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Edward W. Woolery
University of Kentucky, ewoolery@uky.edu

Ali Almayahi
University of Kentucky

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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
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Short Note

Northeast-Oriented Transpression Structure in the Northern New Madrid Seismic Zone: Extension of a Shear Zone across the Reelfoot Fault Stepover Arm

by Edward W. Woolery and Ali Almayahi

Abstract High-resolution seismic-reflection profiles recently acquired 12 km northeast of the New Madrid seismic zone's Reelfoot thrust and along the central axis of the Reelfoot rift, imaged steeply dipping N30°E striking faults that have uplifted and arched post-Paleozoic sediments in a manner consistent with a dextral strike-slip component of displacement. The subparallel fault strands have been traced 1.4 km between reflection profiles. In order to evaluate the structure's potential regional scale, the strike was projected northeast 22 km to its intersection with a nearby industry profile. At the intersection, this lower-resolution profile exhibits a discrete 0.75 km wide structure with style and offset similar to the high-resolution lines. The high-resolution images indicate the deformation extends above Paleozoic bedrock, affecting the Late Cretaceous and Eocene Mississippi embayment sediments, as well as the base of the Quaternary. The Paleozoic and Cretaceous horizons show as much as 75 and 50 m of relief, respectively, with the middle Eocene and basal Quaternary disrupted 25 and 15 m, respectively. Geologic and geophysical logs from a borehole adjacent to the seismic lines constrain the depth, velocity, and stratigraphic interpretations. We interpret the faults as a minimum 34 km northeast extension of the Axial fault zone from a throughgoing intersection with the left-stepover Reelfoot thrust.

Introduction

The New Madrid seismic zone (NMSZ) is an intraplate area of high seismic energy release. Along with the sequence of large earthquakes that occurred during the winter of 1811–1812 and similar clustered events found in the paleoseismic record, the NMSZ is the major contributor to the seismic hazard for much of the central United States (Johnston and Schweig, 1996; Tuttle *et al.*, 2002) (Fig. 1). Most of the contemporary seismicity lies within the early Paleozoic Reelfoot rift system and beneath the Late Cretaceous and early Tertiary Mississippi embayment, an elongate southwest-plunging sediment-filled re-entrant basin (Cox and Van Arsdale, 2002; Csontos and Van Arsdale, 2008). Although the NMSZ is certainly more complex than a simple three-fault model, focal solutions allow it to be generalized as two northeast-oriented dextral strike-slip fault zone segments offset by a central northwest-oriented left-stepping restraining-bend thrust; however, its driving mechanism(s) remains relatively equivocal (Chiu *et al.*, 1992; Johnston and Schweig, 1996; Pratt, 2012). In addition, ambiguity associated with slip rate, total displacement, strain accommodation, and location of related deformation is

problematic for regional seismic-hazard evaluations. This has hindered a broad-based scientific consensus of the hazard and generated a significant amount of study and debate (e.g., Pratt, 1994, 2012; Schweig and Ellis, 1994; Newman *et al.*, 1999; Cox *et al.*, 2000; Van Arsdale, 2000; Tuttle *et al.*, 2002; Calais *et al.*, 2005, 2010; Smalley *et al.*, 2005; Calais and Stein, 2009; Pratt *et al.*, 2012; Pryne *et al.*, 2013). The physical evidence needed for better defining the spatial and temporal seismotectonic characteristics as well as improving the associated seismic-hazard estimation models is complicated by the sparse surface deformation and poor preservation of tectonic-based geomorphic signatures; several mechanisms, however, are suggested to explain this: young seismicity, migrating seismicity, active Mississippi River fluvial dynamics, and broadly distributed strike-slip faulting (Pratt, 1994, 2012; Schweig and Ellis, 1994; Newman *et al.*, 1999; Stein and Newman, 2004). Using reprocessed industry and recently acquired high-resolution seismic-reflection data, Pratt *et al.* (2012) interpreted several faults that displace shallow Quaternary sediment. Their fault interpretations were located in and outside the

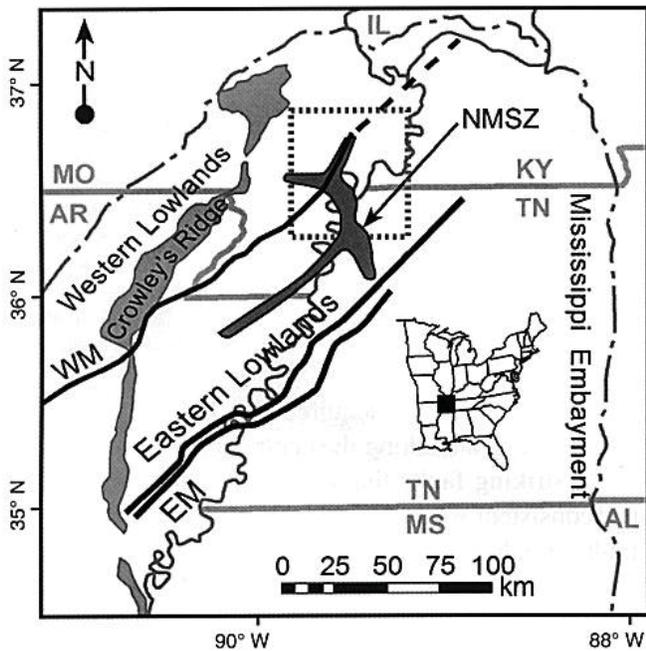


Figure 1. The NMSZ (dark-gray shaded area) is located primarily inside the Reelfoot rift (heavy black lines) (modified from Csonotos *et al.*, 2008). The structural tectonic features of the Reelfoot rift area are overlain by the Mississippi embayment sediments. The seismicity's southern arm is coincident with the Axial fault, and the central left stepover arm of seismicity is coincident with the Reelfoot fault. The gray dashed box defines the boundaries of Figure 2.

