Bulletin of the Seismological Society of America

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THE SEISMOLOGICAL SOCIETY OF AMERICA
400 Evelyn Ave., Suite 201
Albany, CA 94706-1375
(510) 525-5474; FAX (510) 525-7204
www.seismosoc.org

Bulletin of the Seismological Society of America, Vol. 89, No. 1, pp. 140–155, February 1999

Deformation and Quaternary Faulting in Southeast Missouri across the Commerce Geophysical Lineament

by W. J. Stephenson, J. K. Odum, R. A. Williams, T. L. Pratt, R. W. Harrison, and D. Hoffman

Abstract High-resolution seismic-reflection data acquired at three sites along the surface projection of the Commerce geophysical lineament in southeast Missouri reveal a complex history of post-Cretaceous faulting that has continued into the Quaternary. Near Qulin, Missouri, approximately 20 m of apparent vertical fault displacement has occurred in the Quaternary. Reflection data collected at Idalia Hill, about 45 km to the northeast, reveal a series of reverse and possibly right-lateral strike-slip faults with Quaternary displacement. In the Benton Hills, 45 km northeast of Idalia Hill, seismic data image a complicated series of anticlinal and synclinal fault-bounded blocks immediately north of the Commerce fault. We infer that most of the deformation imaged in the upper 400 m of these three data sets occurred since post-Cretaceous time, and a significant portion of it occurred during Quaternary time. Collectively, these seismic data along with geomorphic and surface-geologic evidence suggest (1) the existence of at least one potential seismogenic structure in southeastern Missouri outside the main zones of New Madrid seismicity, and (2) these structures have been active during the Quaternary. The geographic location of the imaged deformation suggests it is related to structures along with the Commerce geophysical lineament.

Introduction

The New Madrid Seismic Zone (NMSZ) has been intensively studied over the past three decades since its recognition as a major seismic hazard to the central United States (Nuttli, 1973; Zoback *et al.,* 1980; Kane *et al.,* 1981; Penick, 1981; Johnston and Nava, 1985). During that time, we have gained significant knowledge concerning the seismotectonics and seismogenic characteristics of the NMSZ (e.g., Johnston and Shedlock, 1992), but we have also realized the complexity of the Quaternary fault history in the central United States (Johnston and Schweig, 1996). As seismic hazard studies have expanded outside of the main bands of seismicity defining the NMSZ, the search for potentially active Quaternary fault zones has become a key part of understanding this complex history (Schweig and Van Arsdale, 1996).

One area that has been receiving increased attention is along the Commerce geophysical lineament (CGL), which is comprised of a series of linear, northeast-trending magnetic and gravity anomalies traceable for more than 400 km that lie roughly 50 km northwest of the NMSZ source region (Fig. 1a; Hildenbrand and Hendricks, 1995; Langenheim and Hildenbrand, 1997). The CGL has received attention because of several intriguing correlations between its surface projection and geomorphic and geologic features. The CGL coincides with the surficial trace of the Commerce fault (Harrison, 1998), a structure that recently has been shown to have Quaternary displacement (Harrison *et al.,* 1995; Palmer *et al.,* 1997a,b; Harrison *et al.,* 1997). Paleoliquefaction features and Tertiary-age faults have been mapped at other locations along the CGL (Stewart, 1942; Vaughn, 1994; Nelson *et al.,* 1997). Thus the CGL, a deep-seated magnetic/gravity feature, may be associated with Quaternary deformation at several sites. If so, this suggests the presence of another potentially hazardous seismic source zone outside of the main zones of New Madrid seismicity.

We acquired approximately 10.1 km of high-resolution seismic-reflection data at three sites across the surface projection of the CGL (Fig. 1a) to identify possible young faulting and to characterize the style of deformation. These data, acquired on five profiles, reveal complex deformation of Paleozoic through Quaternary units overlying the CGL.

Geologic Setting

The primary structural element in the northern embayment is the Reelfoot rift, a northeast-trending graben (approximately 300 km long and 70 km wide, Fig. 2) that is best defined by aeromagnetic and gravity data (Hildenbrand, 1985). The rift originally formed in Precambrian time and magnetic modeling suggests that the magnetic basement is roughly 4 to 5.5 km deep in the graben. Felsic and mafic igneous rock (Howe and Thompson, 1984; Kolata and Nel-

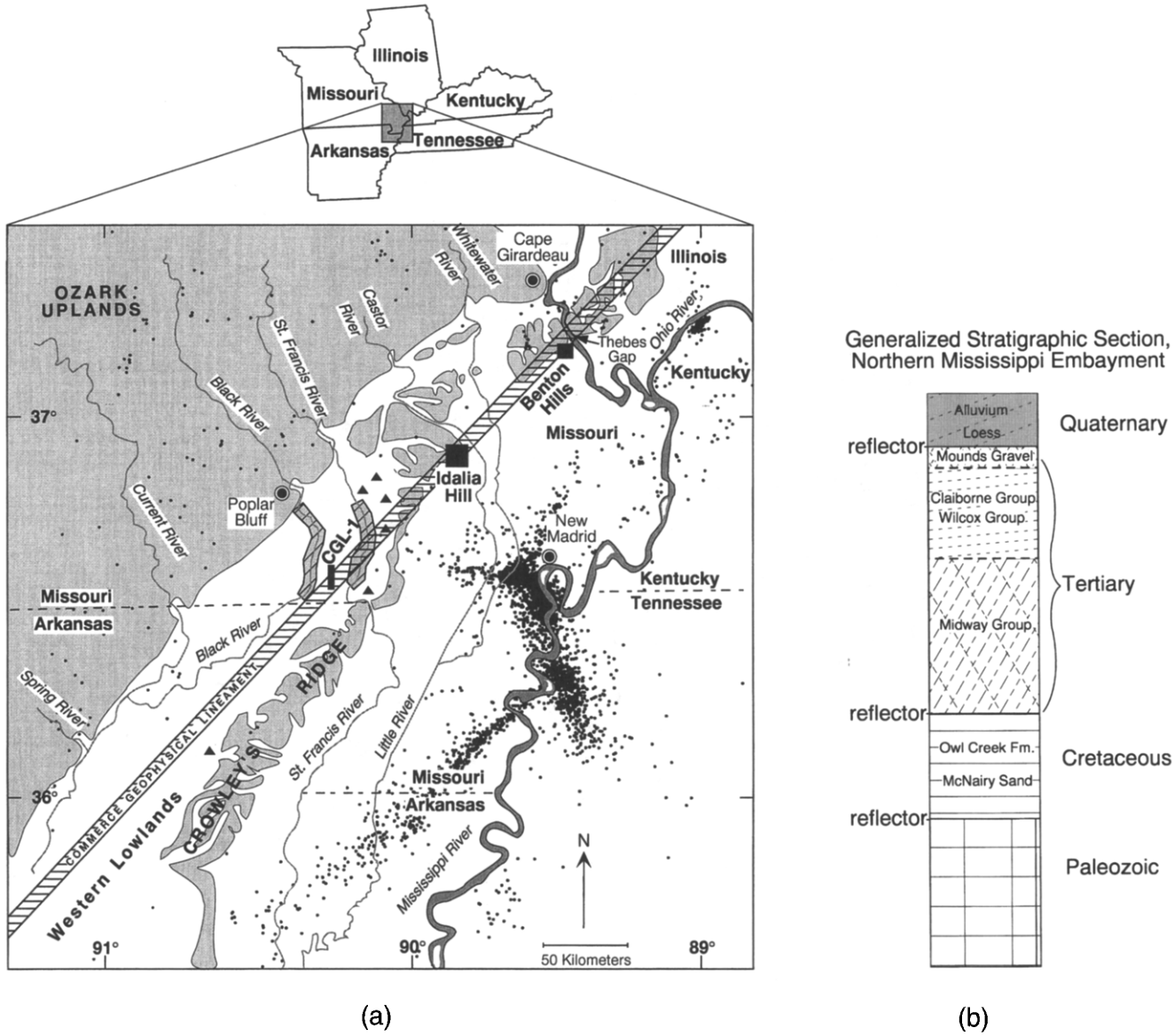

Figure 1. (a) Regional map of southeastern Missouri showing the surface projection of the Commerce geophysical lineament (horizontal hatch pattern). Black boxes show sites of high-resolution seismic-reflection studies (CGL-1, Idalia Hill, and Benton Hills). The pre-Quaternary deposits (light gray fill pattern), Quaternary alluvium (white), and main rivers (medium gray) are also shown. Sites of paleoliquefaction features (Vaughn, 1994) are shown by triangles, and areas of anomalous river drainage patterns on the Black and St. Francis rivers (Fischer-Boyd and Schumm, 1995) are shown by diagonal-hatch gray patterns. Epicenters of recorded seismicity from 1974 to 1995 are shown by black dots. (b) Generalized stratigraphic section for the study area. Primary seismic reflectors for region are annotated on left side of section.

son, 1991) intruded zones of weakness along the rift margins and along an axial fault zone. Emplacement of several mafic to ultramafic plutons identified along the rift margins and within the graben occurred as late as the late Mesozoic (Hildenbrand and Hendricks, 1995). Compressive stresses, probably associated with the late Paleozoic Ouachita and Allegheny orogenies, induced strike-slip, oblique, and reverse fault movement on Reelfoot rift boundary faults (Howe and Thompson, 1984; Kolata and Nelson, 1991). Currently, and probably beginning as early as the Miocene, the Mississippi embayment is being compressed by predominantly uniform horizontal stresses (Zoback and Zoback, 1989; Johnston and Nava, 1990).

