Late Pliocene and Quaternary deformation of the Reelfoot rift.

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Late Pliocene and Quaternary deformation of the Reelfoot rift

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Abstract

The Reelfoot rift is a N45°E-trending Cambrian rift that has controlled late Pliocene and Quaternary deformation and current seismicity beneath the central Mississippi River Valley. Analysis of 557 well logs between 35°N and 37°N latitude reveals that

Upland Complex in Crowley's Ridge of eastern Arkansas have been displaced by east-striking normal faults that extend across the Eastern Lowlands of the Mississippi

River Valley. The normal faults extend east and west of the margins of the Reelfoot rift, thus indicating that the region between the Commerce fault and the Big Creek–Ellendale fault has been subjected to right-lateral simple shear since the Pliocene.

An additional 3334 well logs in the lowlands of the Mississippi River Valley between 35°N and 37°N were analyzed for structural displacement of the unconformity at the base of the Quaternary-age Mississippi River alluvium. No Quaternary displacement is seen on the east-striking normal faults in the Eastern Lowlands identified in this study, suggesting their Quaternary displacement is below the resolution of the mapping. However, our base-of-Quaternary mapping has confirmed previously mapped structures and identified new structures that allow the estimation of uplift rates. In the Western Lowlands, the Quaternary unconformity (locally 24–27 ka) is displaced 30 m down-to-the-southeast across the northwestern Reelfoot rift margin, indicating a displacement rate of ~1.2 mm/yr. In the Eastern Lowlands, within the last 12 k.y., the Charleston uplift has been lifted 36 m, resulting in an average uplift rate of 3 mm/yr; Lake County (Reelfoot North fault) uplift is 21 m (1.8 mm/yr), Blytheville arch uplift is 25 m (2.1 mm/yr), Joiner Ridge uplift is 20 m (1.7 mm/yr), and the Meeman-Shelby fault zone uplift is 28 m (2.3 mm/yr). Absence of a Quaternary fault scarp or surface monocline on the subsurface Reelfoot South fault suggests that this seismically active fault zone may have become reactivated during the earthquake sequence of 1811–1812.

The Reelfoot rift and its outboard faults have undergone right-lateral simple shear since the Pliocene, resulting in (1) right-lateral strike-slip occurring along the northeast-striking basement faults, (2) east-west compression across north-striking reverse faults (stepover zones), and (3) north-south extension across east-striking normal faults. The origin of these structures is illustrated within the strain field of a simple strain ellipse that should be considered in future field strain measurements of the New Madrid seismic zone region. Quaternary deformation in the Reelfoot rift region provides insights into intraplate strain and associated seismicity that may apply to intraplate rifts globally.

INTRODUCTION

Several models have been proposed to explain Quaternary deformation within the Reelfoot rift and its associated New Madrid seismic zone (Figs. 1 and 2; Table 1). In this study, 3891 geologic well logs (Fig. 3 and Supplemental Tables 1[1] and 2[2]) were interpreted and subsurface structure contour maps were constructed of the base of the Mississippi River Quaternary alluvium and top and bottom of the Pliocene Upland Complex (a Mississippi River terrace alluvial section) between 35°N and 37°N latitude to assess the structural evolution of the region during the Pliocene and Quaternary. These maps reveal deformation along faults of the Reelfoot rift and late Quaternary tectonic uplift rates, and they result in a model of strain accumulation during the late Pliocene and Quaternary that may provide insights into deformation and seismicity in similar intraplate rifts.

The Reelfoot rift, which lies beneath the northern Mississippi Embayment, is a N45°E-striking Cambrian basement rift that cuts across southeast-striking Proterozoic basement faults (Fig. 2; Table 1; Csontos et al., 2008). Reactivation of the basement faults is responsible for regional Quaternary deformation and the New Madrid seismic zone (Csontos et al., 2008; Van Arsdale, 2009; Pratt, 2012; Pratt et al., 2012). Quaternary right-lateral strike-slip has occurred across the northeasterly striking margins of the Reelfoot rift (Van Arsdale et al., 1995; Cox et al., 2001a, 2006; Pryne et al., 2013) and across the Axial fault in the middle of the rift (Csontos et al., 2008; Odum et al., 2001; Pratt et al., 2012). Compressional stepover zones within the rift consisting of the Reelfoot fault, Joiner Ridge, and the southern portion of Crowley's Ridge are reverse fault–bounded structural uplifts (Nelson and Zhang, 1991; Van Arsdale et al., 1995; Purser and Van Arsdale, 1998; Csontos et al., 2008; Odum et al., 2010). Quaternary faulting is not restricted to the Reelfoot rift but has also occurred on outboard faults of the rift, including the Commerce fault segment of the Commerce geophysical lineament (Langenheim and Hildenbrand, 1997; Harrison et al., 1999; Stephenson et al., 1999) and the Big Creek fault (Spitz and Schumm, 1997; Harris and Sorrells, 2006; Tavakoli et al., 2010), which may continue northeast (Johnson et al., 1994) as the Ellendale fault (Velasco et al., 2005; Van Arsdale et al., 2012). Faults have also been identified along the boundaries of the northern portion of Crowley's Ridge immediately north of Jonesboro, Arkansas, and are interpreted to have been active during the Wisconsinan (Van Arsdale et al., 1995). Recently, Cox et al. (2013) identified Holocene faulting along the southeastern margin of the Reelfoot rift 20 km northwest of Memphis, Tennessee. Similarly, Hao et al. (2013) identified Quaternary faulting on the Meeman-Shelby fault zone immediately west of Memphis that they interpreted to be a P shear (van der Pluijm and Marshak, 2004).

Surface deformation in the Mississippi River Valley is subtle because much of the faulting appears to be strike slip, and the rift is buried beneath a thick Phanerozoic sedimentary cover, capped by Mississippi River alluvium, and loess. Some of the Reelfoot rift faults are seismically active (Figs. 1 and 2), with earthquakes primarily occurring between depths of 4 and 14 km along the Axial, New Madrid North, and Reelfoot faults within the New Madrid seismic zone (Chiu et al., 1992; Mueller and Pujol, 2001; Csontos and Van Arsdale, 2008). The New Madrid seismic zone is responsible for the very large earthquakes of 1811–1812 (Nuttli, 1973; Johnston, 1996; Hough et al., 2000).

Stratigraphy of the Central Mississippi River Valley

The Upland Complex of the Mississippi River Valley is a high-level terrace deposit of the ancestral Mississippi River system (Figs. 3 and 4; Autin et al., 1991; Van Arsdale et al., 2007). This terrace alluvium is preserved on uplands along the Mississippi River Valley at least as far north as Illinois and south to Louisiana. The Upland Complex alluvium is called the Grover and Mounds Gravel in Illinois, Mounds Gravel in Missouri, Lafayette Gravel in Kentucky, Upland Complex in Tennessee and Arkansas, pre-loess terrace deposits in Mississippi, and Citronelle Formation in Louisiana. The age of the Upland Complex has been cited as being Miocene to early Pleistocene, but the most recent summary of the data assigns a Pliocene age of ca. 4 Ma (Van Arsdale et al., 2007). Both the top and bottom of the Upland Complex are erosional unconformities, and the Upland Complex averages 10 m thick. The basal unconformity is believed to be ca. 4 Ma and the Upland Complex is covered by Pleistocene loess, the oldest dated loess being the 250–200 ka

Crowley's Ridge loess (Markewich et al., 1998). Thus, the unconformity at the top of the Upland Complex is ca. 250–200 ka. This fluvial sand and predominantly chert gravel (Potter, 1955) Upland Complex deposit sits on top of Paleozoic sedimentary rock north of the Mississippi Embayment and on Paleogene sediments within the Mississippi Embayment. The base of the Upland Complex averages 77 m above the base of the Quaternary Mississippi River alluvium; thus, there has been 77 m of incision by the ancestral Mississippi River system. The unconformity at the base of the Upland Complex terrace provides an originally gently southerly sloping, essentially flat surface (Van Arsdale et al., 2007) that we use as a structural datum to evaluate post–4 Ma deformation in the northern Mississippi Embayment.