margins of the NMSZ's southern seismicity arm Axial fault. They further observed that most faults exhibit strike-slip displacement characteristics, possibly indicative of a broad migratory shearing across the embayment. Odum *et al.* (2010) speculated, and more recently Pratt *et al.* (2012) further demonstrated, that the previously recognized bend in the NMSZ central stepover where it crosses the southern arm can be explained with the southern arm acting as a throughgoing dextral shear zone (Fig. 2). Between 10 and 12.5 km of strike-slip offset on the central arm's Reelfoot fault (Pujol *et al.*, 1997; Csonotos and Van Arsdale, 2008; Csonotos *et al.*, 2008), and approximately 5.5 km of horizontal displacement along its surface expression (Reelfoot scarp), were estimated (Pratt *et al.*, 2012). This suggests a significant amount of accommodation prior to the Holocene was not transferred to the central stepover thrust fault but more likely continued to the northeast as strike slip, and that a component of throughgoing northeast accommodation may continue. Although Light Detection and Ranging surveys may eventually reveal surface deformation, substantiated seismotectonic topographic evidence for a northeast-extended shear zone is presently undefined northeast of the NMSZ's central stepover, an area that exhibits a much more diffuse seismicity pattern than its southern and central arms (Wheeler, 1997; Pryne *et al.*, 2013).

We evaluate northeast-oriented fault strands that were recently discovered during a seismic-reflection investigation located approximately 12 km northeast of the Reelfoot scarp

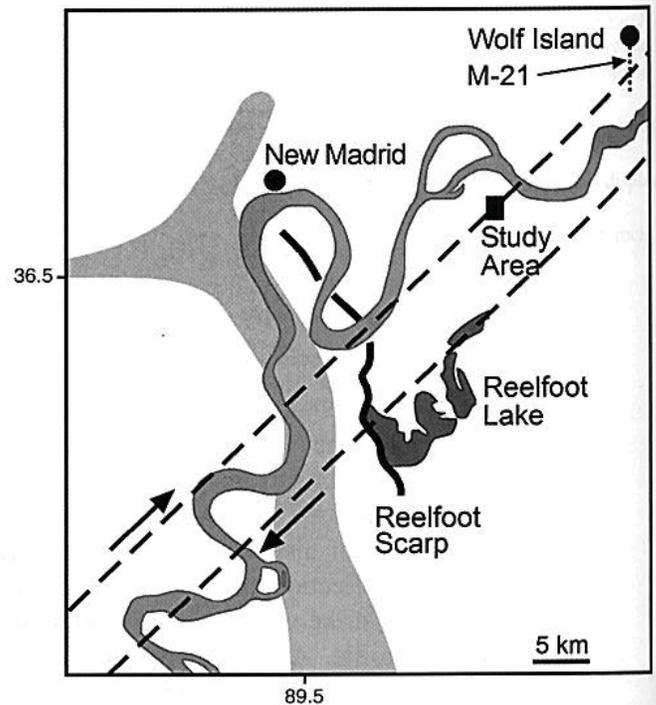


Figure 2. Northeast-striking shear zone representing the southern Axial fault and its projection (dashed lines) across the Reelfoot fault stepover as generally defined by the northwest-oriented contemporary seismicity (light gray area) (Pratt *et al.*, 2012). Pujol *et al.* (1997) and Csonotos and Van Arsdale (2008) among others interpret the bend in the seismicity pattern near the intersection of the stepover with the Axial fault as between 10 and 12.5 km of right-lateral offset along the Reelfoot fault. Pratt *et al.* (2012) report ~5.5 km of lateral surface displacement along the Reelfoot scarp (black solid line). This significant difference in the subsurface and surface displacement estimates suggests a northeast continuation of the shear zone. Our high-resolution seismic reflection lines were collected in an area (black rectangle) surrounding a vertical seismic observatory 12 km northeast of the Reelfoot scarp and along the western edge of the projected Axial fault. A section from a lower-resolution industry seismic line, M-21 (dotted line), also crosses the western edge of the projection and was used for regional correlation. M-21 is located 22 km northeast of the high-resolution data near the community of Wolf Island, Missouri (figure modified from Pratt *et al.*, 2012).

in the context of a hypothesized northeast extension of the southern Axial shear zone through the central stepover thrust fault (Odum *et al.*, 2010; Pratt *et al.*, 2012). Our dataset includes four high-resolution *P*-wave seismic-reflection surveys totaling nearly 4.5 km that were collected in a 1 km radius of the central United States seismic observatory (CUSSO). CUSSO is a vertical borehole array of accelerometers and broadband seismometers located in a small rural community situated atop a subtle topographic high (~3 m), called Sassafras ridge, within the Mississippi River floodplain of westernmost Kentucky (Fig. 3). The observatory's borehole penetrated the 585 m of embayment sediments and terminated approximately 8 m below the top of Paleozoic bedrock (Fig. 4). These borehole data allowed us to correlate five relatively coherent and continuous reflectors on the high-resolution profiles with the following stratigraphic