The depositional history of the northern Mississippi embayment from Paleozoic time to the Holocene has been well documented (Groshkopf, 1955; Stearns, 1957; Pryor, 1960;

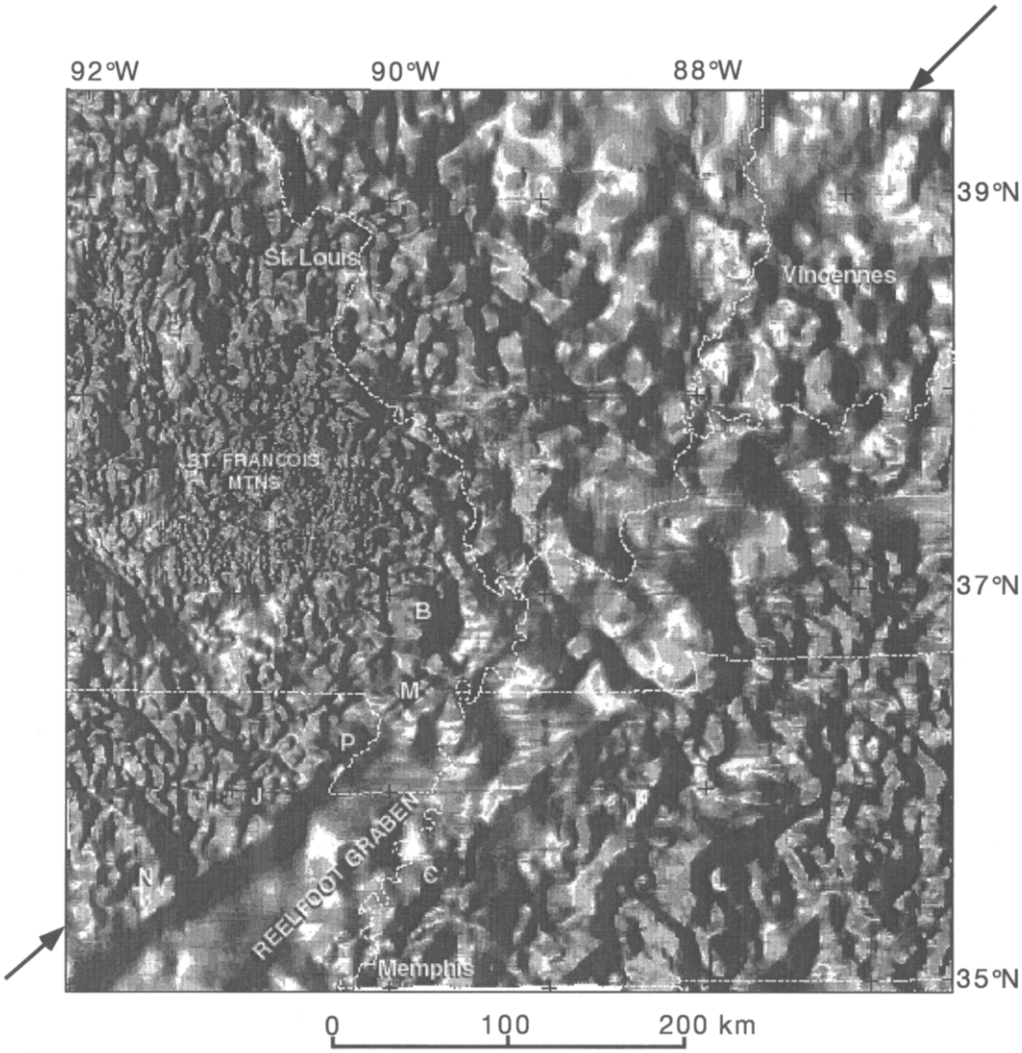

Figure 2. Total field, reduced-to-the-pole, aeromagnetic map showing the Reelfoot rift (graben) and the Commerce geophysical lineament (shown by arrows; from Langenheim and Hildenbrand, 1997). Bloomfield, Newport, Jonesboro, Paragould, Malden, and Covington plutons are denoted by 'B', 'N', 'J', 'P', 'M', and 'C', respectively). Commerce geophysical lineament is traceable for over 400 km.

Cushing *et al.,* 1964; Howe and Thompson, 1984). The general depositional history of this area from the late Cretaceous to historic time provides the context for interpreting Quaternary-age faulting. Generally, the stratigraphic section overlying Paleozoic rocks is less than 300 m thick along the CGL. A generalized stratigraphic column of Paleozoic and younger rocks is shown in Figure 1b.

Within the study area, extensive erosion during the late Paleozoic and/or early Mesozoic removed several kilometers of rock from the uplifted Pascola arch, leaving a Paleozoic bedrock surface of limestone or sandstone that dips gently southeastward toward the embayment axis at a slope of approximately 6.6 m/km (Groshkopf, 1955; Marcher and Stearns, 1962; Boswell *et al.,* 1965). Paleozoic bedrock is unconformably overlain in the northern embayment by the Upper Cretaceous McNairy Sand and Owl Creek Formation (Pryor, 1960). These Cretaceous rocks gradually pinch out in the northernmost Mississippi Embayment and are unconformably overlain by Paleocene marine sediments.

During the Paleocene, a marine transgression completely flooded the embayment and resulted in deposition of shallow- to deep-water clay that comprises the lower formation of the Midway Group. In the northern embayment, a distinct unconformity separates the Midway Group from the overlying Paleocene-lower Eocene Wilcox Group, which consists of the shallow-water and back-beach/deltaic sand and silt deposits. Following cessation of subsidence in middle to late Eocene time, the northern embayment underwent regional uplift and erosion (Stearns, 1957).

The Wilcox Group is unconformably overlain by de-

posits of late Pliocene and early Pleistocene coarse-grained alluvium. This Pliocene–Pleistocene Mounds Gravel is overlain by mid to late Pleistocene glacial outwash, colluvium, and windblown loess that mantles valley and upland surfaces within and adjacent to the Mississippi embayment (Guccione *et al.,* 1990; Autin *et al.,* 1991). During the Holocene, the Mississippi and Ohio Rivers have reworked relict braided stream deposits, glacial-outwash, and modern alluvial deposits (Royall *et al.,* 1991; Autin *et al.,* 1991).

Commerce Geophysical Lineament

Vaughn (1992) first suggested the existence of a northeast-trending seismogenic structure in southeastern Missouri (outside of main NMSZ) based on the presence of paleoliquefaction deposits in the Western lowlands (Fig. 1). This structure was initially named the Dexter dextral lineament (DDL) because it is located near the town of Dexter, Missouri. Later, Langenheim and Hildenbrand (1994) analyzed magnetic and gravity anomalies that form a geophysical lineation along trend with and generally underlying the DDL. They named this lineation, which trends N45°E, the Arkansas–Illinois lineament because it extends for over 400 km from northeastern Arkansas to southwestern Illinois (Fig. 2). Langenheim and Hildenbrand (1997) later renamed the feature the "Commerce geophysical lineament" after the Commerce fault (e.g., Harrison and Schultz, 1994; Harrison, 1998), which overlies the surface projection of the CGL in southeastern Missouri (Fig. 1a).

Inverse modeling of aeromagnetic and gravity data (Langenheim and Hildenbrand, 1997) suggests that the CGL anomalies could be caused by a series of mafic dikes intruded as shallow as 1.5 km deep across a 5- to 10-km-wide zone. Langenheim and Hildenbrand (1997) also interpret left-lateral displacement across the CGL on the Bloomfield Pluton, an igneous intrusive believed to be late Mesozoic in age (Fig. 2). The CGL may have experienced episodic faulting and igneous intrusive activity throughout the Phanerozoic (Langenheim and Hildenbrand, 1997). Within the Reelfoot rift system, NE–SW-trending faults similar to those associated with the CGL may respond to the regional stresses with predominantly dextral strike slip along with minor normal, oblique, and reverse movement (Russ, 1982; Zoback and Zoback, 1989; Dart and Swolfs, 1998). The northwestern boundary of the Reelfoot rift is nearly parallel with the CGL over much of its length, although the amplitude of the CGL anomaly is typically 6 to 10 times less than the anomaly that defines the northwestern margin of the Reelfoot rift. This subparallel relation may be evidence of a deep-seated structural relationship between these two magnetic structures.

Indicators of Earthquake Activity along CGL

Paleoliquefaction features are one of the few geological indicators of the size and location of historic and prehistoric strong ground shaking events throughout much of the central United States (Obermeier, 1989). Sand blows and clastic dikes along the St. Francis River and several associated drainage ditches led Vaughn (1994) to infer that a nearby seismogenic structure or structures had generated as many as four large earthquakes in the past 25 ka (Fig. 1a). The larger paleoliquefaction features (sand blows and dikes) in the Western Lowlands, dated to 14 to 9 ka, are too distant to be related to seismicity in the main NMSZ, over 50 km to the southeast. However, smaller cross-cutting features in the Western Lowlands are possibly liquefaction related to the 1811 to 1812 earthquake events in the NMSZ (Vaugh, 1994). Vaughn (1992) speculated that the larger liquefaction features were caused by earthquakes on a northeast-trending fault (the DDL), although he also noted that these and other paleoliquefaction features could have been caused by slip on a north-northwest-trending structure (Vaughn, 1994).

Several stream channel anomalies are also geomorphic indicators of possible ground deformation in the vicinity of our studies. Fisk (1944) suggested that escarpment and angular drainage patterns throughout much of the northern Mississippi embayment, including the Western Lowlands, were evidence of fault control. Fischer-Boyd and Schumm (1995) analyzed topographic and stream drainage in the Western Lowlands and delineated anomalous reaches in the Black and St. Francis Rivers, approximately 15 km north of the Missouri/Arkansas border, that mimic each other in an unusual eastward deflection (Fig. 1a). From this, they inferred an east–west-trending uplift crossing the lowland slightly north of the surface projection of the CGL. Fischer-Boyd and Schumm (1995) also suggest the general flow pattern of the Black River southwestward through the Western Lowlands is evidence of tectonic control in the area.