The Eastern and Western Lowlands of the Mississippi River Valley (Fig. 4) contain Pleistocene and Holocene river alluvium (Autin et al., 1991; Saucier, 1994; Rittenour et al., 2007) with Pleistocene loess capping the older Pleistocene terraces. Most of the Quaternary sediments in the Western Lowlands were deposited by the ancestral Mississippi River, and the Quaternary sediments in the Eastern Lowlands were deposited by the ancestral Mississippi and Ohio Rivers (Rittenour et al., 2007). Floodplain sediments of the Western Lowlands consist of the ancestral Mississippi River Dudley (50–64 ka), Melville Ridge (34–41 ka), and Ash Hill (24–27 ka) braid belts preserved as terraces, and Holocene floodplain sediments of the White, Black, Cache, Bayou De View, and L'Anguille Rivers (Rittenour et al., 2007). Both ancestral Ohio and Mississippi River sediments of the Eastern Lowlands consist of the Paragould meander belt terrace (85 ka) and the Sikeston (17–19 ka), Kennett (14–16 ka), Charleston (14 ka), Blodgett (13 ka), and Morehouse (12 ka) braid belt terraces (Rittenour et al., 2007). The Holocene Mississippi River sediments mark the time when the ancestral Mississippi and Ohio Rivers merged at Cairo, Illinois, to form the modern Mississippi River. It is not known whether the Mississippi River's Holocene alluvium (⍰10 ka) of the Eastern Lowlands is underlain by Pleistocene alluvium (Saucier, 1994) or whether it sits on Eocene formations or, locally, both. If indeed the Mississippi River Holocene floodplain is erosionally inset into Pleistocene alluvium, as suggested by Saucier (1994), then the underlying Pleistocene alluvium is probably 12 ka, since 12 ka Morehouse terraces are present both west and east of the Holocene floodplain (Fig. 4). The unconformity at the base of Quaternary alluvium in the Eastern and Western Lowlands provides an originally gently southerly sloping, essentially flat surface (Van Arsdale et al., 2007) that we use as a structural datum to evaluate post–85 ka deformation in the northern Mississippi Embayment.

METHODS

Structure contour maps were made of the top and bottom of the Pliocene Upland Complex and the base of the Quaternary-age Mississippi River alluvium (Fig. 3) to determine if these surfaces have been tectonically deformed. The maps were made by interpreting lithologic well logs provided to the University of Memphis by the North American Coal Corporation (see Data and Resources) and data provided by the U.S. Army Corps of Engineers (R. Saucier, 2003, personal commun.). These lithologic well logs were made by Philips Coal Company and Corps of Engineers geologists, respectively. The top and bottom of the gravel facies of the Pliocene Upland Complex were mapped using 404 wells for western Tennessee and Kentucky and 153 wells for Crowley's Ridge, Arkansas (Bresnahan, 2004; Van Arsdale et al., 2007). In the Eastern and Western Lowlands of the Mississippi River Valley, 3334 wells were used to map the base of the Quaternary Mississippi River alluvium (Csontos, 2007; Csontos et al., 2008). The wells were 91 m deep and spaced 3 km or less apart. Both the base of the Upland Complex and the base of the Quaternary alluvium are readily identified as fluvial sand and gravel over Eocene fine sand and clay.

The top of the Eocene Memphis Sand in western Tennessee and immediately adjacent areas of Arkansas, Mississippi, and Kentucky was mapped by Martin (2008) (Fig. 5A), and his data were recontoured in this study (not shown). All of the structure contour maps were made using the ArcGIS 10.0 suite. Interpolation for the structure contour maps was done using kriging, inverse distance weighting, natural neighbor, and spline algorithms, but kriging was chosen for interpretation because it best represented the lateral continuity of the surfaces and best matched maps hand contoured by us. The raster surfaces of the structure contour maps were also displayed in three dimensions (3-D) in ArcScene for further examination (Fig. 3B). Data for north-south longitudinal profiles along each of the contoured Upland Complex surfaces (Fig. 4) were acquired using the 3D Analyst's Interpolate Line tool. The data were then exported to Microsoft Excel to make down-valley profiles of the contoured Upland Complex surfaces (Figs. 6 and 7A).

Structural Contour Mapping of the Top and Bottom of the Upland Complex

Structure contour maps were constructed of the top and bottom of the Upland Complex in western Kentucky and Tennessee and along Crowley's Ridge in Arkansas (Figs. 3 and 7). Down-valley topographic profiles of the top and bottom of the Upland Complex were then made from these surfaces (Figs. 4, 6, and 7A). Regression analyses of the data in Figure 6 reveal that the top and bottom of the Upland Complex slope southerly an average of 0.12 m/km (R^2 = 0.3467) and 0.12 m/km (R^2 = 0.4209), respectively, under western Kentucky and Tennessee, slope southerly 0.06 m/km (R^2 = 0.1205) and 0.07 m/km (R^2 = 0.1304), respectively, under Crowley's Ridge, and have up to 60 m of local relief (Fig. 3B). Figures 6 and 7A illustrate that the top and bottom of the Upland Complex are nearly parallel. When superimposing the profile of the bottom of the Upland Complex of western Kentucky and Tennessee on the Crowley's Ridge basal profile, it is evident that the lows and highs on these surfaces are nearly identical and can be correlated across the Eastern Lowlands (Fig. 7). To test this relationship, we conducted a Kolmogorov-Smirnov statistical test. This K-S test confirm that the two profiles in Figure 7A have no statistically significant difference (p value = 0.1038).

Structure Contour Mapping of the Base of the Quaternary Mississippi River Alluvium

Structure contour maps were made of the base of the Quaternary Mississippi River alluvium (unconformity on top of the Eocene section) within the Eastern Lowlands and the Western Lowlands (Figs. 3 and 7). Regression analyses of down-valley profiles reveal that the Eastern Lowlands unconformity slopes southerly an average of 0.09 m/km (R^2 = 0.7493) and has local relief highs of 20 m to 25 m, and the Western Lowlands unconformity slopes south at 0.17 m/km (R^2 = 0.732) and has one linear zone across which there is 30 m of local relief. The ages of the base-of-alluvium unconformities in the Eastern and Western Lowlands are not known. However, our map area is over 600 km north of New Orleans, and the base of the alluvium is locally below current sea level, thus suggesting that this deep incision was caused by extremely low sea level (–120 m) conditions during the late Pleistocene (Miller et al., 2011). Based on this argument, the ages of the unconformities at the base of the Pleistocene terraces in the Eastern and Western Lowlands are assigned the same ages as their overlying sediments as reflected in their terrace ages (Fig. 4) (Rittenour et al., 2007).

Figure 7B illustrates gently south-sloping unconformities beneath the Quaternary alluvium of the Eastern and Western Lowlands. Immediately south of the label WM in Figure 7, within the Western Lowlands, there is a N45°E-trending zone across which the unconformity drops 30 m down-to-the-southeast. This apparent fault displacement coincides with the trace of the northwestern margin of the Reelfoot rift (Figs. 3B and 7B). In the northern and eastern portions of the Eastern Lowlands, there is also clear evidence of local uplift of the unconformity (Fig. 8) that has been documented in previous studies to be due to Quaternary faulting. Starting in the north of Figure 8 and continuing south, there is the Charleston uplift (36 m) (Pryne et al., 2013), Lake County uplift–Reelfoot North fault (21 m) (Russ, 1982; Purser and Van Arsdale, 1998; Csontos et al., 2008), Blytheville arch (25 m) (Pratt et al., 2012), Joiner Ridge (20 m) (Csontos et al., 2008; Odum et al., 2010), and a high area southwest of Memphis that coincides with the Meeman-Shelby fault (28 m) (Hao et al., 2013). The New Madrid North fault, Reelfoot North fault (Lake County uplift), Blytheville arch, and the southeastern Reelfoot rift margin have surface deformation, whereas the Charleston uplift, Joiner uplift, and Meeman-Shelby fault zone have no mapped surface deformation. The Reelfoot South fault has subtle geomorphic evidence of 1811–1812 deformation (Van Arsdale et al., 1999).

DISCUSSION

East-West Normal Faulting in the Upland Complex

The apparently identical distributions of highs and lows in the structure of the Upland Complex in western Kentucky and Tennessee with respect to Crowley's Ridge in Arkansas suggest a common origin. The highs and lows in the top and bottom of the Upland Complex in western Kentucky and Tennessee may be due to erosion by west-flowing tributaries of the Mississippi River (Fig. 3). Most of the lows in the Upland Complex of Figure 3 are coincident with these river valleys. Therefore, it is possible that the lows in the Upland Complex maps are actually Pleistocene terrace gravels of these west-flowing tributaries that were inadvertently included in the Pliocene Upland Complex data set. However, in selecting the wells used in the Upland Complex maps, a concerted effort was made to stay outside of the tributary river valleys to avoid this very issue. Similarly, relief on the Upland Complex cannot be due to reactivation or differential compaction above underlying Cretaceous plutons, since there is no spatial correlation between relief in the Upland Complex and the plutons (Rhea and Wheeler, 1995).