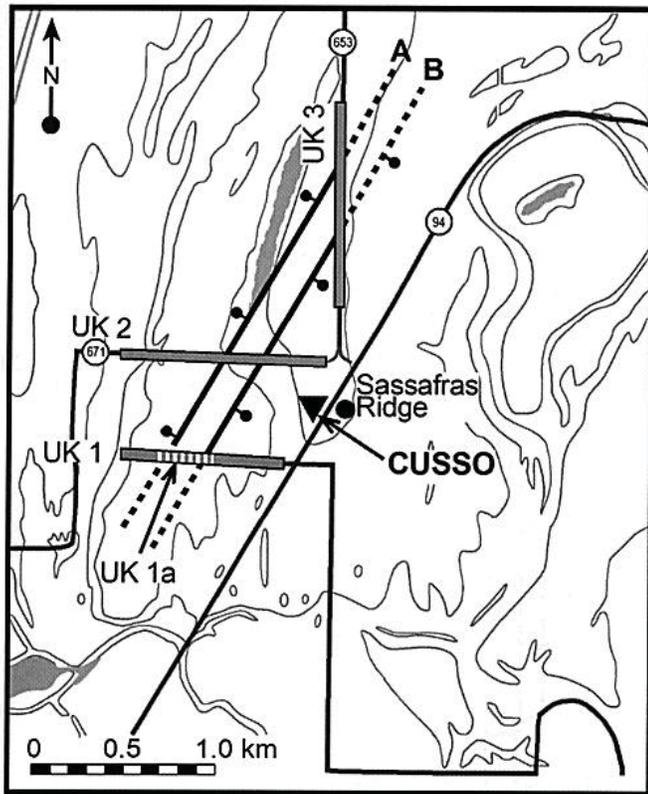


Figure 3. The seismic-reflection profiles are located in a small rural community, called Sassafras Ridge (black-filled circle), Kentucky, which sits atop a subtle topographic rise within the Mississippi River floodplain. The seismic lines were collected in a 1 km radius of the central United States seismic observatory (CUSSO) borehole (black-filled triangle) that penetrated 585 m of Quaternary, Tertiary, and Late Cretaceous (K) sediments and terminated in the underlying Paleozoic (Pz) bedrock. Lines UK 1, 2, and 3 (heavy gray lines) imaged the deeper K and Pz horizons. Line UK 1a (white dashed line) was collected coincident with part of UK 1 but designed to image the shallower Tertiary and basal Quaternary sediments. The heavy black lines, labeled A and B, approximate the boundaries of an imaged pop-up horst feature that was correlated between the seismic lines. The labels are indexed to the fault interpretations on UK 1, 2, and 3. Highways are dark gray lines with their identifying number circled.

units (Hunter, 2011): top of Paleozoic bedrock (Pz), top of Late Cretaceous Clayton-McNairy formation (K), top of Paleocene Porters Creek Clay (Tp), Eocene member of the Wilcox formation (Tw), and top of Eocene Jackson formation (Tj). Above the Jackson formation are Quaternary (Q) alluvial sands and gravels. The CUSSO borehole cuttings log along with downhole electrical and sonic velocity surveys provide constraint for the stratigraphic and depth-migrated seismic-reflection interpretations (Figs. 4, 5, 6, and 7).

Seismic-Reflection Data and Interpretation

The seismic-reflection data consist of four recently acquired high-resolution profiles (this study) and reinterpretation of a part of an older lower-resolution industry profile.

We collected east–west-oriented (lines UK 1, 1a, and 2) and north–south-oriented (UK 3) seismic-reflection profiles along rural roads in a 1 km radius of the CUSSO site (Fig. 3). These 12-fold data were recorded with a 24-bit engineering seismograph using *P*-wave energy generated from a 4 kg hammer and 15 cm × 15 cm hardened aluminum plate. Five vertical hammer strikes were stacked at each shot point. In addition, two different receiver array geometries were used to optimally image both the relatively deep and shallow target stratigraphy. Specifically, a 10 m group/shot interval and 100 m near-offset source were used in lines UK 1, 2, and 3 to optimally image reflections from the tops of the deeper Cretaceous (K) and Paleozoic bedrock (Pz) stratigraphic horizons (Figs. 4 and 5); however, a reduced 2 m array interval and 50 m near-offset source were used for UK 1a. The smaller array dimension for the latter profile produced better reflected images for the Tertiary and base of the Quaternary stratigraphic horizons.

A conventional processing procedure was applied to all profiles and included band-pass filters, gain correction, residual statics, coherent noise mutes, and iterative velocity analysis. Frequency–wavenumber filtering, adaptive subtraction, frequency–offset deconvolution, and poststack Kirchhoff depth migration were also applied. The signal exhibited an average 50 Hz dominant frequency and 1900 m/s velocity. This yielded vertical and detectable resolution of approximately 9.5 and 4.5 m, respectively.

The stacked high-resolution reflection profiles are too closely spaced to confidently extrapolate the local geologic results to a meaningful regional scale, however. To provide better regional context for the high-resolution data interpretations, we also incorporate and evaluate a 6 km segment of a north–south-oriented 48 km long industry seismic line, Dow Chemical M-21, located approximately 22 km northeast of the CUSSO site (Fig. 2) (Howe, 1985). The 48-fold M-21 data were collected with vibratory energy sources and a 67 m (220 ft) shot/group interval; however, this array aperture and other associated acquisition parameters were not optimal for imaging the near-surface stratigraphy. The useful reflecting signals are limited to the K-T and K-Pz stratigraphic horizons and deeper. In addition, the data are significantly lower resolution than the CUSSO seismic data. The dominant signal frequency for M-21 is approximately 25 Hz, yielding a vertical and detectable resolution of 19 and 10 m, respectively. These relatively long-wavelength signals often make separating the two primary reflectors difficult in some areas of the longer profile, as the end of the K reflection can interfere with the onset of the Pz reflection; however, this was not problematic in our section of interest, thus providing a usable temporal separation.

Lines UK 1 and 1a

Line UK 1 is a 650 m east–west-oriented profile collected along a level road 0.25 km south of CUSSO (Figs. 3 and 6). The two most prominent reflections are from the tops