Surface faults that have been active at least since post-early Tertiary are mapped at several locations in the northern embayment; many of these faults are along the surface projection of the CGL. Harrison (1998) and Nelson *et al.* (1997) discuss faulting on the Commerce fault near Thebes Gap. At least 2 to 4 m of vertical Quaternary movement has recently been documented on the English Hill fault zone in the Benton Hills (Fig. 1a), which is closely associated with the Commerce fault (Harrison *et al.,* 1995, 1997; Palmer *et al.,* 1997b). Fifty kilometers to the southwest, Stewart (1942) and Groshkopf (1955) mapped surface faults at Idalia Hill that displace Tertiary Midway and Wilcox Groups as well as the late Tertiary Mounds Gravel. Heyl and McKeown (1978) describe a photo-lineament they called the Commerce photo-lineament, which extends from the Commerce fault toward Idalia Hill. Recent field investigations along the northern end of Crowley's Ridge near Idalia Hill have revealed Quaternary loess possibly faulted against Tertiary Wilcox sand (Hoffman, 1998). Taken together, these studies show that faulting has occurred at several sites that closely coincide with the surface projection of the CGL.

Little historic seismicity has been observed along the CGL (Fig. 1a), however, several small-to-moderate earthquakes have been recorded along its length over the past several decades. Harrison and Schultz (1994) first discussed

12 historic earthquakes possibly attributable to the CGL, though their primary interest was the Thebes Gap/Commerce fault area. Langenheim and Hildenbrand (1997) list 16 earthquakes on or near the CGL; these events have body-wave magnitudes of m_b 3.0 to 5.5, with a median of m_b 3.9. Focal mechanisms for some of these earthquakes are consistent with dextral strike-slip faulting in the modern stress regime (compression with principal axis oriented N80°E) while several are not. Those mechanisms that are not consistent could indicate slip on subsidiary structures having different strikes. If all 16 earthquakes (Langenheim and Hildenbrand, 1997) are associated with the CGL, then they suggest a diverse faulting pattern.

Seismic Data Acquisition and Processing

The five high-resolution seismic-reflection profiles presented here were acquired along the surface projection of the CGL. The line locations were selected primarily on surface evidence of post-Tertiary deformation, such as nearby paleoliquefaction features. These data were obtained using different sources and acquisition parameters, as listed in Table 1. Data processing varied somewhat from area to area (Tables 2a, 2b, and 2c). Differing depths of investigation, source characteristics, and signal quality caused sufficient variation between the data sets to warrant these variations in processing. Data resolution will be discussed as needed on a case-by-case basis. Overall, the dominant frequency bandwidth was broad, between 40 and 200 Hz, implying reasonably high resolution in these data.

Seismic Data Interpretation

Several key reflecting horizons are consistently observed in seismic-reflection data throughout much of the Mississippi Embayment: (1) the Cretaceous/Paleozoic contact; (2) the Tertiary/Cretaceous contact; and (3) the Quaternary/Tertiary contact (e.g., Hamilton and Zoback, 1982; Sexton and Jones, 1986; Odum *et al.*, 1995; Williams *et al.*, 1995; Woolery *et al.*, 1996). These reflecting horizons are interpreted on the sections we present, unless insufficient local stratigraphic information is available. Reflections from stratigraphic horizons within the Quaternary and Tertiary are also interpreted on some profiles, and where available, we correlate reflecting horizons to subsurface stratigraphy from nearby water wells.

CGL-1

A 6-km-long, north–south, high-resolution seismic-reflection profile (Fig. 3a) was acquired across the surface projection of the Commerce geophysical lineament near late Pleistocene and younger paleoliquefaction features reported by Vaughn (1994; Fig. 1a). No other surface features (scarps, fractures) related to Quaternary faulting have been identified in this immediate area. In fact, surface topography varies only about 3 m over the 6 km length of the profile. We used the log of a water well drilled for the nearby city of Qulin (Missouri Department of Natural Resources Log Number 23187) and subsurface horizon maps by Groshkopf (1955) to correlate reflections to subsurface stratigraphy. The water well is located from 2.5 km west of this profile, which is reasonable given the very gentle regional stratigraphic dip. The lithologic boundaries interpreted from the well log include the Quaternary/Tertiary at about 51 m depth and the Tertiary/Cretaceous at about 60 m depth. The well was drilled to a depth of 98 m, terminating in Cretaceous rock.

Four main reflecting contacts are interpreted on profile CGL-1. We interpret the Cretaceous/Paleozoic contact at 225 m depth on the southern end of the line. This reflecting horizon shows a complex history of deformation and cannot be traced north of an interpreted fault near station 260. The Tertiary/Cretaceous boundary (Fig. 3b) is imaged at about 90 m depth on the northern end of the line and gradually steps down to about 120-m depth at the southern end of the line. Maximum apparent vertical displacement of this reflector is about 20 m near about station 805. Interpretation of the Tertiary/Cretaceous boundary is based on its continuous high-amplitude reflection, which is typical throughout much of the embayment, its depth relative to the Cretaceous/Paleozoic contact, and by extrapolating the thickness of Tertiary strata from the Qulin well using the maps of Groshkopf (1955). The Tertiary stratigraphic section thins from more

Table 1
Generalized Acquisition Parameters for High-Resolution Seismic-Reflection Profiles

Line Name (nearest town)	Source Type*	Source Interval (m)	Receiver Interval (m)	Number Channels	Field Filters	Sample Rate (msec)	Trace Length (msec)
CGL-1 (Qulin, MO)	hammer	6.1	6.1	48	60 Hz	1	1024
IDAL-1 (Idalia, MO)	Wacker®	5	5	60	60 Hz	1	1024
IDAL-2 (Idalia, MO)	Wacker®	5	5	60	60 Hz	1	1024
ALB-2 (Commerce, MO)	shotgun	3	3	60	60 Hz	0.5	1024
ALB-3 (Commerce, MO)	shotgun	3	3	60	60 Hz	0.5	1024

*Wacker® is a registered trademark of Wacker Corporation. It is an earth compactor used as a seismic source in this study. Three compactors were run simultaneously in-line during acquisition, spaced 2.5 m apart.

Hammer denotes a 4.55 kg sledgehammer source.

Shotgun denotes a 12-gauge gun that fired black-powder blanks into an 0.45-m-deep, 0.04-m-diameter hole.

Table 2a
Generalized Processing Steps for Seismic Reflection Profile CGL-1

Processing Step	Comment
Data reformat	convert from SEG 2 to ProMAX® internal
Geometry	install coordinate data into trace headers
Trace edit	kill bad traces, fix polarity reversals
Top mute	zero all data amplitude before and including first arrivals
Bandpass filter (Hz)	40–80–250–500 Hz
AGC gain correction	adjust amplitudes using 400 msec rms gain window
Adaptive spiking deconvolution	L1-norm, 80 msec operator length
Air blast attenuation	attenuate high-amplitude air wave at 400 m/sec
Elevation statics	time shifts very small because profile straight and flat
Sort to CMP	reorder data by common mid-point number
NMO correction	apply stacking velocities (best of 3 analysis passes)
Residual statics	Surface consistent, based on maximum stack power
Stack	zero-offset mean stack
Migration	reverse-time TK algorithm, 70% of mean stacking velocity
Eigenvector filtering	0–40% eigenimage accepted
Time-to-depth conversion	digital conversion using best stacking velocity function

Table 2b
Generalized Processing Steps for Seismic Reflection Profiles IDAL-1 and IDAL-2

Processing Step	Comment
Data reformat	convert from SEG 2 to ProMAX® internal
Geometry	install coordinate data into trace headers
Trace edit	kill bad traces, fix polarity reversals
Top mute	zero all data amplitude before and including first arrivals
Bandpass filter	35–65–250–500 Hz(IDAL-1); 25–50–150–250 Hz (IDAL-2)
AGC gain correction	adjust amplitudes using 400 msec rms gain window
Elevation statics	time-shift data traces based on elevation differences
Adaptive spiking deconvolution	L1-norm, 240 msec operator length
Surgical mute	mute out surface-wave energy
NMO correction	apply stacking velocities (best of 3 analysis passes)
Residual statics	Surface consistent, based on maximum stack power (2 passes)
Stack	zero-offset mean stack
Migration	explicit finite-difference time migration, 70% stacking velocity
Eigenvector filtering	0–40% eigenimage accepted
Time-to-depth conversion	digital conversion using best stacking velocity function

ProMAX® is a registered trademark of Landmark Graphics Corporation.

Table 2c
Generalized Processing Steps for Seismic Reflection Profiles ALB-1 and ALB-2

Processing Step	Comment
Data reformat	convert from SEG 2 to ProMAX® internal
Geometry	install coordinate data into trace headers
Trace edit	kill bad traces, fix polarity reversals
Top mute	zero all data amplitude before and including first arrivals
Bandpass filter	20–40–250–500 Hz (ALB-1 and ALB-2); notch 180, 152, 212 Hz
AGC gain correction	adjust amplitudes using 200 msec mean gain window
Elevation statics	time-shift data traces based on elevation differences
Air Blast attenuation	attenuate linear energy at 340 m/sec
NMO correction	apply stacking velocities (best of 3 analysis passes)
Residual statics	surface consistent, based on maximum stack power (2 passes)
Dip moveout	common offset *T-X* algorithm
Stack	zero-offset mean stack
Eigenvector filtering	0–40% eigenimage accepted
Time-to-depth conversion	digital conversion using best stacking velocity function

than 50-m thickness on the southern end of the profile to less than 15 m on the northern end (Fig. 3b).