The highs and lows in the Upland Complex of western Kentucky and Tennessee appear to be of tectonic origin. Support for this interpretation is provided by Martin (2008), who mapped east-trending grabens beneath western Tennessee in the underlying Eocene Memphis Sand (Fig. 5A). Martin's (2008) well data were used to construct a north-south profile of the top of the Memphis Sand (Fig. 6A), which illustrates its close similarity with the base and top of the overlying Upland Complex. Easterly trending faults in western Tennessee and Kentucky have also been proposed by Parks and Carmichael (1990) and Cox et al. (2001b) (Fig. 5B). Cox et al. (2001b) believed their faults bound blocks that were tilted north and south during the Wisconsinan stage, thereby influencing river locations.

Tectonic uplift of Crowley's Ridge has been documented (Nelson and Zhang, 1991; Van Arsdale et al., 1995; Williams et al., 2007), and tectonic deformation has been proposed within Crowley's Ridge (Cox, 1988a, 1988b; Boyd and Schumm, 1995; Spitz and Schumm, 1997). Geomorphic analyses by Boyd and Schumm (1995) and Spitz and Schumm (1997) identified apparent tectonic tilting within Crowley's Ridge, and they divided Crowley's Ridge into a series of fault-bounded blocks.

Parallelism of the top and bottom of the Upland Complex illustrated in Figures 3B and 6A and the 60 m of local relief on the Upland Complex strongly indicate tectonic deformation. Perhaps the most compelling argument for a structural origin for the highs and lows of the Upland Complex in western Kentucky and Tennessee is that essentially identical highs and lows are seen along the full length of Crowley's Ridge (Fig. 7). If these are correlative highs and lows, as we have interpreted them, it would require that post–Upland Complex rivers would have followed the blue lines in Figure 7, thereby flowing east-west (perpendicular to regional river flow) and parallel to each other for 110 km, across western Kentucky and Tennessee, to also cut across Crowley's Ridge. We consider this to be highly improbable. Therefore, the deformed Upland Complex appears to reflect east-west–striking fold axes or faults (Figs. 7 and 8). If they are folds or reverse faults due to shortening, then there must have been post–4 Ma north-south horizontal compression. Schweig and Ellis (1994) proposed north-south compression in the time period of 11–3 Ma; however, there has been no subsequent study that supports their hypothesis. The prevailing evidence is that the maximum compressive stress in this region is due to the western drift of North America (Liu and Bird, 2002) and has been horizontal and oriented ~N60°E to N80°E (Zoback and Zoback, 1981) at least since the Neogene. It seems that the most plausible explanation for the east-west–striking structures is that they are due to north-south extension and reflect normal faulting. These normal faults are mapped across the northwest and southeast margins of the Reelfoot rift locally to the outboard Big Creek–Ellendale and Commerce faults (Figs. 7 and 8).

The north-south extension responsible for the normal-faulted Upland Complex may be manifest as fault-bounded tilted blocks (Cox et al., 2001b; Spitz and Schumm, 1997) or horst and graben structure (Martin, 2008) (Fig. 5). Whichever normal fault geometry is correct, the faults appear to have locally influenced the location of the major west-flowing streams in western Tennessee and Kentucky (Figs. 3 and 5B). However, there is no evidence of these east-trending normal faults in our map of the base of the Quaternary alluvium (Fig. 7). Thus, either Wisconsinan or Holocene displacement on these faults is below the resolution of our drill-hole data, or the faults have had no Wisconsinan or Holocene displacement. However, there is good correspondence between our normal faults 2, 3, and 5 (Fig. 8) and proposed faults that cross the Mississippi River (Boyd and Schumm, 1995; Spitz and Schumm, 1997). Similarly, a seismic-reflection survey recently conducted on the Mississippi River from Cairo, Illinois, to south of Memphis by M. Magnani (2013, personal commun.) revealed that normal faults 2 through 6 of Figure 8 are evident in the Eocene strata imaged in her survey.

Quaternary Faulting in the Mississippi Valley Lowlands

There is extensive evidence for Quaternary deformation in the upper Mississippi Embayment (Fig. 2; Table 1) that is due to reactivation of Reelfoot rift faults (Howe, 1985; Nelson and Zhang, 1991; Csontos et al., 2008; Van Arsdale, 2009; Pratt, 2012; Pratt et al., 2012). Right-lateral transpressive faulting is occurring along the Reelfoot rift and its outboard faults, including the Commerce fault, northwestern Reelfoot rift margin, Axial fault, southeastern Reelfoot rift margin, and Big Creek–Ellendale faults. As a consequence of this simple shear, the north-trending southern Crowley's Ridge, Reelfoot fault, Joiner Ridge, and possibly Meeman-Shelby fault are stepover zones with local east-west compression (Fig. 8).

Our data do not allow us to evaluate Quaternary deformation in the northern portion of the Western Lowlands or the northern portion of Crowley's Ridge. However, there are structures in the Western and Eastern Lowlands for which ages (Fig. 4) and magnitudes of uplift (Fig. 8) can be assessed. A Western Lowlands fault, located immediately south of the label WM in Figure 7, underlies Dudley, Melville Ridge, and Ash Hill braid belts. Thus, the 30 m of interpreted structural relief has occurred within the last 24–27 k.y. (Ash Hill), resulting in an average displacement rate of between 1.3 mm/yr and 1.1 mm/yr. As discussed earlier herein, it is possible that in the Eastern Lowlands Morehouse alluvium (12 ka) underlies the Holocene Mississippi River floodplain, and for the following discussion, we will assume this to be the case. The Charleston uplift underlies the Charleston (14 ka) terrace, Blodgett (13 ka) terrace, and the Holocene floodplain. Since there is no difference in structural relief along the length of the Charleston uplift, the 36 m of uplift identified by Pryne et al. (2013) occurred within the last 12 k.y. The Lake County uplift (Reelfoot fault) underlies Holocene floodplain, and so its 21 m of uplift is younger than 12 ka. Blytheville arch uplift occurs beneath the Morehouse terrace and Holocene floodplain, and thus a portion of this structure has been uplifted 25 m within the last 12 k.y. Joiner Ridge lies beneath Morehouse terrace and Holocene floodplain, and so it too was uplifted 20 m subsequent to 12 ka. The Meeman-Shelby fault zone underlies Holocene alluvium, and so we propose that it also has been uplifted 28 m (Hao et al., 2013) within the past 12 k.y. These Eastern Lowland uplift magnitudes occurring over the last 12 k.y. result in average uplift rates of 3 mm/yr for the Charleston uplift, 1.75 mm/yr for Reelfoot North fault, 2.1 mm/yr for Blytheville arch, 1.7 mm/yr for Joiner Ridge, and 2.3 mm/yr for the Meeman-Shelby fault zone. However, surface deformation only exists on the seismically active Reelfoot North fault, Blytheville arch, and New Madrid North fault, thus revealing that these structures have been active during the Holocene. There is also Holocene faulting on the southeastern margin of the Reelfoot rift, 20 km north of Memphis (Cox et al., 2013), but a displacement rate at this location has not been calculated. Absence of surface faulting along the Western Lowland fault, Charleston uplift, Joiner Ridge, and Meeman-Shelby fault zone suggests that these are blind faults for which surface expression has been obscured by surface erosion and sedimentation or that the displaced base of the alluvium is older than the surface sediments that overlie these structures.

Quaternary Deformation Mechanism in the Reelfoot Rift and New Madrid Seismic Zone

Right-lateral simple shear across the Reelfoot rift was the principal faulting mechanism for the region during the Pliocene and Quaternary, and for the New Madrid seismic zone in particular (Csontos et al., 2008; Tavakoli et al., 2010; Pratt, 2012; Pratt et al., 2012). Csontos et al. (2008) argued that the Reelfoot fault, southern Crowley's Ridge, and Joiner Ridge are fault-bounded compressional stepovers within this system (Fig. 2). Pratt et al. (2012) documented 5–12 km of post-Eocene right-lateral strike slip across the Axial fault (their Cottonwood Grove fault) of Figure 2. The observations of these previous authors and the post–Upland Complex deformation described herein further support this model of regional shear, but with modification. We propose regional right-lateral simple shear deformation that is illustrated using a strain ellipse with a north-south–oriented long axis (Fig. 8B). The east-west normal faulting of the Upland Complex that extends both east and west of the Reelfoot rift margins identified in this current study reflects north-south extension within the strain ellipse. Right-lateral simple shear across the Reelfoot rift, including the outboard Commerce geophysical lineament/fault and Big Creek–Ellendale fault, has also caused local east-west compression, thus causing the north-south–trending zones of uplift (southern Crowley's Ridge, Joiner Ridge, and Reelfoot fault stepover zones) parallel to the long axis of the ellipse. Our model suggests that the Meeman-Shelby fault may be a stepover fault between the Big Creek–Ellendale fault and the southeastern margin of the Reelfoot rift (Fig. 2). Regardless of whether the Meeman-Shelby fault zone is a stepover zone or a P shear as proposed by Hao et al. (2013), this structure strongly suggests that right-lateral shear extends southeast to the Big Creek–Ellendale fault. To further support our model, the Bootheel fault (Guccione et al., 2005) appears to be a right-lateral P shear, and the Risco fault (Csontos and Van Arsdale, 2008) appears to be a left-lateral antithetic shear (Figs. 2 and 8B; Tavakoli, et al., 2010; Hao et al., 2013).