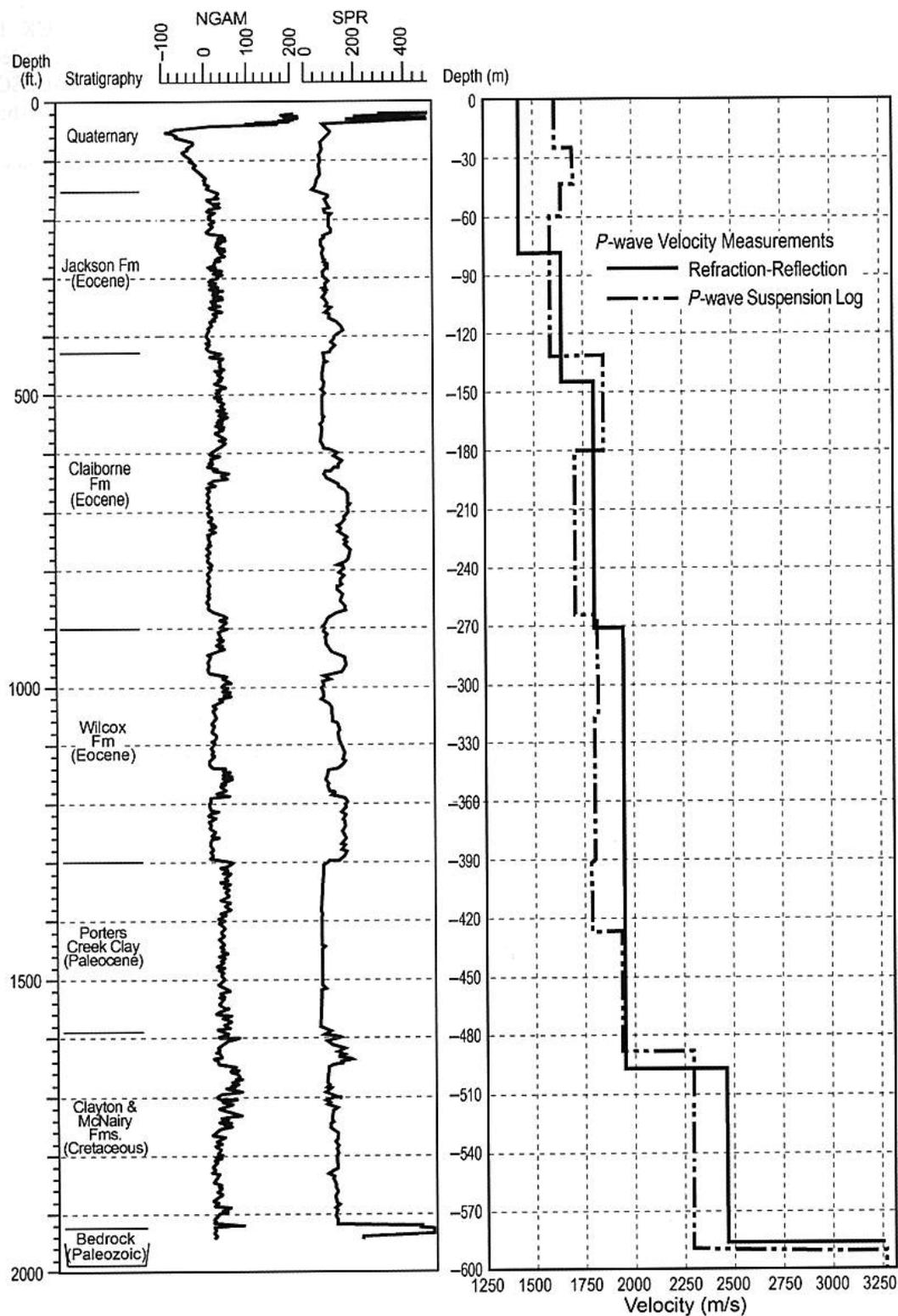


Figure 4. The stratigraphic and geophysical well-log interpretations from the CUSSO borehole are shown on the left side of the figure. In addition to the self-potential resistivity (SPR) and natural gamma (NGAM), borehole velocity measurements were made. The results from the *P*-wave suspension log are compared with the averaged reflection stacking velocities at the site (plotted on the right side of the figure). The surface elevation at the well is 91 m.

of the K and Pz stratigraphic horizons; their resultant seismic migration depths agree with borehole data. Figure 6 shows the uninterpreted and interpreted seismic-reflection profiles.

Although the reflections above the K horizon have weaker and more discontinuous characteristics, the Porters Creek Clay and Wilcox formations are relatively coherent across

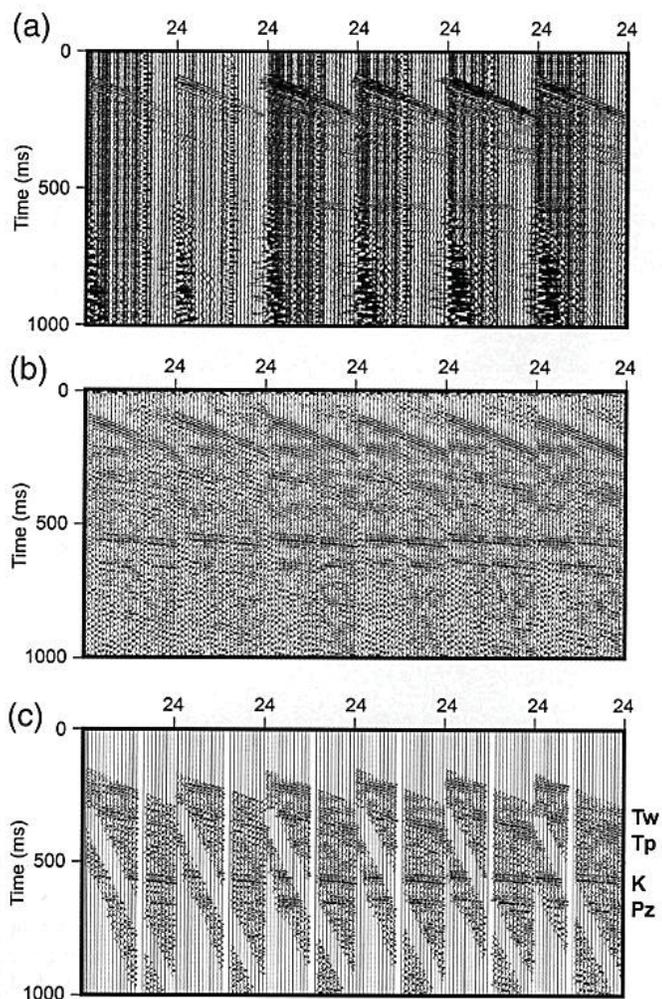


Figure 5. Six consecutive example 24-trace field file panels from UK 1 are shown. The 10 m spaced source and receiver arrays were used to optimally image the K and Pz horizons. The field files are shown in their (a) raw, (b) band-pass filtered/trace balanced, and (c) muted forms.

