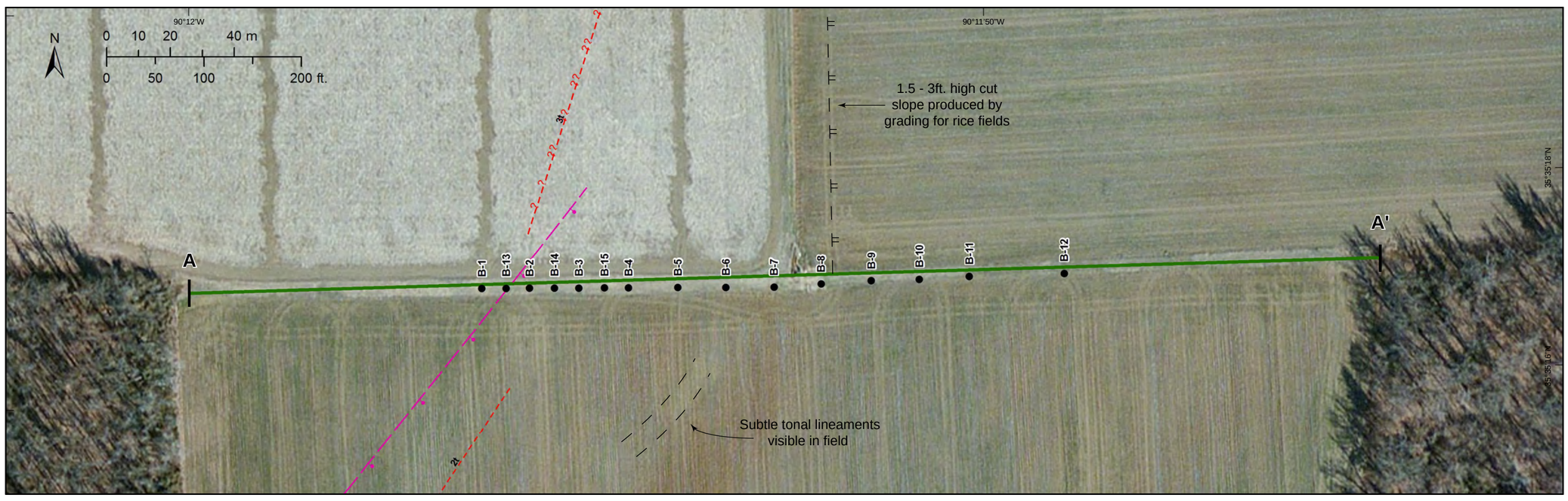
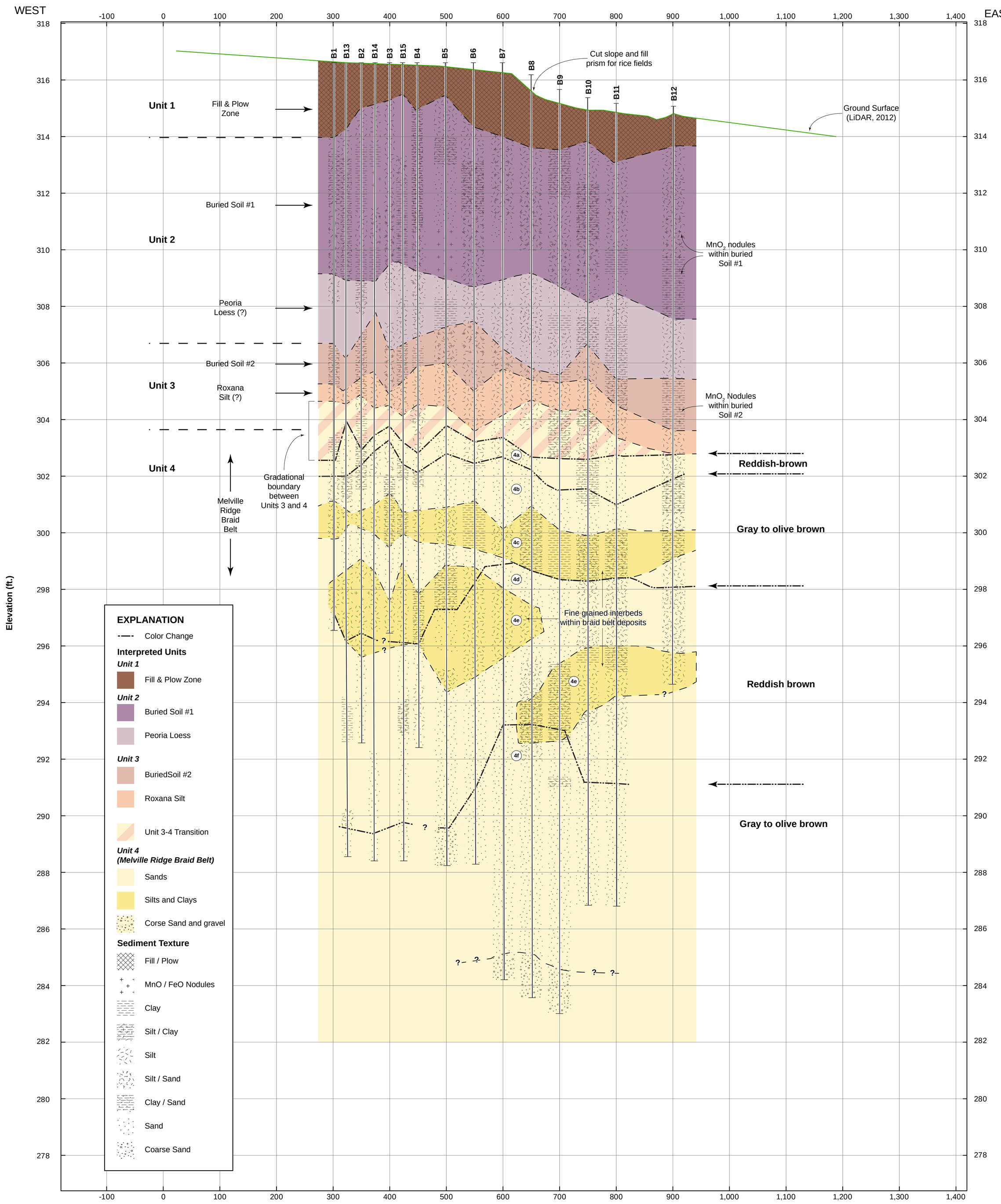
Geologic and Geomorphic Mapping, Qulin Study Site

PLATE 1





0 50 100 ft

Horizontal scale: 1 inch = 100 feet

Vertical scale: 1 inch = 2 feet

All units are feet. Elevation exaggeration: 50x.

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Plate 2:
A - A' Cross Section

Note: Areas within boreholes without a texture pattern are areas where the soil core was compressed and the deposit type is inferred.