CONCLUSIONS

Although we generally agree with the regional right-lateral simple shear deformation model of Csontos et al. (2008) to explain Quaternary tectonics within the Reelfoot rift, we wish to modify their model. In our model, the right-lateral simple shear extends across the currently defined southeastern and northwestern margins of the Reelfoot rift and includes the outboard Commerce geophysical lineament/fault and Big Creek–Ellendale fault (Fig. 8). Regional shear is primarily manifest as right-lateral strike slip on the northeast-striking basement faults of the Reelfoot rift, but it has also produced north-south reverse faults (east-west compression) that have been called stepover zones (Csontos et al., 2008; Pratt et al., 2012) and east-west normal faults (north-south extension). Displacement magnitudes and rates have not been calculated for the east-west normal faults; however, the structures that deform the Quaternary unconformity at the base of the Mississippi River alluvium reveal a regional average late Quaternary slip rate of ▯2 mm/yr.

Numerical analysis of the simple shear strain model presented in this study may provide a more accurate assessment of the post–4 Ma strain field and shearing across the Reelfoot rift, which should include the outboard Commerce geophysical lineament/fault and Big Creek–Ellendale fault. Specifically, it may be possible to quantify the amount of shortening across the north-striking stepovers and the amount of extension across the east-striking normal faults, which will constrain the maximum amount of right-lateral shear that has occurred across the entire rift over the last 4 m.y. This would provide a long-term slip rate within the current stress field. A rotating and deforming strain ellipse provides a model for the contemporary strain field that may give insights into global positioning system (GPS) strain analyses (e.g., Smalley et al., 2005; Frankel et al., 2012) and provide guidance for future GPS monument emplacement, which should encompass the Commerce geophysical lineament, southeastern Reelfoot rift margin, and Big Creek–Ellendale faults.

The uplifted stepover zones illustrate that fault locations (seismic zones) move through time and can be put into chronological order, with the oldest being the southern portion of Crowley's Ridge, the intermediate age being Joiner Ridge and Meeman-Shelby fault zones, and the seismically active Reelfoot North and Reelfoot South faults being the youngest. The Reelfoot South fault is a seismically active step over that is clearly evident in seismic-reflection data of Eocene and older sediments, yet it has only very subtle geomorphic evidence of Quaternary uplift (Van Arsdale et al., 1999). Such evidence is consistent with the Reelfoot South fault zone (Fig. 2) being an old fault zone that is experiencing historical (1811–1812) reactivation.

We wish to conclude by pointing out that future light detection and ranging (LiDAR) data may identify surface deformation that is currently below our detection threshold and that our strain rates are driven by uncertain sediment ages. Specifically, the Upland Complex is herein presented to be Pliocene (Van Arsdale et al., 2007), but it could be as old as Miocene or as young as early Pleistocene (Autin et al., 1991). Similarly, the basal Quaternary alluvium faulted in the Eastern Lowlands is herein interpreted as 12 ka, but it could be older Pleistocene or as young as 10 ka. Clearly, some hard dates are needed for these soft sediments. New $^{10}Be/^{26}Al$ dates could be obtained for the Upland Complex by sampling active Upland Complex quarries in western Tennessee and eastern Arkansas, and water well drilling through the Mississippi River alluvium could provide samples for optically stimulated luminescence dating of the base of the Quaternary alluvium.

DATA AND RESOURCES

The lignite exploration geologic well logs were recorded by the Phillips Coal Company and were provided to the Ground Water Institute at the University of Memphis under special agreement with the North American Coal Corporation. The well logs are publicly available for viewing at the Ground Water Institute.

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[1]Supplemental Table 1. Excel file of Eastern and Western Lowlands base of alluvium. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00906.S1 or the full-text article on www.gsapubs.org to view Supplemental Table 1.

[2]Supplemental Table 2. Excel file of Upland Complex base and top data points. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES00906.S2 or the full-text article on www.gsapubs.org to view Supplemental Table 2.

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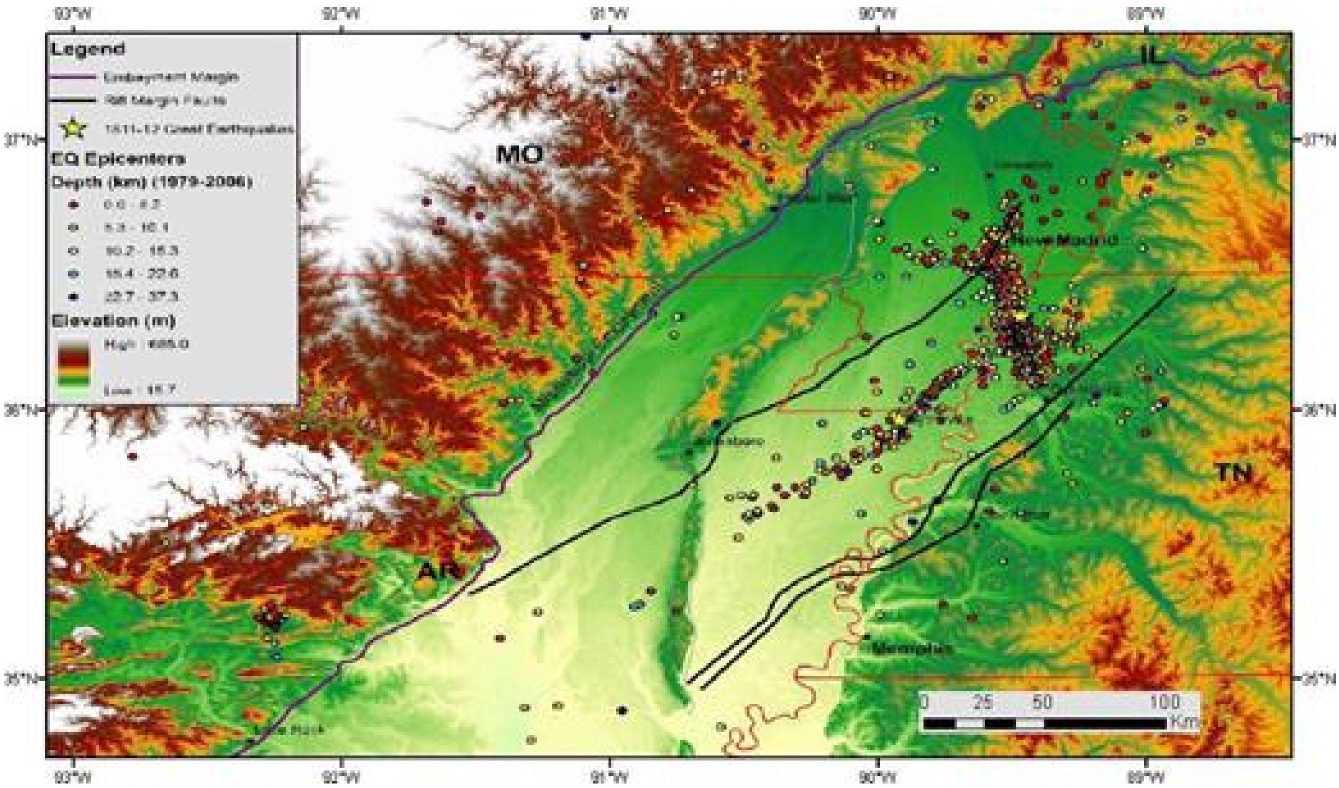
FIGURES & TABLES

Figure 1.