the profile. These stratigraphic interpretations also correlate with the adjacent borehole information. Structurally, we interpret a near-vertical fault that crosses the monoclinical flexure of the K and Pz reflectors near UK 1's trace number 80, labeled A in the lower part of Figure 6c. The fault affects the overlying horizons, including the Wilcox and younger strata. Vertical relief across this structure is approximately 50 and 75 m on the K and Pz horizons, respectively. A smaller fault is interpreted near trace 55, labeled B in the lower part of Figure 6c. This feature has an estimated eastern downthrow of approximately 30 m for both the K and Pz horizons. As a composite, the shallower uplifted reflectors between faults A and B are arched and define a narrow, upward splaying, asymmetric pop-up or horst structure. We also interpret a fault at trace 100, shown as a dashed line and labeled C in the lower part of Figure 6c, based on the abrupt change in the dip of the reflections, as well as a small reversed displacement. The fault C deformation in this profile is very

subtle across the K and Pz horizons. The fault would not be suggested if not for the dip changes in the shallower reflections and the projection of a fault to this approximate station in the more definitive structural observations made in the other profiles. It is also possible that the primary deformation associated with the deeper part of fault C is located off the western end of UK 1. Without additional data acquisition, the geologic reliability of the fault C interpretation is unknown.

Line UK 1a was acquired coincident with a part of UK 1 and across its interpreted structure (Fig. 3). The 330 m image, shown in Figure 6b and the upper part of Figure 6c, was arrayed to better image the Tertiary and basal Quaternary horizons. The stacked dataset is rich in reflected signal; however, the two most prominent and continuous are the tops of the Wilcox and Jackson formations. The primary faults, A and B, imaged in UK 1 are also exhibited at the coincident UK 1a stations. The imaged faults appear to cross the Jackson formation, displacing the base of the Quaternary. The tops of the Wilcox and Jackson horizons have as much as 25 and 15 m of vertical relief, respectively. The near-surface structural characteristics also show arched reflectors bounded by two primary near-vertical faults, A and B, that diverge upward similar to that imaged in UK 1. The structure exhibited in the more detailed UK 1a image has characteristics consistent with a strike-slip induced pop-up or flower structure. UK 1a also shows the extension of fault C into the near-surface sediment. The abrupt change in dip and reversed displacement is more clearly resolved in this image than in UK 1.

Line UK 2

Line UK 2 is an 800 m long east-west-oriented profile (Fig. 7) collected 0.20 km north of CUSSO (Fig. 3). This profile was arrayed to image the deeper K and Pz target horizons. The reflections above the K horizon are more discontinuous than the K or Pz; however, the reflections from the tops of the Porters Creek and Wilcox formations appear relatively coherent across the profile and correlate with the interpreted borehole stratigraphy. Two near-vertical faults are interpreted near trace numbers 90 and 45 based on the anti-formal warping of the K and Pz horizons, as well as vertical elevation differences and abrupt dip changes on either side of fault traces. These faults are labeled A and B, respectively. The composite structure is interpreted as the same pop-up feature imaged along lines UK 1 and 1a. The K and Pz appear to have nearly 45 and 70 m of offset, respectively, somewhat less than that estimated on UK 1; however, similar to UK 1, the largest vertical relief appears on the western side of the structure (i.e., fault A). A third near-vertical fault, labeled C, is interpreted at trace 125; but it has less offset (~30 m) and an opposite throw (westside up) as fault A. Nonetheless, the measured fault C vertical offset in this line is more than that observed in UK 1. All faults appear to deform the Tertiary horizons.