The Quaternary/Tertiary contact is between 40 and 55 m deep along the profile. This contact appears to be faulted down to the south with as much as 20 m of apparent vertical displacement at station 820, a similar amount to that observed on the Paleozoic surface. Typical vertical resolution of these data at 50 m depth is on the order of 5 m, based on the quarter-wavelength rule (Widess, 1973). Thus, we have reasonable resolution for interpreting deformation on the base of the Quaternary. Beginning at about station 340, the top of the Tertiary gradually warps up to the south. Assuming the Tertiary sediments were originally deposited with a gentle southeastward dip, then the current geometry of the Tertiary surface suggests it is upwarped from about station 260 to beyond the southern end of the profile.

Evidence for Quaternary Faulting

The interpreted faults (Fig. 3b) are concentrated along the southern 3 km of the line. The most obvious deformation occurs between stations 750 and 850, where faults appear to rupture through the Cretaceous and Tertiary deposits, and into Quaternary deposits. One intra-Quaternary horizon (Fig. 3b) at roughly 25 m depth can be traced along much of the profile. This horizon is generally continuous from at least station 320 to station 715. It is not imaged between stations 715 and 805, and then it is again distinct south of station 805. As shown in Figure 3b, the Quaternary deposits below the intra-Quaternary reflector thin slightly to the south from stations 520 to 715.

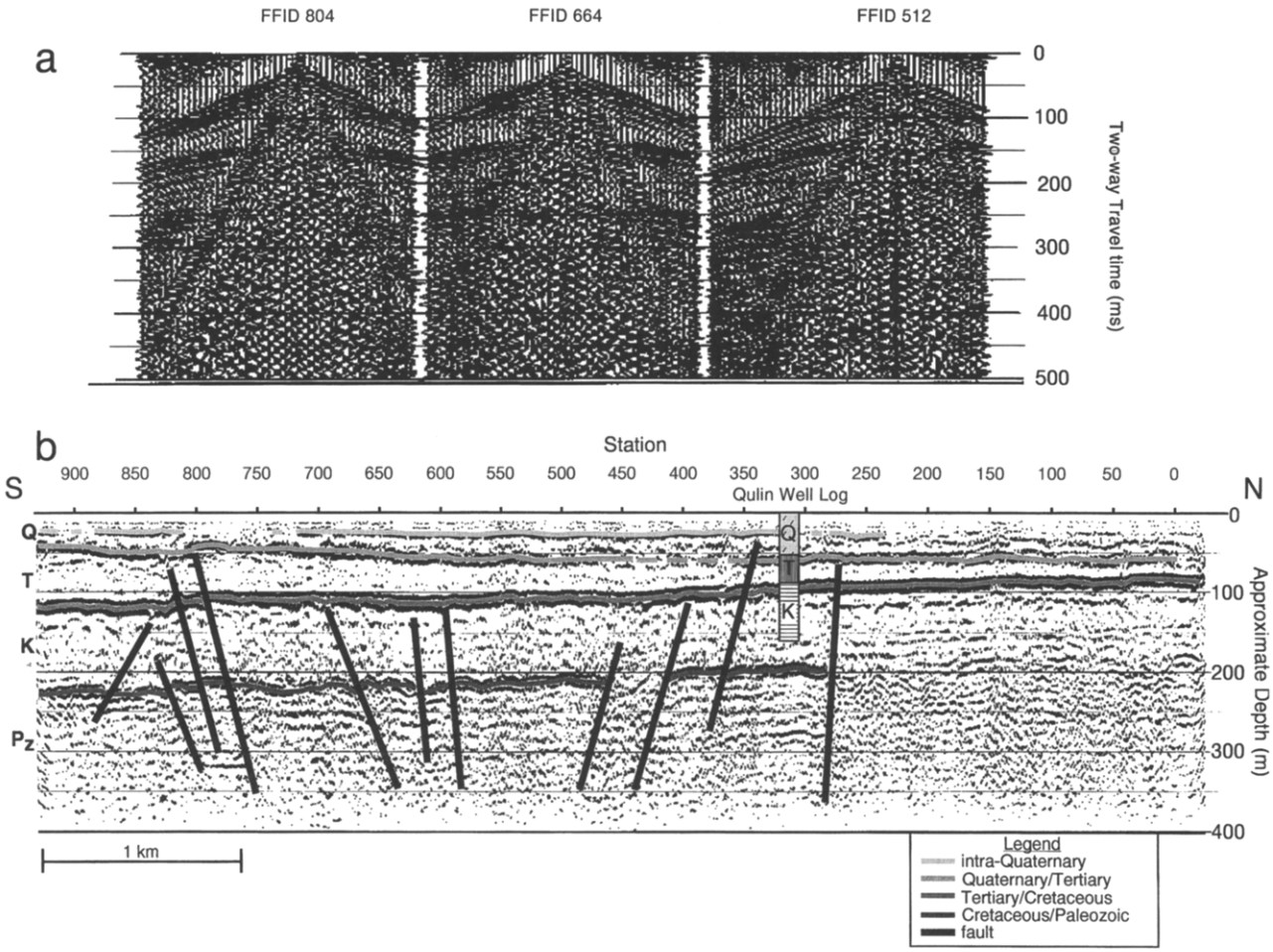

Figure 3. (a) Typical shot records from CGL-1. Data show a series of strong reflections in the upper 300 ms. (b) Migrated, depth-converted seismic-reflection profile CGL-1. Quaternary (*Q*), Tertiary (*T*), Cretaceous (*K*), and Paleozoic (P_z) strata labeled; interpreted faults shown by heavy black lines. Well log from nearby town of Qulin, Missouri, projected into profile. Deformation between stations 750 and 850 is Quaternary in age.

The intra-Quaternary reflection may be missing between stations 715 and 805 because faulting raised the reflector to a depth too shallow for imaging, or the reflector has been uplifted and eroded. Alternatively, faulting could have intensively fractured the reflector, resulting in the loss of continuity and impedance properties needed to generate a reflection. Another possibility is that the reflector may not have been deposited beneath these stations; the reflection from this horizon is discontinuous elsewhere along the profile, although the distance over which it is missing between stations 715 and 805 is significantly wider than at other locations. We speculate that this anomalously wide nonreflecting zone above the Quaternary/Tertiary contact may be caused by a now-buried topographic high resulting from post-earliest Quaternary faulting. All of these scenarios suggest fault deformation younger than earliest Quaternary. No clear evidence is observed at the surface to suggest uplift has occurred since deposition of the Holocene surficial sediments.

Horizon-Flattening Analysis

A horizon-flattening technique was used to estimate the timing of deformation along the southern 2 km of seismic profile CGL-1 (e.g., Brown, 1996; Fig. 4a). In Figure 4b, the Tertiary/Cretaceous horizon was flattened to 150 msec two-way travel time. The vertical black lines are the approximate bounds of the main fault zone, to the top of the Cretaceous rocks. The upper two gray lines in Figure 4b follow the general trends of the intra-Quaternary and Quaternary/Tertiary contacts, with their slopes differing somewhat on opposite sides of the fault zone. Within the 5-m resolution of these data, there appears to be a comparable amount of apparent vertical deformation on both the Cretaceous and Tertiary boundaries, as suggested by the depth and alignment of the Quaternary/Tertiary boundary across the fault zone. This strongly implies that vertical deformation did not start until after Tertiary time. Similarly, the intra-Quaternary reflector aligns reasonably well across the fault zone after re-