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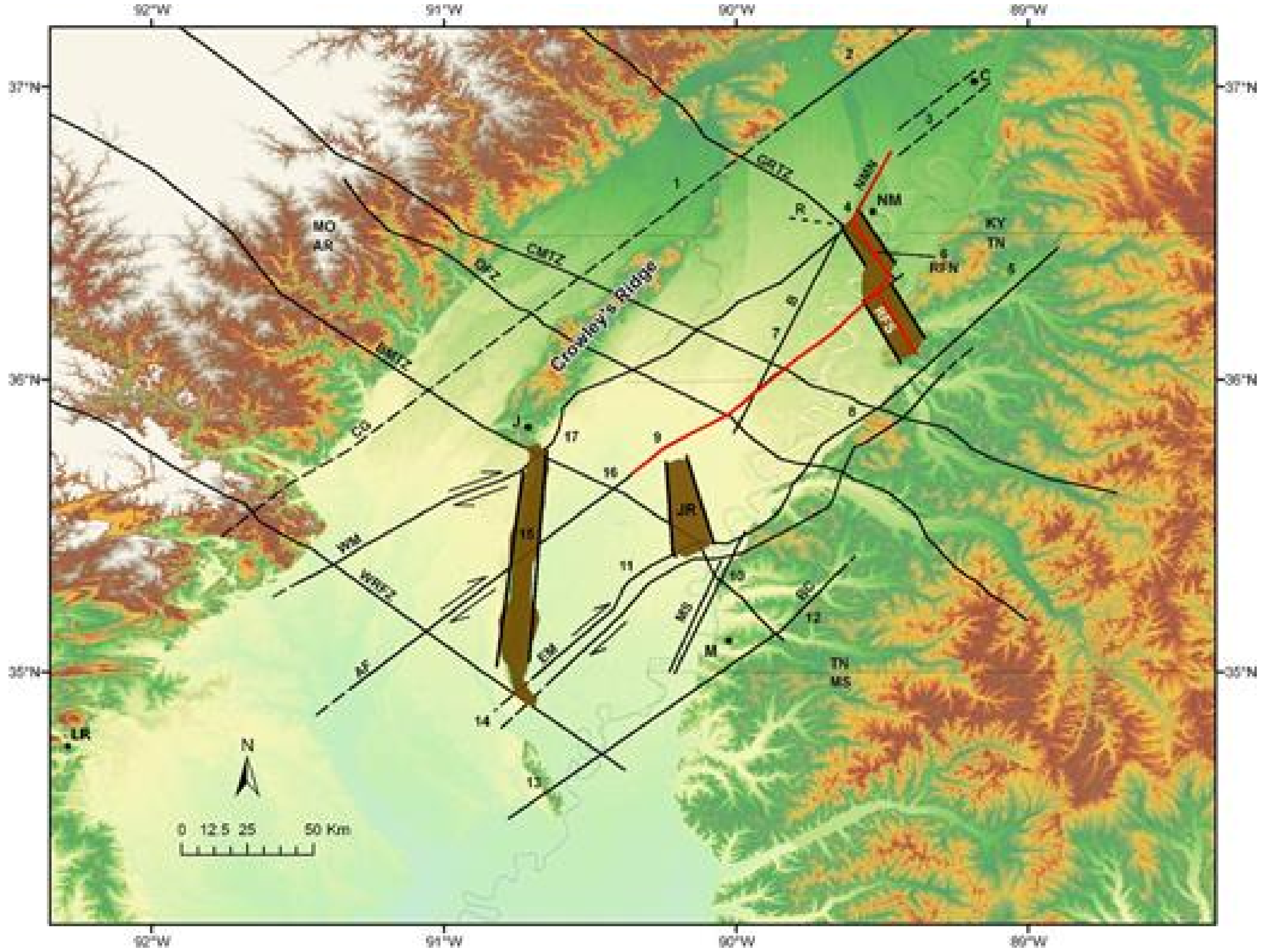
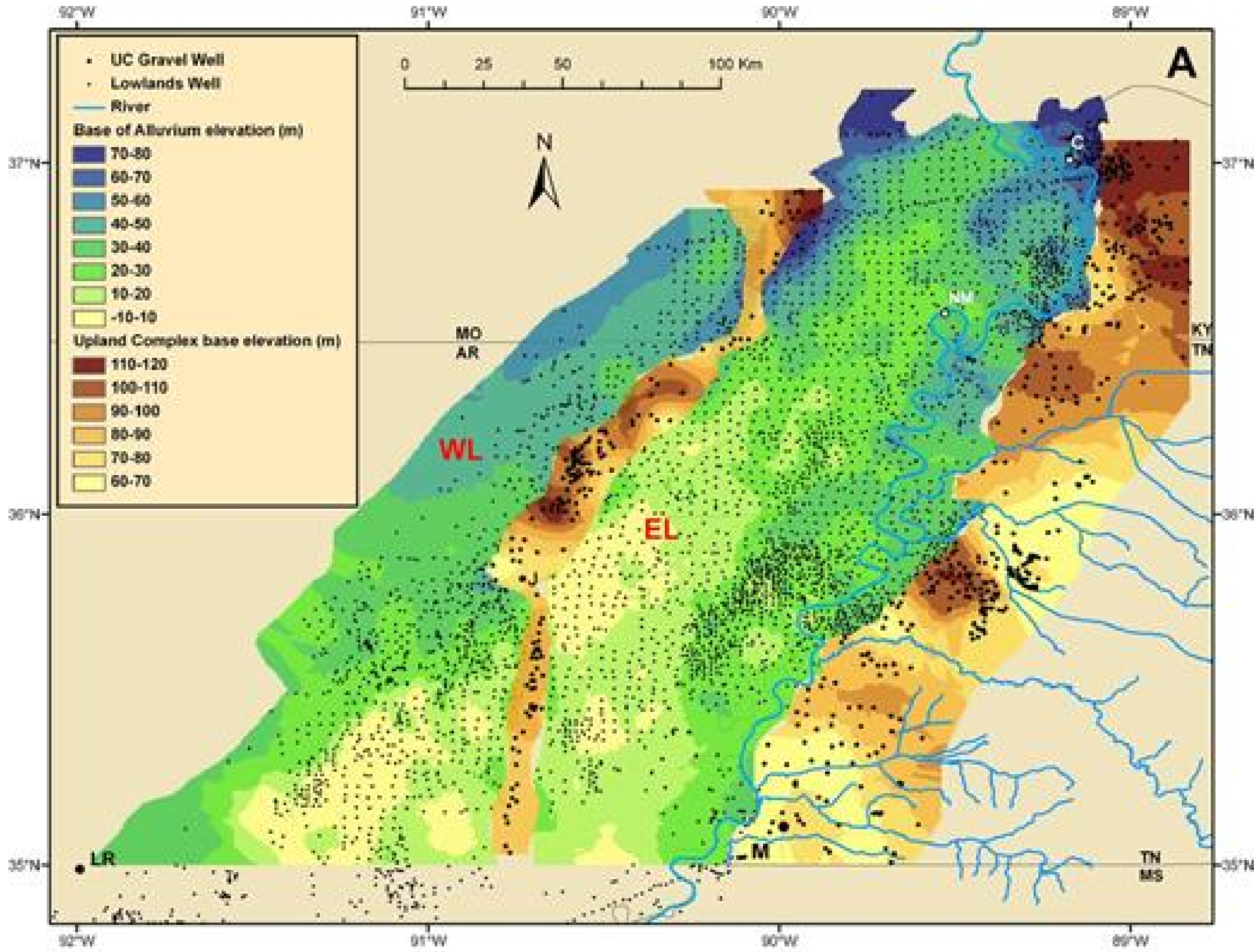
Reelfoot rift and New Madrid seismic zone of the central United States (from Csontos et al., 2008). AR—Arkansas, MO—Missouri, TN—Tennessee.

Figure 2.



Reelfoot rift faults and numbered locations of documented Quaternary faulting and liquefaction (modified from Csontos et al., 2008). Numbers are locations of studies identified in Table 1. Right-lateral shear across the Reelfoot rift is responsible for the New Madrid seismic zone earthquakes, which occur along the faults colored red. Quaternary right-lateral shear on the rift faults is also causing uplift of the Lake County uplift–Reelfoot North fault (RFN), Joiner Ridge (JR), and the southern portion of Crowley's Ridge. WRFZ—White River fault zone, BMTZ—Bolivar Mansfield tectonic zone, OFZ—Osceola fault zone, CMTZ—Central Missouri tectonic zone, GRTZ—Grand River tectonic zone, EM—southeastern Reelfoot rift margin faults, WM—northwestern Reelfoot rift margin fault, AF—Axial fault, NMN—New Madrid North fault, RFS—Reelfoot South fault, MS—Meeman-Shelby fault zone, CG—Commerce geophysical lineament/fault, BC—Big Creek–Ellendale fault, B—Bootheel fault, R—Risco fault (defined by seismicity), M—Memphis, LR—Little Rock, NM—New Madrid, C—Cairo, KY—Kentucky, TN—Tennessee, MO—Missouri, AR—Arkansas, MS—Mississippi.

Figure 3.