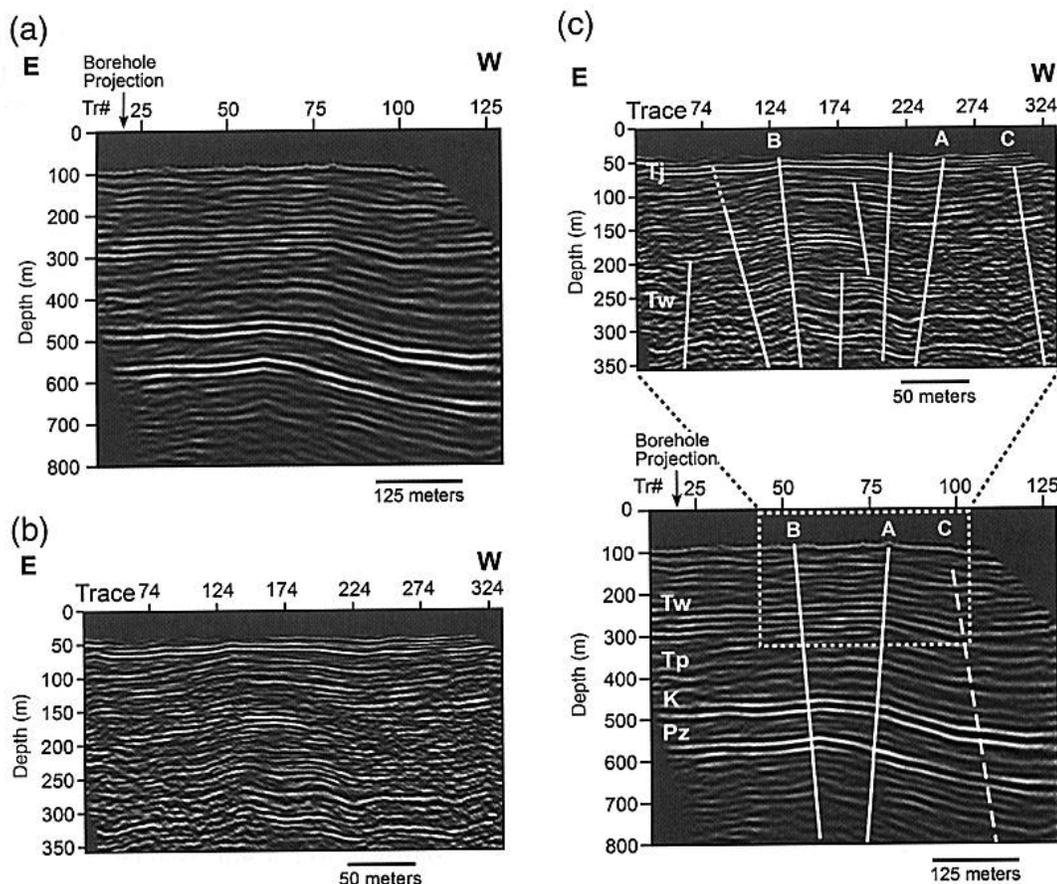


Figure 6. Uninterpreted stacked profiles of the east–west-oriented lines (a) UK 1 and (b) UK 1a. The profile locations are shown in Figure 3. (c) The spatial relationship between the interpreted UK 1 and 1a. UK 1 was arrayed to target the deeper K and Pz stratigraphic horizons. UK 1a was collected coincident with part of UK 1 using a shorter array spacing to better image the shallow stratigraphy and structure within the zone defined by the white dashed rectangle. A pop-up structure, bounded by high-angle faults A and B, crosses the Tj and deforms the base of the Quaternary sediment. Another fault, C, has a more pronounced expression in UK 1a than in UK 1.

Line UK 3

Line UK 3, a 900 m long north–south-oriented profile (Fig. 8), was collected 0.30 km northeast of CUSSO (Fig. 3). The survey targeted the deeper horizons; however, unlike lines UK 1 and 2, the top of the Porters Creek is the most prominent reflection observed on the UK 3 profile. Although visible, the typically strong K and Pz reflections are relatively weak and less coherent. We interpret near-vertical faults at traces 130 and 80 that bound a region of uplifted strata that exhibit antiformal folding. These faults are labeled A and B, respectively. Both A and B faults cross the reflected tops of the Pz, K, and Porters Creek, as well as affect the overlying horizons, including the Wilcox and younger strata. The largest amount of vertical relief occurs across fault A, which has 50 and 75 m of displacement on the K and Pz horizons, respectively. The Porters Creek also exhibits nearly 50 m of structural relief. The reflectors in the area bounded by faults A and B are uplifted and antiformally warped, comparable to, and interpreted to be, the northeast continuation of the flower structure on lines UK 1 and 2. Another evident and significant deformation consisting of two faults, labeled C, is at trace 150, near the northern end of the line (Fig. 8).

Fault C displacement has a pronounced apparent southern downthrow of ~50 m on the Tp horizon; however, weakened signal deeper in the record precludes a definitive estimate along the K and Pz horizons. This is the largest observed vertical offset for fault C at the site. We also interpret a fault at trace 30 near the southern end of the profile. It is near vertical with ~20 m of displacement and projects just off the eastern ends of lines UK 1 and 2 using a strike equivalent to that defined by faults A and B.

Line M-21

The north–south-oriented M-21 is located in the Mississippi River floodplain of eastern Missouri and the stacked profile shown in Figure 9. Both the northeast extension of the Axial fault and the projected northeast strike for the fault stands interpreted in the higher-resolution lines intersect M-21 south of the community of Wolf Island, Missouri (Fig. 2). The enlarged inset in Figure 9 shows the 6 km section of the profile that is centered on the projected intersection and defines our area of interest. The two most prominent reflections are the K and Pz, at approximately 350 ms and 450 ms two-way travel time (TWTT), respectively. These

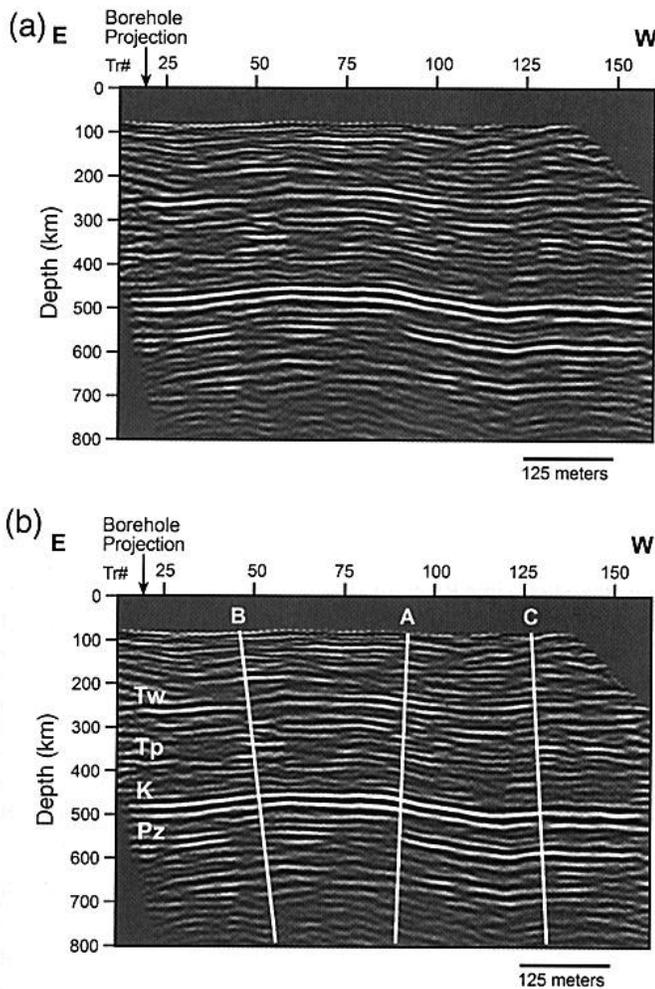


Figure 7. (a) Uninterpreted and (b) interpreted stacked profile of the east-west-oriented UK 2. The line location is shown in Figure 3. A pop-up structure, bounded by high-angle faults A and B, displace the Pz and K reflectors and deforms the resolved Tertiary sediments. Fault C near the end of the profile also disturbs Tertiary sediments.