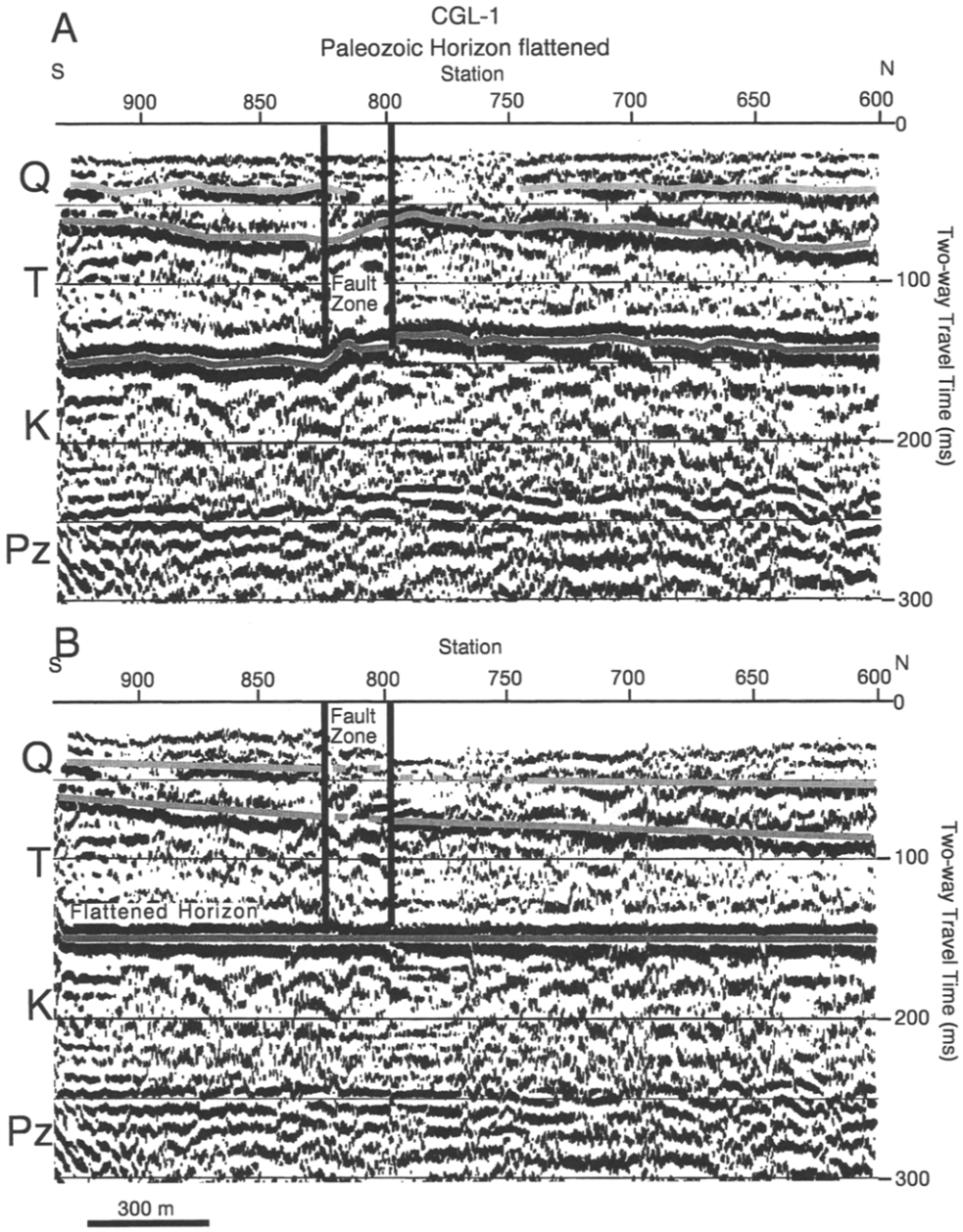

Figure 4. (a) Portion of seismic-reflection profile CGL-1 showing detail of fault zone between stations 795 and 825. (b) Horizon-flattened section of data shown in (a). The Tertiary/Cretaceous boundary was flattened to 150-msec two-way travel time to estimate Quaternary and Tertiary vertical-fault displacement. The southward thickening of the Tertiary section should be constant across the fault zone at about station 815 if this structure has been active primarily after development of the Cretaceous erosion surface. Differences in expected thickness across the fault zone imply deformation prior to the development of this surface. If much of the apparent vertical deformation on this boundary occurred prior to the deposition of the Cretaceous and Quaternary strata, then a linear projection of these contacts across the fault zone would not be possible. Thus, the flattening indicates that most fault motion occurred after deposition of the Tertiary and Quaternary strata.

construction, although it appears to be slightly higher south of the zone (Fig. 4b). Given the sense of down-to-the-south apparent displacement on the fault zone (Fig. 4a), these relations suggest that most, but not all, of apparent vertical uplift across the fault occurred after deposition of this intra-Quaternary reflector.

Idalia Hill: IDAL-2

Approximately 3.15 km of seismic-reflection data were acquired along two profiles northeast of CGL-1 near Idalia Hill, Missouri (Figs. 1 and 5). Idalia Hill is a topographic high along the eastern edge of Crowleys Ridge (Fig. 1), a landform shown to be fault-bounded further to the south and to have experienced post-middle Eocene deformation (Van Arsdale *et al.,* 1994). The CGL projects directly beneath and parallel to the eastern edge of Idalia Hill and the Idalia Hill fault of Stewart (1942). Profile IDAL-2 is 1.65 km long and crosses the southeastern edge of the hill and the Idalia Hill fault (Fig. 6). The topographic relief along this profile was over 40 m, and these data were adjusted to a datum elevation at the base of Idalia Hill to correct for topography. A water well log (Missouri Department of Natural Resources Log Number 8572) about 200 m north of the profile lists depths to the Tertiary/Cretaceous and Cretaceous/Paleozoic boundaries at 79 and 140 m, respectively.

Profile IDAL-2 shows numerous interpreted faults over most of the profile length. The Tertiary/Cretaceous and Cretaceous/Paleozoic contacts in the well correlate reasonably to the respective reflecting horizons (Fig. 6). Overall, the Paleozoic surface drops about 20 m across four interpreted faults between stations 140 and 290, with significant deformation between these faults. The Tertiary/Cretaceous contact emulates the deformation on the Paleozoic surface over the western half of the profile, suggesting that the observed faulting did not begin until the Tertiary. At about station 300, the seismic line crosses the surface trace of the Idalia Hill fault, and the seismic data near this station reveal a steep westward-dipping feature that we interpret as the subsurface expression of the Idalia Hill fault. We interpret the faults west of the Idalia Hill fault as secondary features, based on their smaller apparent vertical displacement.

Eastward from the Idalia Hill fault into the Mississippi River flood plain, the subsurface structure is even more complex. We interpret three east-dipping faults that displace the Paleozoic surface between stations 320 and 370, but these faults do not appear to cut through the Cretaceous surface. Instead, the Cretaceous deposits seem to be arching perhaps in response to the deeper faulting or to faults flattening out within a flower-type structure. The Cretaceous surface east of station 375 was difficult to interpret and is thus shown as dashed in Figure 6.

The west-dipping fault at station 390 terminates at the base of a series of subhorizontal reflectors. Extrapolation of stratigraphic data from another water well located roughly 3.5 km east of station 400 (Missouri Department of Natural Resources Log Number 8574) allows us to interpret the light

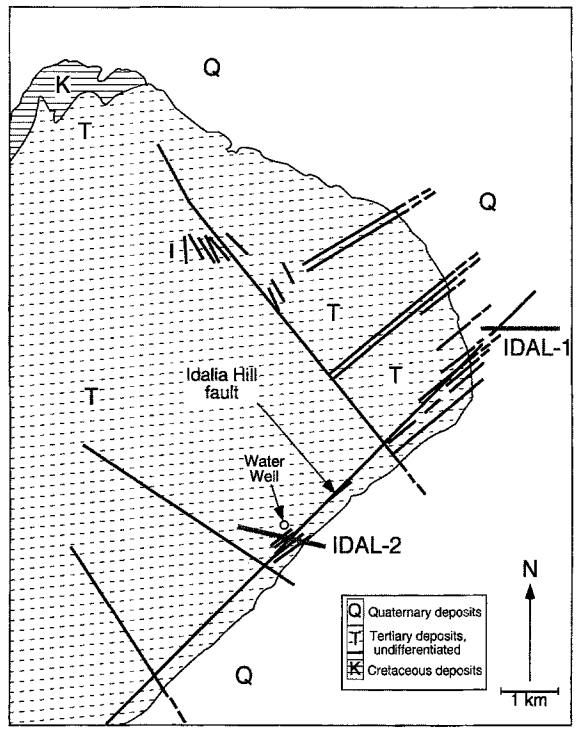

Figure 5. Simplified geologic map of Idalia Hill study area showing locations of IDAL-1 and IDAL-2 seismic-reflection profiles. Contacts between Quaternary (*Q*), Tertiary (*T*), and Cretaceous (*K*) deposits are shown. Heavy black lines are faults mapped at the surface. Location of water well north of IDAL-2 shown by the circle. Modified from J. Palmer and D. Hoffman, Missouri Department of Natural Resources (unpublished report).

gray horizon (Fig. 6) at 30 m depth is as the Quaternary/Tertiary boundary. Beneath station 372, the reflector has a distinct up-to-the-east break with about 5 m of apparent vertical displacement. If this horizon is the Quaternary/Tertiary boundary, then this may be significant evidence of Quaternary faulting in this part of southeastern Missouri. It further suggests the CGL is associated with recent fault activity.

Idalia Hill: IDAL-1

The 1.5-km-long profile IDAL-1 is about 5 km northeast of IDAL-2, and it is located off the eastern edge of Crowleys Ridge in the Western Lowlands, on the northeastern projection of the Idalia Hill fault and the CGL (Fig. 5). As on profiles CGL-1 and IDAL-2, the Paleozoic section contains significantly more deformation than the overlying strata (Fig. 7). However, on this profile, the Paleozoic surface has only a subtle uplift, possibly related to a fault, below station 185. The overlying Cretaceous strata are also not visibly disrupted by this deeper deformation. With the exception of an interpreted fault under station 130, none of the underlying faults appear to deform the Cretaceous surface. The Quaternary/Tertiary contact is not well resolved in these data, which may be caused by poor source and receiver cou-