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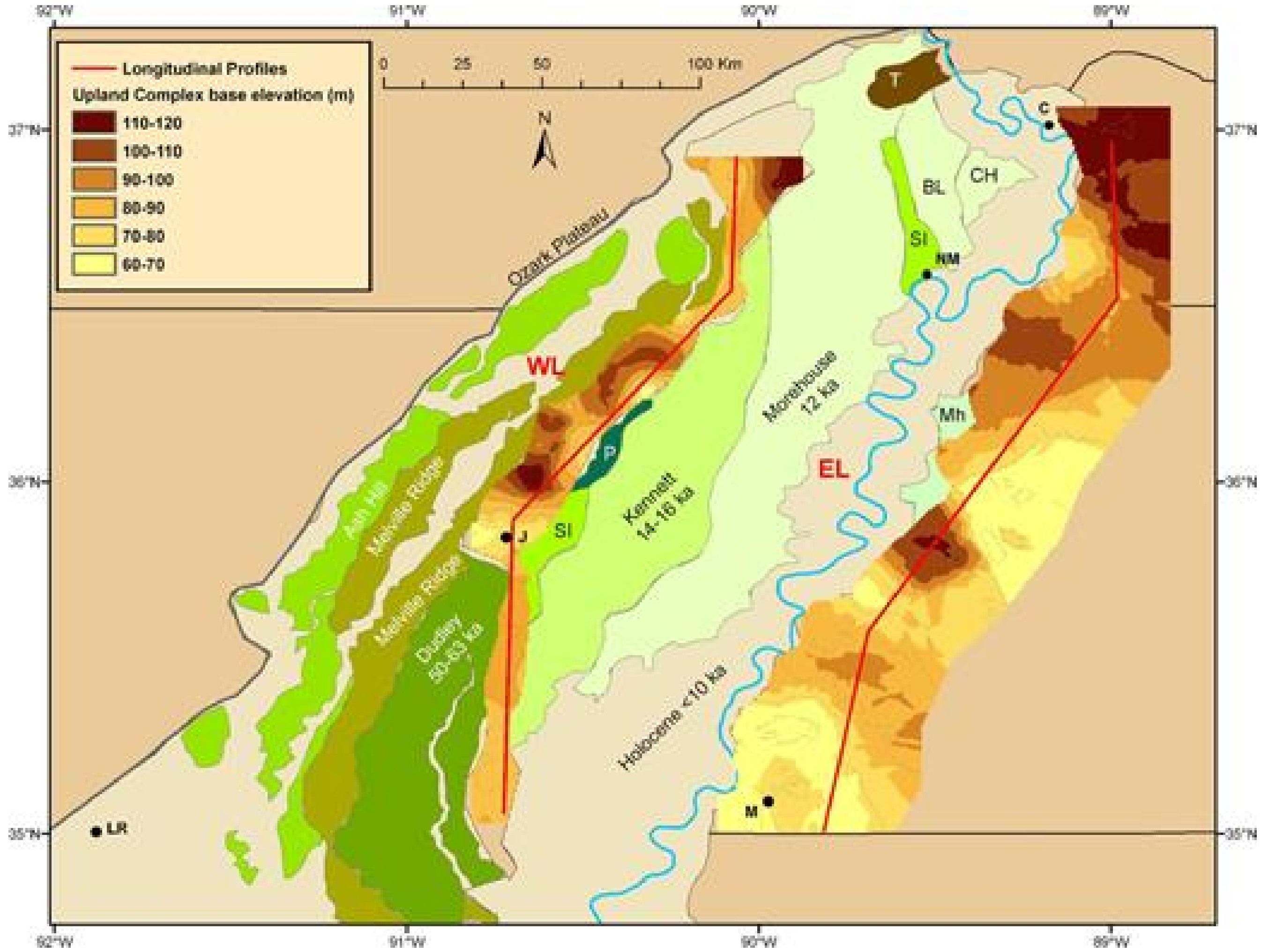
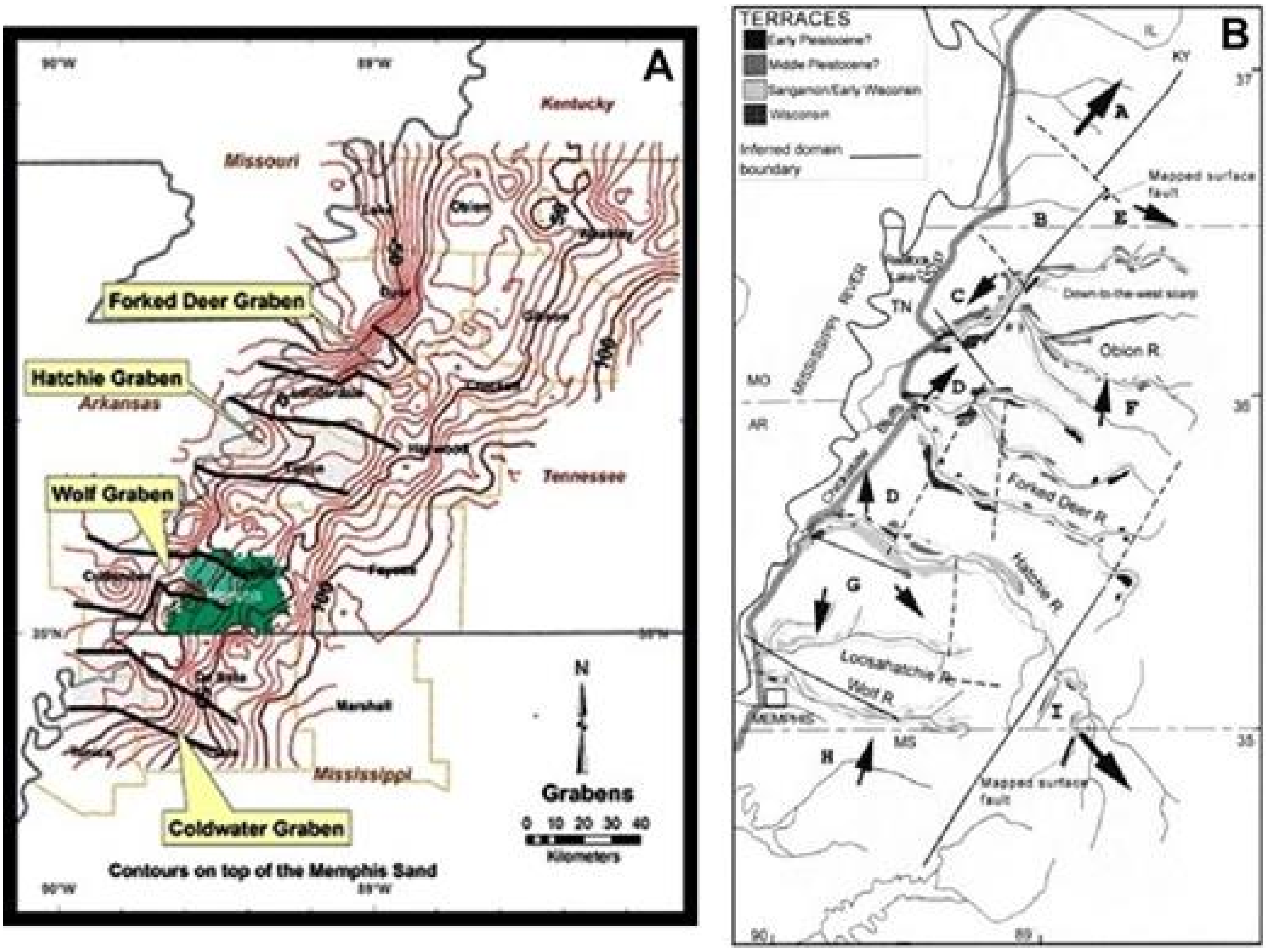
(A) Location of wells used to construct the structure contour maps of the base of the Upland Complex (browns) and the base of the Quaternary Mississippi River alluvium (blues and greens) in the Eastern (EL) and Western Lowlands (WL). Contour interval = 10 m. LR—Little Rock, J—Jonesboro, NM—New Madrid, C—Cairo, M—Memphis, KY—Kentucky, TN—Tennessee, MO—Missouri, AR—Arkansas, MS—Mississippi. (B) Three-dimensional interactive model of the base and top of the Pliocene Upland Complex and the base of the Mississippi River Quaternary alluvium. To view the interactive model, please visit http://dx.doi.org/10.1130/GES00906.S3 or the full-text article on www.gsapubs.org.

Figure 4.