reflection boundaries are similar to our high-resolution results and typical of those found in most seismic-reflection datasets in the embayment. Moreover, the stratigraphic correlations and data quality are consistent with those found in another nearby line from the same industry dataset (Baldwin *et al.*, 2005). In the section of interest, we interpret three high-angle faults, labeled A, B, and C, that disrupt the K and Pz horizons. Although the correlation of projected structure at long distances can be uncertain, the offset and style of the M-21 faults are very similar to those imaged in the high-resolution data. Specifically, the interpreted faults A and B define a narrow (~0.75 km wide), upward splaying asymmetric horst structure with uplifted antiformal reflectors. This is kinematically consistent with a northeast extension of the positive flower structure interpreted in lines UK 1, 2, and 3. The interpreted fault C in M-21, located just north of A and B, is also geometrically similar to the structure imaged in the high-resolution data. We further note that there is a broad and

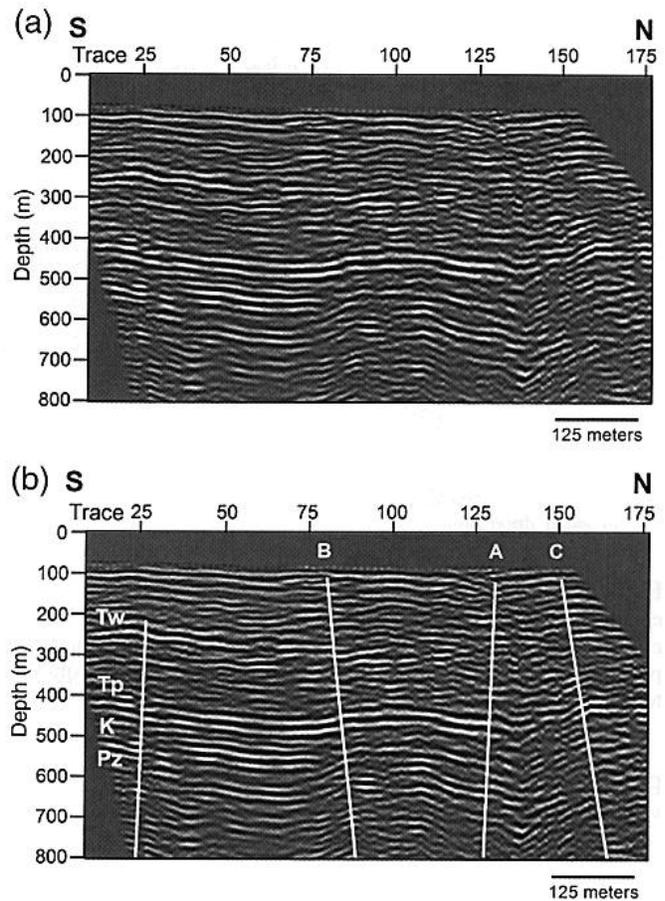


Figure 8. (a) Uninterpreted and (b) interpreted stacked profiles of the north-south-oriented UK 3. The line location is shown in Figure 3. A prominent pop-up structure is located between traces 80 and 130 (labeled B and A, respectively) and extends above the Pz affecting all resolvable stratigraphic horizons. Fault C, located at trace 150, exhibits more deformation here than in UK 1 and 2.

significant structural rise immediately north of our interpreted transpression feature. This is likely associated with the Charleston uplift and/or beginning of the northwestern margin structures of the Reelfoot graben, suggesting that our projected transpression feature cojoins, crosses, or is truncated by these structures northeast of this location (Pryne *et al.*, 2013). The M-21 data also show deep-seated deformation, truncating reflections perhaps as deep as 2 s TWTT. The overall low resolution in the dataset quality precludes us from making precise geometric measurements, thus our interpretations are pattern based. In addition, we do not attempt any interpretation for the less coherent data shallower than 350 ms TWTT.

Discussion and Conclusions

A goal for intraplate tectonics and its derivative seismic-hazard research in the NMSZ region is a better understanding of the parameters used for geodynamic modeling and seismic-hazard calculation, respectively. Pratt *et al.* (2012) made recent observations that the bend in the seismicity

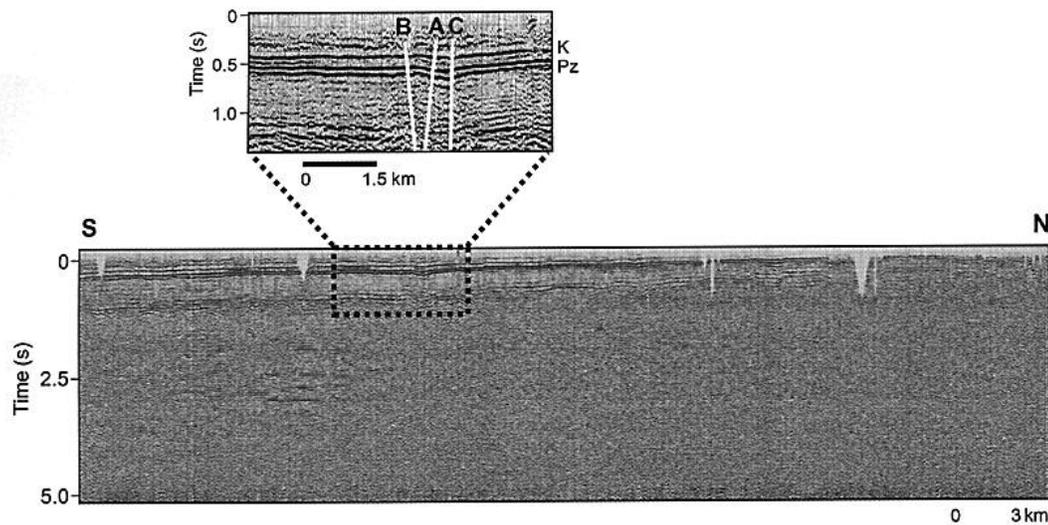


Figure 9. Dow Chemical Vibroseis line M-21 oriented north–south along the Mississippi River floodplain in southeastern Missouri. The enlarged 6 km area surrounds the point of structural intersection with the projected N30°E strike defined by the high-resolution seismic-reflection profiles. High-angle upward-splaying transpression faults similar to those identified in lines UK 1 to UK 3 are exhibited at the projected structural intersection. The data are much lower resolution but reveal uplifted and antiformally warped Pz and K reflections similar to those imaged in the higher resolution data.