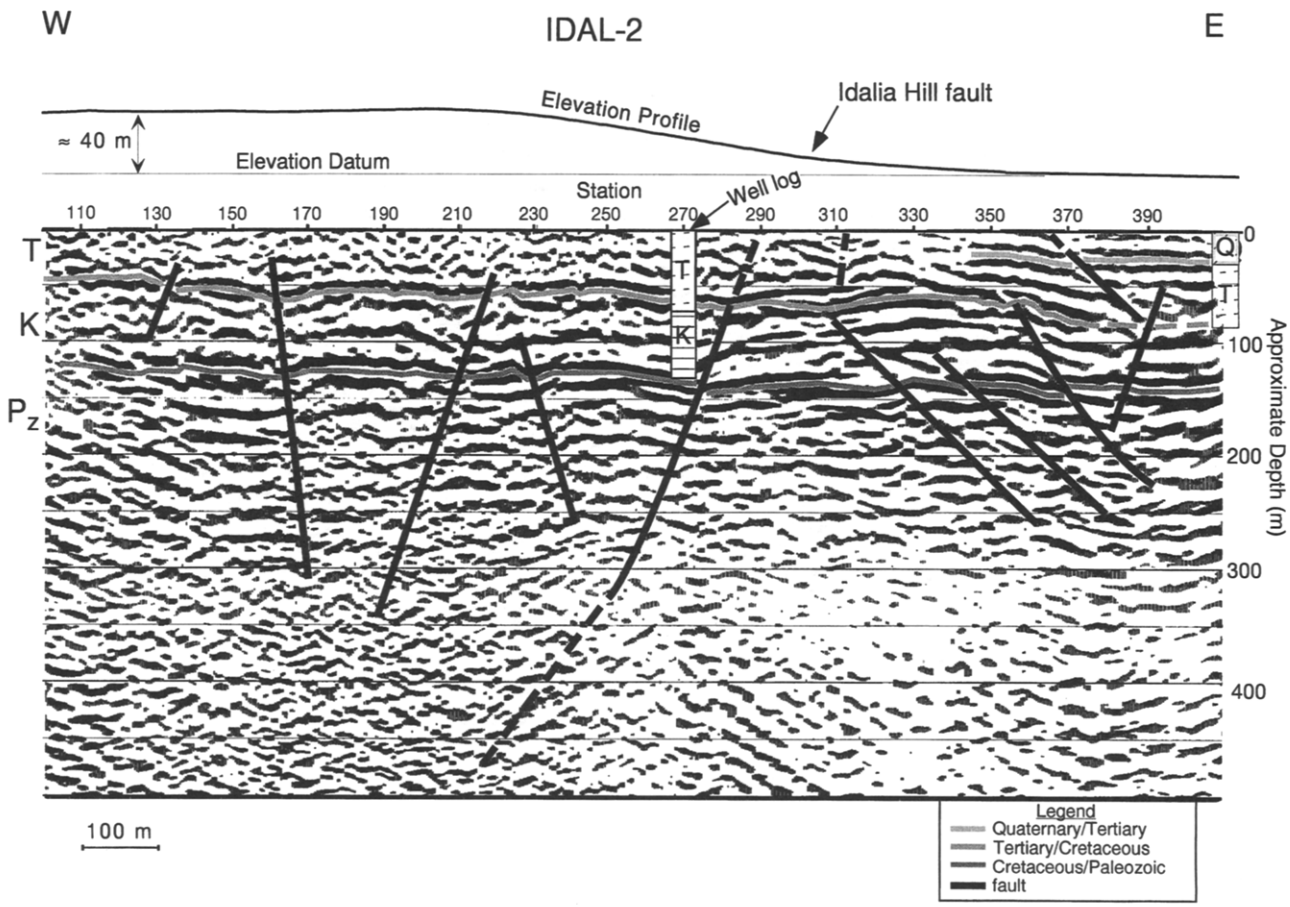

Figure 6. Migrated, depth-converted seismic-reflection profile IDAL-2. Water well is projected into profile at about station 270 from approximately 200 m north. Quaternary (*Q*), Tertiary (*T*), Cretaceous (*K*), and Paleozoic (P_z) strata labeled; interpreted faults shown by heavy black lines. Most of deformation occurred post-Cretaceous time. Pattern of deformation complex on eastern half of line, with apparent post-earliest Quaternary faulting seen at about station 370.

pling along the profile. Although this profile crosses the surface projection of the CGL, it may have missed significant Quaternary deformation because of its short length or because faulting along the CGL is not occurring along a simple linear path. Faults along the CGL could exhibit step-over behavior similar to the English Hill fault in the Benton Hills (Harrison *et al.,* 1997).

Benton Hills: Lines ALB-2 and ALB-3

Quaternary deformation along the English Hill fault in the Benton Hills has been documented by trenching and previous seismic-reflection studies (Harrison *et al.,* 1997; Palmer *et al.,* 1997a,b). We acquired seismic-reflection profiles ALB-2 and ALB-3 about 4 km east of English Hill and 500 m north of Commerce, Missouri (namesake for the Commerce fault and Commerce Geophysical lineament), to better characterize the style of faulting and its relationship to mapped young faults at the eastern end of the Benton Hills (Figs. 1a and 8a). Profile ALB-3 crossed profile ALB-2 along an east–west-trending valley. Stratigraphic correlation here is based on the boreholes and cross section of Stewart and McManamy (1941), which shows a discontinuous veneer of Quaternary deposits overlying varying thicknesses of Tertiary and Cretaceous deposits within 30 m of the surface.

Profile ALB-2 extends 450 m northward from the northern edge of the town of Commerce (Fig. 8b). Few stratigraphic horizons above the Cretaceous have been successfully imaged with reflection data in the Benton Hills (Palmer *et al.,* 1997a,b). Profile ALB-2 consists of weakly to nonreflective data in the upper 50 m, the depth range where Stewart and McManamy (1941) mapped Quaternary, Tertiary, and Cretaceous deposits. It is possible that shallow strata in this area are dipping too steeply to be imaged with two-dimensional acquisition methodology (measured dips of at least 70°; Harrison, 1998). Furthermore, the shallow deposits may not have sufficient reflection impedance contrasts and therefore are seismically transparent. In addition, ground roll

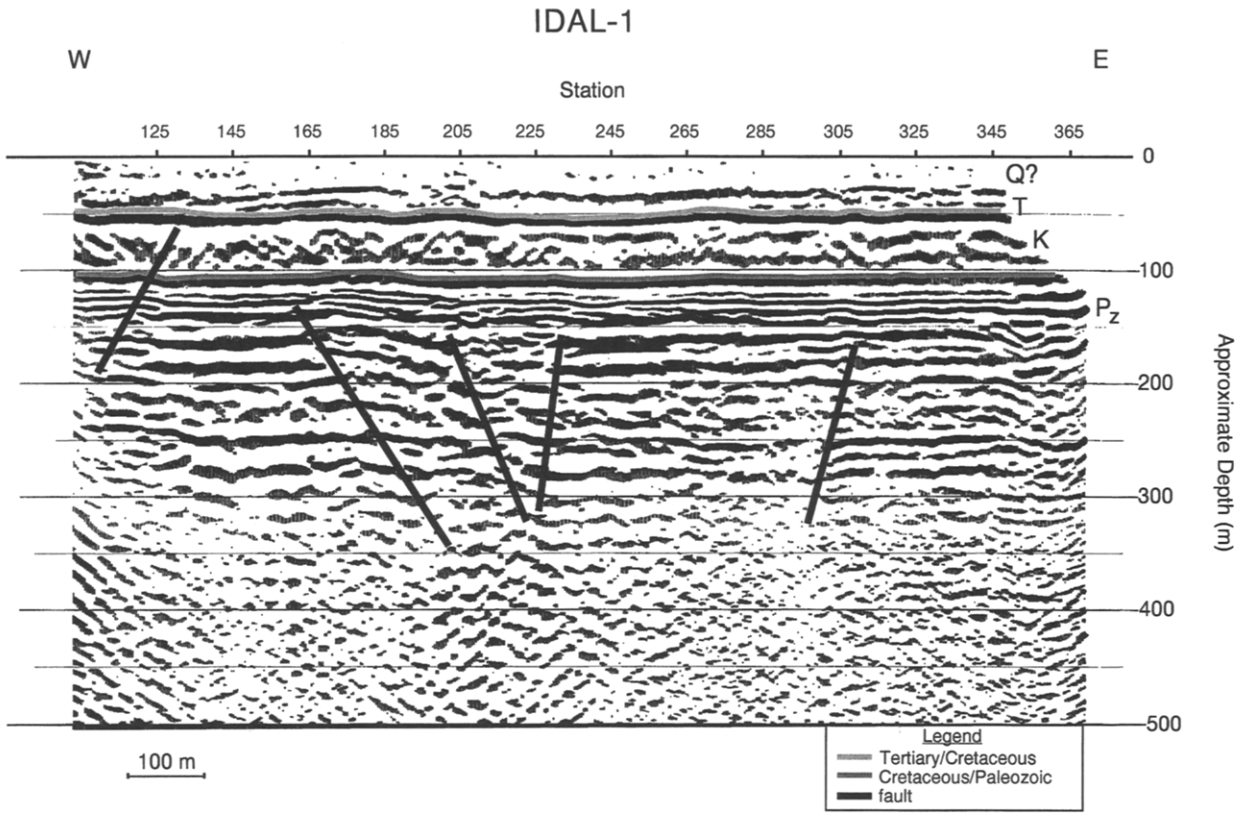

Figure 7. Migrated, depth-converted seismic-reflection profile IDAL-1. Quaternary (*Q*), Tertiary (*T*), Cretaceous (*K*), and Paleozoic (P_z) strata labeled; interpreted faults shown by heavy black lines. Faulting predominantly confined to Paleozoic strata.

was also a major problem in the near surface, and it is possible this high-amplitude ground roll noise obliterated any reflected energy in the upper 50 m. The prominent reflective package observed on ALB-2 between about 50 and 200 m deep is probably from competent Paleozoic rocks.

During data acquisition, we discovered several faults in a recently eroded embankment about 5 m west of the line. These faults project into the subsurface below stations 168 and 185 (Fig. 8b), respectively, which is consistent with the locations of two interpreted faults and with changes in reflection dips between 100 and 200 m depth. At the surface, these faults juxtapose Tertiary deposits. The overall style of deformation of the reflectors between 50 and 200 m depth is a series of fault-bounded anticlines and synclines.