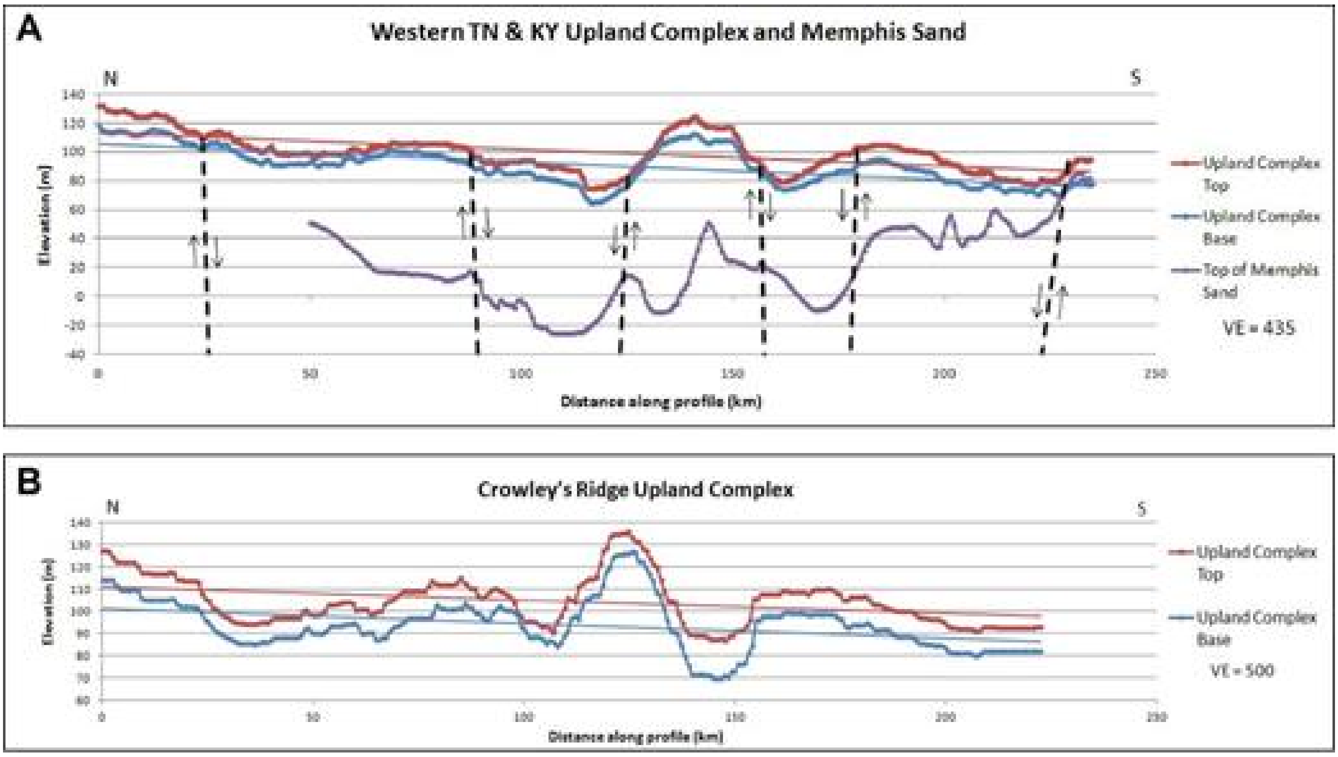
Base of Upland Complex (browns), Pleistocene Mississippi River terraces (blues and greens), Holocene floodplain of the Mississippi River (beige), and Uplands (tan) (modified from Rittenour et al., 2007). Red lines locate longitudinal profiles of the Upland Complex in Figures 6 and 7A. LR—Little Rock, J—Jonesboro, NM—New Madrid, C—Cairo, M—Memphis, P—Paragould terrace (85 ka), SI—Sikeston terrace (17–19 ka), Mh—Morehouse terrace (12 ka), BL—Blodgett terrace (13 ka), CH—Charleston terrace (14 ka), T—Tertiary uplands, WL—Western Lowlands, EL—Eastern Lowlands. The Ash Hill terrace is 24–27 ka, and Melville Ridge terrace is 34–41 ka.

Figure 5.



(A) Grabens mapped on the top of the Memphis Sand in western Tennessee and northwestern Mississippi (from Martin, 2008). (B) Tilted block domain boundaries (solid and dashed lines) and stream migration vectors (arrows) in western Kentucky and Tennessee and in northwestern Mississippi (from Cox et al., 2001b). IL—Illinois, KY—Kentucky, TN—Tennessee, MO—Missouri, AR—Arkansas, MS—Mississippi.

Figure 6.



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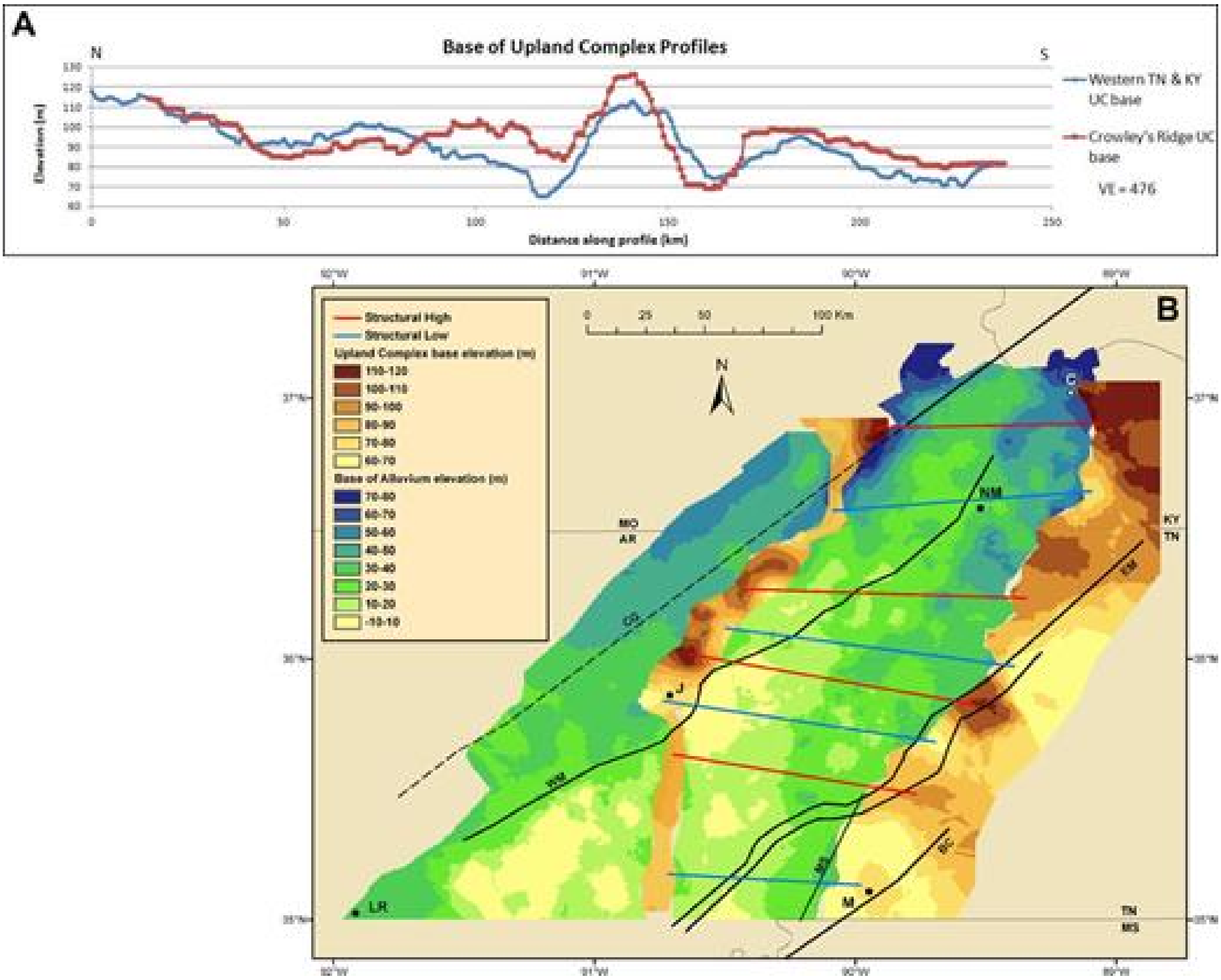
(A) Down-valley profiles of the top and bottom of the Upland Complex in western Kentucky and Tennessee and the top of the Memphis Sand in Tennessee with interpreted faults. Thin lines are best-fit regression lines of the elevation of the top of Upland Complex (red) and base of the Upland Complex (blue). (B) Down-valley profiles of the top and bottom of the Upland Complex in Crowley's Ridge of eastern Arkansas. Thin lines are best-fit regression lines of the elevation of the top of the Upland Complex (red) and base of the Upland Complex (blue). Profiles are located in Figure 4. VE—vertical exaggeration.