pattern at the northeast-oriented Axial fault's intersection with the central stepover thrust results from right-lateral displacement along the Reelfoot fault, and that the lateral displacements between the Reelfoot fault and its surface expression, Reelfoot scarp, are unbalanced. These observations formulate the hypothesis that the Axial shear zone continues to the northeast across the stepover to accommodate the differential strain (Fig. 2). We acquired a series of seismic-reflection profiles in an area 12 km northeast of the central stepover and along the western margin of the Pratt *et al.* (2012) shear-zone projection (Fig. 3). These data exhibit a set of steeply dipping faults that have uplifted and arched post-Paleozoic sediments in a manner consistent with positive flower structures found in dextral strike-slip displacement, and similar to transpression features interpreted in other regional seismic profiles (e.g., Van Arsdale *et al.*, 1995; Odum *et al.*, 1998; among others). Our interpreted fault zone strikes approximately N30°E and was correlated and traced 1.4 km between the reflection surveys. These data are too closely spaced for a meaningful regional scaled inference. Consequently, we projected the structure northeast along strike approximately 22 km to its intersection with a lower-resolution industry reflection profile as an initial evaluation of the areal extent (Fig. 10). The reflection image at the site of intersection revealed a discrete set of upward-splaying high-angle faults that bounded a subsurface area with an uplifted and arched K reflection. This ~750 m wide zone has a comparable style to the ~200 m wide structural feature imaged on the high-resolution seismic-reflection profiles acquired at the CUSSO site. The increase in structural width is perhaps influenced by the broader nearby structures seen in the profile; however, it may be an artifact of the horizontal resolution, a changing strike, and/or an incom-

plete imaging of a broader structure at the CUSSO site. Whereas lines 1–3 were too closely grouped to make an indisputable regional structural interpretation, we also recognize that their significant separation from the industry data can also make a correlative interpretation equivocal. Having said that, the current dataset is kinematically indicative of a significant regional transpression structure. The high-resolution data also show that structural relief extends above Pz bedrock, crossing K, T, and the base of the Quaternary sediments. We note the Mississippi River floodplain at the CUSSO site is marked by a subtle topographic high (~3 m) that may be structurally influenced, but this relationship remains speculative and requires further higher resolution study (i.e., ground penetrating radar, shallow drilling, trenching, etc.). The Pz and K horizons, however, show as much as 75 and 50 m of structural relief, respectively, with the middle Eocene and basal Quaternary displaced 25 and 15 m, respectively. The fault orientation and deformation style at the CUSSO site and the positive regional correlation with the industry data indicate a northeast-oriented transpression structure orthogonal to the Reelfoot stepover and along the central embayment axis. The structure is too far inboard to have an association with northeast-oriented Reelfoot rift margins but is coincident with the projection of the Axial fault. Therefore, we interpret these newly discovered faults to be part of Pratt *et al.* (2012) hypothesized northeast-oriented shear zone extension that crosses the NMSZ left-stepover thrust. Our interpretation extends the shear zone a minimum 34 km. In addition, our interpretation is consistent with the interpretation of Odum *et al.* (1998) of northeast-oriented partitioning strike-slip faults in the hanging wall of the central stepover Reelfoot thrust and potentially part of their interpreted New Markham fault that was discovered

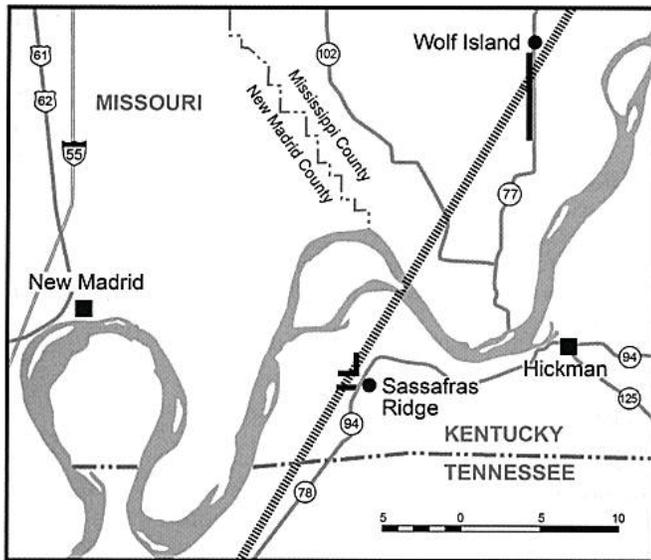


Figure 10. Relationship of the transpressional feature (short dashed line) interpreted between the high-resolution lines UK 1 to UK 3 and the lower-resolution M-21. Additional study is required to better validate the spatial and temporal relationships; however, these data provide the first corroborative physical evidence for a significant transpression structure that crosses the NMSZ's left-stepped arm, accommodating the unbalanced strain between the Reelfoot fault and scarp.

just north of the stepover with an anomalous north-oriented strike. The modeling and analog comparisons of Pratt (2012) for the New Madrid stepover structure also resulted in a kinematic framework that included a major northeast-oriented shear zone, although it was spatially located in Missouri, northwest of our site. Consequently, our interpretation reveals initial physical evidence consistent with recent model- and observation-based hypotheses regarding strain accommodation. In addition, it provides well-constrained location and geometry for Quaternary-active faults, thus providing more definitive spatial and eventual temporal parameters that can improve central United States intraplate tectonics and seismic-hazard models. More comprehensive geophysical and geologic study is required to evaluate the spatial and temporal limits of these structures as well as the range of their implications.

Data and Resources

All data presented in this study are part of the University of Kentucky seismic-hazard database. The high-resolution seismic-reflection data were collected and processed by faculty and students at the University of Kentucky. Unprocessed and processed versions are available from the authors. The seismic signal processing was performed with VISTA13 by Schlumberger-GEDCO. Topographic information used for construction of Figure 3 was constructed from maps downloaded from the Kentucky Geological Survey using <http://kgs.uky.edu/kgsweb/main.asp> (last accessed May 2014).

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Department of Earth and Environmental Sciences
University of Kentucky
101 Slone Research Building
Lexington, Kentucky 40506-0053

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