Similar to ALB-2, data on ALB-3 are weakly to nonreflective in the upper 50 m over the total 540-m profile length (Fig. 8c). The same reflection package seen on ALB-2 is also observed on ALB-3 between 50 and 200 m depth. On ALB-3, this package defines a broad anticlinal structure of a similar shape to one interpreted by Stewart and McManamy (1941) from surface mapping and borehole data. Deformation on ALB-3 is not as complex as along the ALB-2 profile. Overall, the imaged deformation is reminiscent of high-resolution seismic-reflection data collected further west in the Benton Hills by Palmer *et al.* (1997a) and across major strike-slip faults in California (Park *et al.,* 1995; Shedlock *et al.,* 1990). We thus interpret the faults observed on ALB-2 and ALB-3 to be part of a flower structure produced by strike-slip motion along the CGL.

Discussion

Several independent lines of evidence suggest that Quaternary faulting has occurred along the CGL. Paleoliquefaction features throughout the Western Lowland suggest that at least two strong ground-shaking events occurred in the past 25 ka and that the most recent occurred 9 to 13.5 ka (Vaughn, 1994). Quaternary faulting has been documented in the Benton Hills (Harrison *et al.,* 1995; Harrison *et al.,* 1997; Palmer *et al.,* 1997b) and has been inferred near Idalia Hill southwest of the Benton Hills (Hoffman, 1998). Additionally, diffuse seismicity is present throughout this part of southeast Missouri. These three lines of evidence suggest the existence of seismogenic structures in southeastern Missouri. Faults at Idalia Hill and in the Benton Hills, as well as many of the identified paleoliquefaction features, coincide with the surface projection of the CGL. We will focus here on what these newly acquired seismic-reflection data suggest regarding Quaternary earthquake activity in southeast Missouri and a possible relationship to the CGL.

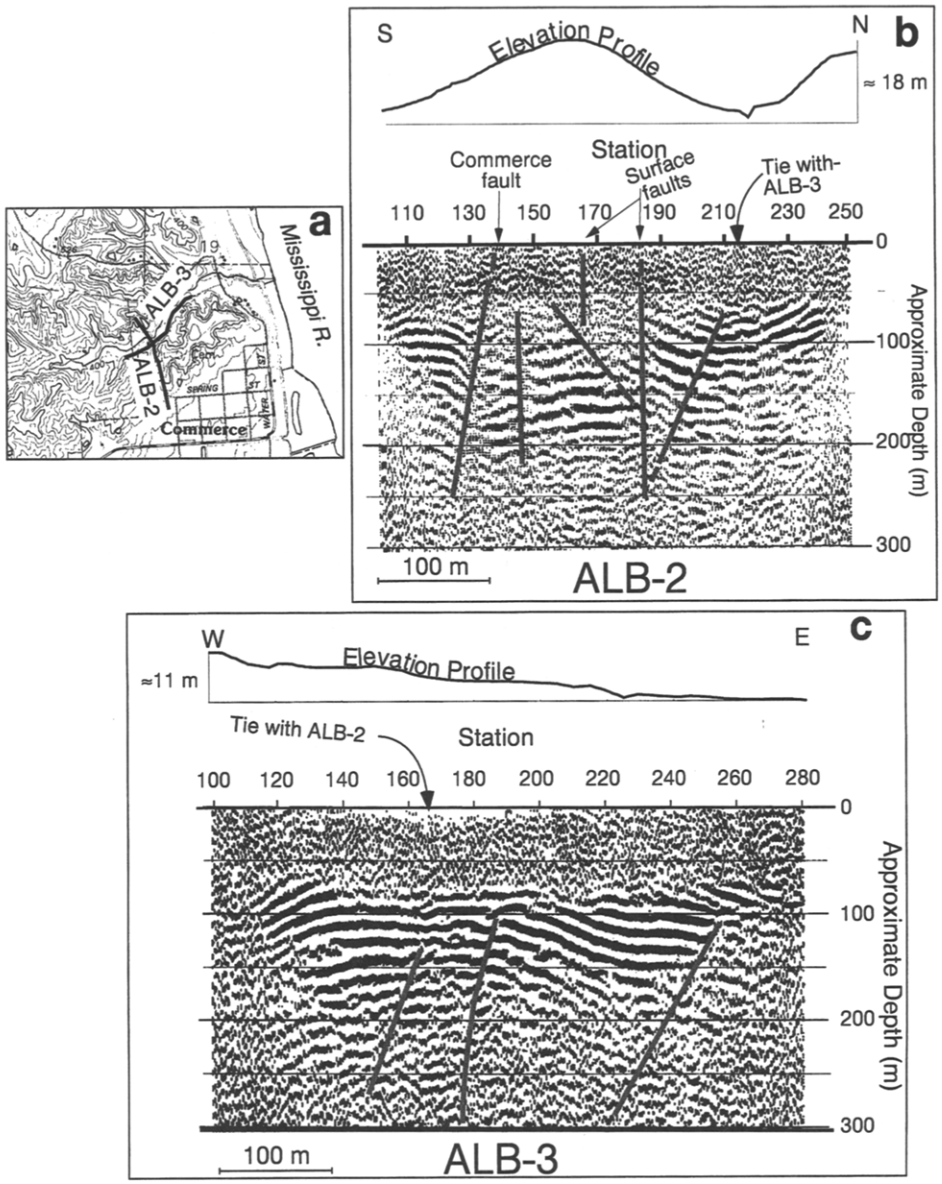

Figure 8. (a) Map of Commerce, Missouri, area and location of seismic profiles ALB-2 and ALB-3. (b) Depth-converted seismic-reflection profile ALB-2. We interpret the reflective package observed across the profile to be from Paleozoic strata. Faults shown by thick dark gray lines. Locations of Commerce fault, two recently discovered unnamed faults, and intersection with profile ALB-3 are shown. The amount of folding and faulting over the 450-m profile is significant for the mid-continent. (c) Depth-converted seismic-reflection profile ALB-3. We interpret the reflective package observed across the profile as Paleozoic strata. Faults shown by thick dark gray lines. Profile is 540-m long and shows a broad anticlinal feature.

Quaternary Faulting above the CGL

Profile CGL-1 shows evidence of Quaternary deformation in the shallow subsurface. If faulting uplifted the intra-Quaternary reflector (Fig. 3b) after it was deposited, and assuming the underlying Quaternary strata were deposited in the early Quaternary, then this deformation is clearly post-early Quaternary in age. If faulting uplifted the reflector, then it should be detectable at its 25 m depth by drilling or by a higher-resolution seismic-reflection profile. Because surface deformation is not obvious in this area, the structure causing the imaged subsurface deformation has not caused significant uplift since the latest Holocene alluvium was deposited in the area. Regardless, given the deformation between stations 750 and 820, shallow faulting appears to have

caused as much as 20 m of vertical uplift since the oldest Quaternary strata were deposited.

Post-Cretaceous deformation on the eastern side of Crowleys Ridge at Idalia Hill is complex. Seismic-reflection data indicate that Idalia Hill is a fault-controlled structure. Similar deformation of the Paleozoic and Cretaceous surfaces suggest much of the deformation is post-Cretaceous in age. Numerous faults at the surface indicate that significant faulting has occurred since the Tertiary. The data on profile IDAL-2 show a series of upwarps that are consistent with a transpressional style of deformation, which is consistent with the current east–west compressive stress field. Faulting interpreted on the eastern end of the profile has occurred after deposition of the oldest Quaternary deposits.

At the eastern end of the Benton Hills, seismic profiles ALB-2 and ALB-3 reveal a series of fault-bounded anticlinal and synclinal blocks. Figure 9 shows the stacked ALB-2 and ALB-3 seismic sections viewed from the southeast. The reflection packages on the two profiles tie reasonably well at their intersection. The profiles delineate a northeast-striking fault (F1) that dips steeply to the northwest (Fig. 9). A second fault (F2) is imaged only on the southern end of ALB-2. We interpret F2 as the mapped Commerce fault (Harrison, 1998), trending at about N55°E and dipping steeply to the southeast. We interpret this overall deformation pattern as a flower structure related to the CGL. Harrison and Schultz (1994) describe faults in the Thebes Gap/Commerce area with near-vertical dips and strikes of N35°E and N55°E, which are consistent with the faults we interpret from these data.

If the CGL has been associated with active Quaternary faulting, then our data indicate that the style of deformation varies along its strike. At CGL-1, the deformation is subtle and dispersed over a large area, with a maximum displacement of about 20 m across one fault zone (Fig. 4). At Idalia Hill, the cumulative apparent vertical displacement is also about 20 m, but the deformation is much more complex. In the eastern Benton Hills, folding and fault deformation is much more dramatic at both the surface and in the seismic-reflection data than at the other two sites. Such variations along structural trend are consistent with strike-slip faulting.