Figure 7.



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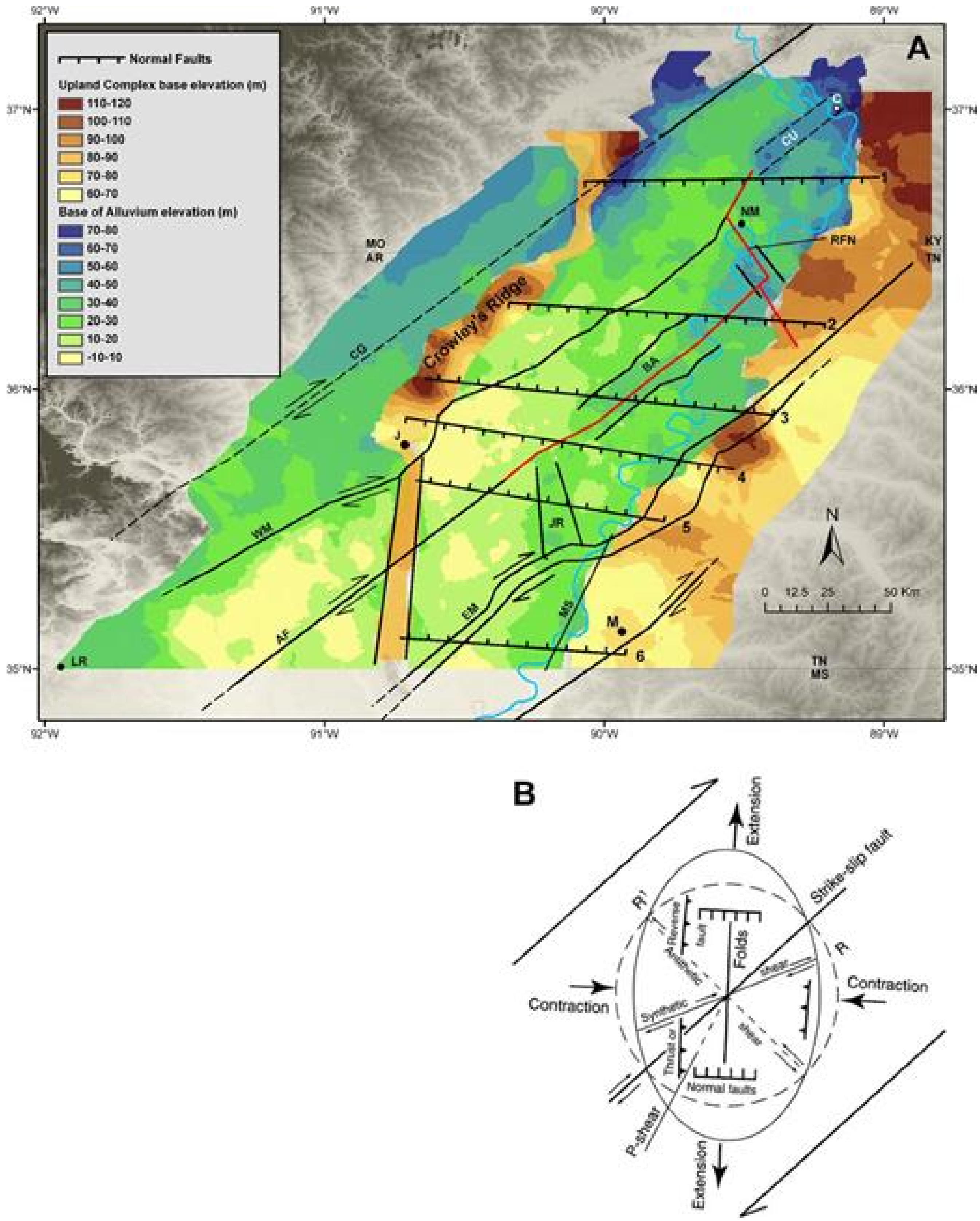
(A) Down-valley profile of the base of the Upland Complex (UC) in western Kentucky and Tennessee superimposed upon the down-valley profile of the base of the Upland Complex in Crowley's Ridge of eastern Arkansas. Profiles are located in Figure 4. (B) Structural highs and lows (from A) correlated and connected with red (high) and blue (low) lines. J—Jonesboro, M—Memphis, LR—Little Rock, C—Cairo, CG—Commerce geophysical lineament/fault, BC—Big Creek–Ellendale fault, MS—Meeman-Shelby fault zone, NM—New Madrid, WM—northwestern Reelfoot rift margin, EM—southeastern Reelfoot rift margin. VE—vertical exaggeration.

Figure 8.



(A) Northeast-striking Reelfoot rift and its outboard faults. North-striking compressional uplifts (stepovers) are bounded by black fault lines (e.g., Joiner Ridge). The black west-striking normal faults have barbs on their downdropped side. Red lines are seismically active faults. CG—Commerce geophysical lineament/fault, WM—northwestern Reelfoot rift margin, AF—Axial fault, EM—southeastern Reelfoot rift margin, BC—Big Creek–

Ellendale fault, CU—Charleston uplift, RFN—Reelfoot North fault–Lake County uplift, NMN—New Madrid North fault, BA—Blytheville arch, JR—Joiner Ridge, MS—Meeman-Shelby fault zone, LR—Little Rock, C—Cairo, NM—New Madrid, M—Memphis. (B) Strain ellipse (from Keller and Pinter, 2002) illustrating right-lateral simple shear that is occurring across the Figure 8A map region and the resulting structures that form in this strain field.

TABLE 1.
REELFOOT RIFT QUATERNARY FAULTING AND LIQUEFACTION LOCATIONS DESIGNATED WITH NUMBERS IN FIGURE 1

TABLE 1. REELFOOT RIFT QUATERNARY FAULTING AND LIQUEFACTION LOCATIONS DESIGNATED WITH NUMBERS IN FIGURE 1

Location/name	Structure	Deformation age	Source
1. Western Lowlands	Faulting and liquefaction	23,000–17,000 and 13,430–9000 yr B.P., A.D. 240–1020 and 1440–1540	Shoemaker et al. (1997); Vaughn (1994)
2. Commerce fault	Faulting	60–50 ka, 35–25 ka, 5 ka, and 3660 yr B.P.	Harrison et al. (1999)
3. Charleston uplift	Faulting	<12 ka	Pryne et al. (2013)
4. New Madrid North fault	Faulting	Wisconsinan	Baldwin et al. (2005)
5. Southeastern Reelfoot rift margin	Faulting	Pleistocene	Cox et al. (2006)
6. New Madrid seismic zone	Faulting and liquefaction	2350 B.C., A.D. 300, 900, 1450, and 1811	Kelson et al. (1996); Tuttle et al. (2002, 2005)
7. Bootheel fault	Faulting	12.5–10.2 ka, 2.7–1.0 ka, and A.D. 1450	Guccione et al. (2005)
8. Southeastern Reelfoot rift margin	Faulting	<20 ka	Cox et al. (2006)
9. Manila High	Faulting	11,500–5400 B.P., A.D. 1450 and 1811	Guccione et al. (2000); Odum et al. (2010)
10. Southeastern Reelfoot rift margin	Faulting	4000–2000 yr. B.P. (2 events); <2000 yr B.P.	Cox et al. (2013)
11. Southeastern Reelfoot rift margin	Faulting	Quaternary	Howe (1985)
12. Ellendale	Faulting	A.D. 400	Velasco et al. (2005)
13. Big Creek	Faulting	<27 ka	Harris and Sorrells (2006)
14. Marianna	Liquefaction	7000–5000 B.P.	Tuttle et al. (2006)
15. Crowley's Ridge	Faulting	Wisconsinan	Van Arsdale et al. (1995)
16. Marked Tree High	Faulting	4440–3350 B.P.	Guccione (2005)
17. Northwestern Reelfoot rift margin	Faulting	<19 ka	Van Arsdale et al. (1995)

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Index Terms/Descriptors

alluvium | boreholes | Cenozoic | clastic sediments | deformation | earthquakes | epicenters | faults | grabens | lithostratigraphy | Mississippi Embayment | Mississippi Valley | Neogene | New Madrid region | normal faults | Pliocene | Quaternary | Reelfoot Rift | rift zones | sediments | seismicity | systems | tectonic elements | Tertiary | United States | upper Pliocene

Latitude & Longitude

N35°00'00" - N37°00'00", W91°00'00" - W89°00'00"

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