Relationship of the CGL to Shallow Deformation

The geologic structures that cause the CGL magnetic and gravity anomalies may also act as zones of weakness that could preferentially accommodate faulting. As discussed by Langenheim and Hildenbrand (1997), the CGL may be an old structure, possibly associated with the Reel-

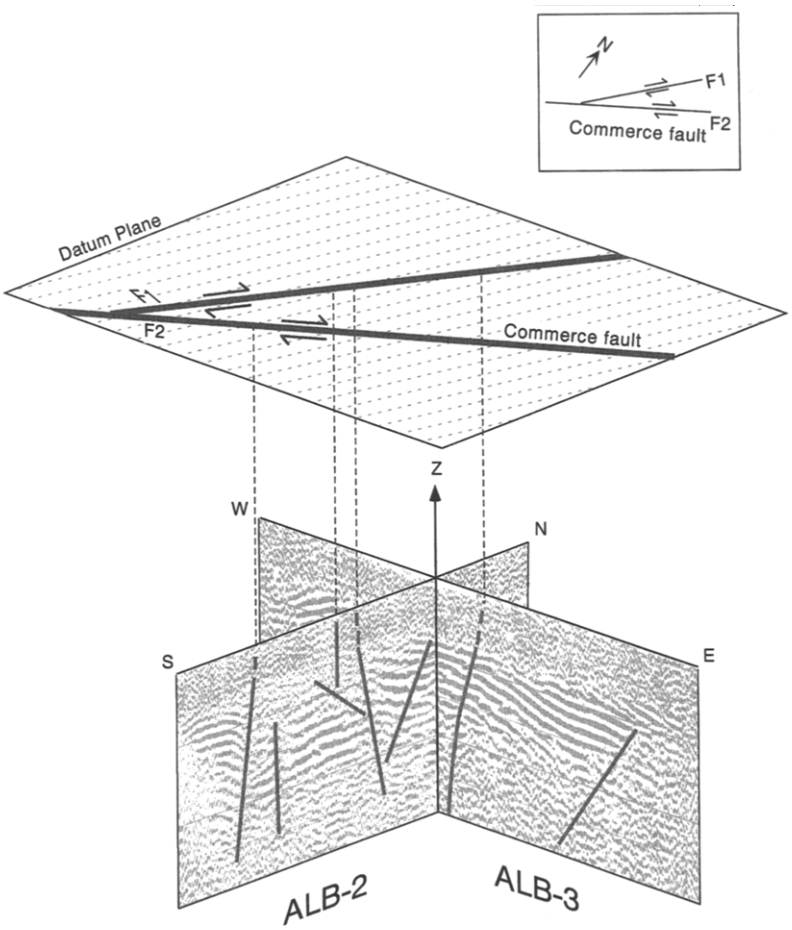

Figure 9. Fence diagram of tied seismic-reflection profiles ALB-2 and ALB-3. Faults interpreted in subsurface are projected onto a datum plane. Data appear to image the Commerce fault and another major fault splaying from it, as interpreted on the datum plane.

foot rift structural system. If this is correct, and given the CGL's long, linear geometry, then we suggest that the CGL originated in the Proterozoic and was subsequently reactivated by rifting during the late Precambrian/early Cambrian and at other times in the Phanerozoic. In the modern compressive stress field, right-lateral movement would be expected on northeast-trending structures (e.g., Zoback and Zoback, 1989). At least some faults associated with the CGL may have reactivated under the modern stress regime. The deformation in the upper 400 m on profiles CGL-1, IDAL-2, ALB-2, and ALB-3 is consistent with deformation caused by transpressional right-lateral strike-slip faulting.

Based on the magnetic and gravity anomalies, the CGL may be part of a dominant northeast-trending structural fabric. Clendenin *et al.* (1993) describes a regional fabric of northeast- and northwest-trending faults in southeastern Missouri, immediately northwest of the Mississippi Embayment. This fabric may continue into the Embayment and through the region surrounding the CGL. Because profile CGL-1 trends north–south, either a northeast- or a northwest-trending structure could have caused the imaged deformation. However, we prefer a northeast-trending structure because of the dominant trend in the magnetic/gravity data.

Figures 10a and 10b show schematic diagrams of the possible relationship between a hypothesized dike system causing the CGL magnetic anomalies (after Langenheim and Hildenbrand, 1997) and the overlying shallow deformation observed in post-Paleozoic deposits beneath seismic-reflection profiles CGL-1 and IDAL-2. These simplified schematic diagrams suggest a possible spatial relationship of deformation between these two profiles. On the basis of regional geophysical data and our studies, we suggest that faulting along the CGL is consistent with strike-slip deformation.

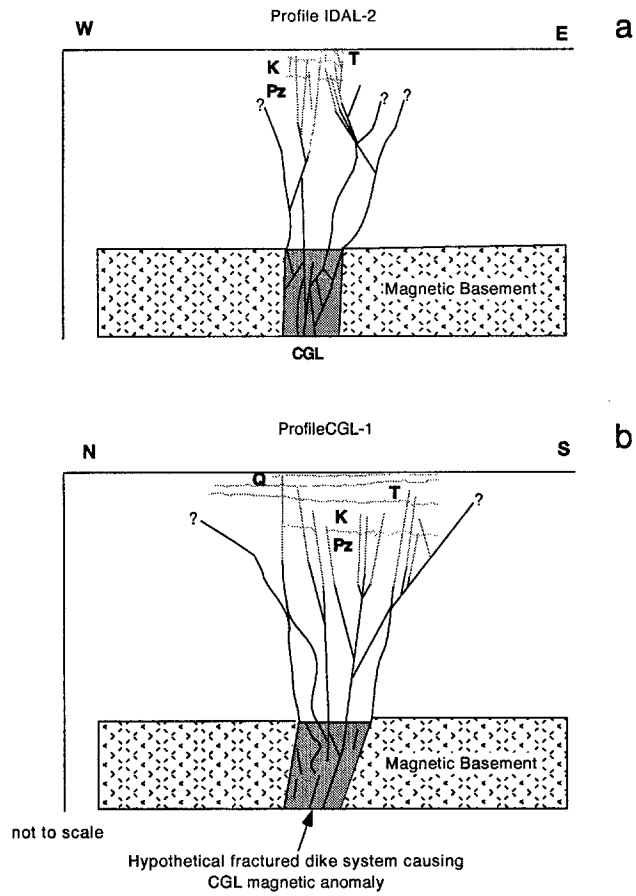

Figure 10. Schematic diagrams (not to scale) of hypothesized faulting along the Commerce geophysical lineament based on seismic profiles CGL-1 and IDAL-2. Reflecting horizons are taken directly from the interpreted sections and are shown in light gray. Similarly, faults interpreted on these two seismic profiles are shown in dark gray. Hypothetical deeper faulting shown in black: (a) schematic of subsurface below IDAL-2; (b) schematic of subsurface below CGL-1. Deformation at both sites is consistent with transpressional right-lateral strike-slip faulting.

Seismic Hazard Implications along the CGL

We suggest that potential seismogenic features, like those recently discovered along the CGL, may be more common in the mid-continent than previously believed. Taken as a whole, with faults within the NMSZ as well as the Crittenden County fault zone (Crone, 1992), Crowleys Ridge (Van Arsdale *et al.,* 1994), and along the Bootheel lineament (Schweig *et al.,* 1992), we speculate the upper Mississippi Embayment may be evolving as a broad zone of dextral shearing during the Quaternary. Within this broad zone, seismicity is now concentrated within the main NMSZ. If this speculation is correct, then potential seismic source zones could exist over a much wider area, thus spreading the seismic hazard over a wider area.

The CGL through southeastern Missouri is potentially associated with faults that may have a long tectonic history and may still be active. If we assume that modern seismicity is a primary indicator of possible seismic hazard, then the current diffuse seismicity on the CGL implies a relatively low hazard. However, several extremely destructive moderate-to-large historical earthquakes have occurred on faults in other parts of the world that either were not illuminated by modern seismicity or would not have been considered to be a significant seismic risk *a priori* (1994 Northridge earthquake, for example). Evidence of prehistoric Quaternary activity is an important indicator of seismic hazard (e.g., Schweig and Van Arsdale, 1996). Thus, evidence of multiple episodes of deformation on faults in southeastern Missouri, as indicated in part by the seismic reflection data, is important to characterize the hazard to urban areas and infrastructure in the region.

Although we know little about the relationship between the CGL and shallow (upper 1 km) structures, it is clear that potentially active faults exist outside of the main NMSZ in southeastern Missouri. The correlation of the CGL's surface projection with geomorphic, geologic, and seismic-reflection features is provocative. While this correlation does not unequivocally mean the faults that caused these features are

directly associated with the CGL, the hazard posed by them may be important to the region and warrants further investigation.

Conclusions

High-resolution seismic-reflection data acquired at three sites along the surface projection of the CGL image deformation that has occurred during the Quaternary. At two sites, our data reveal previously undocumented Quaternary deformation. As much as 20 m of apparent vertical displacement occurred beneath profile CGL-1 and at Idalia since post-Cretaceous time; a significant portion of this has occurred in the Quaternary. These data, along with geomorphic and surface-geologic evidence, suggest the existence of at least one tectonically active structure in southeastern Missouri, outside the main zone of seismicity in the NMSZ. Regardless of whether the faulting and deformation imaged in the upper 400 m at these sites is directly related to seismogenic structures along the CGL, the seismic-reflection data show a complex history of fault activity in this area. We suggest that the structures causing the imaged deformation pose a seismic hazard to the mid-continent, although more information is needed to better understand the hazard. We also suggest that similar recent faulting, such as what we describe here, may be more widespread in the mid-continent than previously believed.

Acknowledgments

We thank colleagues and students who helped in the acquisition of the high-resolution seismic-reflection data. Special thanks to David Worley, Richard Dart (both USGS), Hairl Dayton, Ardel Rueff, Cecil Boswell (all three at Missouri Department of Natural Resources), Jocasta Champion (University of Colorado volunteer), and Milton Benz (volunteer) for all their hard work in support of this study. Reviews by Kaye Shedlock, Roy Van Arsdale, Tony Crone, and Mark Meremonte greatly improved the manuscript. This work was supported by grants from the U.S. Geological Survey National Earthquake Hazards Reduction Program and the Nuclear Regulatory Commission.

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U.S. Geological Survey
Box 25046, MS 966
Denver, Colorado 80225
(W.J.S., J.K.O., R.A.W.)

U.S. Geological Survey
University of Washington
Building WB-10
Seattle, Washington 98195
(T.L.P.)

U.S. Geological Survey
MS 928
Reston, Virginia 22092
(R.W.H.)

Missouri Department of Natural Resources
Box 250
Rolla, Missouri 65401
(D.H.)

Manuscript received 17 April 1998.