Near-surface structural model for deformation associated with the February 7, 1812, New Madrid, Missouri, earthquake

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ABSTRACT

The February 7, 1812, New Madrid, Missouri, earthquake (M [moment magnitude] 8) was the third and final large-magnitude event to rock the northern Mississippi Embayment during the winter of 1811–1812. Although ground shaking was so strong that it rang church bells, stopped clocks, buckled pavement, and rocked buildings up and down the eastern seaboard, little coseismic surface deformation exists today in the New Madrid area. The fault(s) that ruptured during this event have remained enigmatic. We have integrated geomorphic data documenting differential surficial deformation (supplemented by historical accounts of surficial deformation and earthquake-induced Mississippi River waterfalls and rapids) with the interpretation of existing and recently acquired seismic reflection data, to develop a tectonic model of the near-surface structures in the New Madrid, Missouri, area. This model consists of two primary components: a north-northwest–trending thrust fault and a series of northeast-trending, strike-slip, tear faults. We conclude that the Reelfoot fault is a thrust fault that is at least 30 km long. We also infer that tear faults in the near surface partitioned the hanging wall into subparallel blocks that have undergone differential displacement during episodes of faulting. The northeast-trending tear faults bound an area documented to have been uplifted at least 0.5 m during the February 7, 1812, earthquake. These faults also appear to bound changes in the surface density of epicenters that are within the modern seismicity, which is occurring in the stepover zone of the left-stepping right-lateral strike-slip fault system of the modern New Madrid seismic zone.

INTRODUCTION

The northern Mississippi Embayment of the central United States was rocked by hundreds of earthquakes during the winter of 1811–1812. At least three of these earthquakes (December 16, 1811; January, 23, 1812; and February 7, 1812), are estimated to have had moment magnitudes (**M**) between 7.8 and 8.1 (Johnston et al., 1994; Johnston, 1996), and are among the largest to have occurred historically in a stable continental interior (Johnston and Kanter, 1990). Although related ground shaking rang church bells, stopped clocks, cracked pavement, and rocked buildings as far away as Charleston, South Carolina; Washington, D.C.; and Boston, Massachusetts (Fuller, 1912; Penick, 1976); the fault(s) that ruptured during these events have remained undiscovered. The 1811–1812 earthquakes are presumed to have occurred in the southeast Missouri area because: (1) the isoseismal pattern is centered there (Johnston and Nava, 1990); (2) there are dramatic eyewitness accounts of shaking and damage, including surface fissuring and the formation of waterfalls and rapids in the Mississippi River; and (3) a concentration of present-day North American intraplate seismicity (New Madrid seismic zone) is located in this region (Fig. 1). Geologic and geophysical research into the 1811–1812 earthquakes has been concentrated within the inferred epicentral areas of the large historic events and present-day seismicity, and evidence of strong shaking, surface rupture, and tectonic uplift has been found (Usher, 1837; Lyell, 1849; McGee, 1892; Fuller, 1912; Stearns, 1979; Russ, 1979, 1982; Obermeier, 1989; Schweig and Marple, 1991; Kelson et al., 1992, 1994, 1996; Van Arsdale et al., 1991, 1994, 1995).

The New Madrid seismic zone (NMSZ) is recognized as one of the most seismically active regions in North America east of the Rocky Mountains. Nuttli (1982) estimated that the occurrence of an earthquake with a magnitude comparable to any of the 1811–1812 events in the upper Mississippi Embayment today would cause damage to buildings and infrastructure in at least six states. Property loss from such an event would exceed $3.6 billion (Algermissen, 1990; Hamilton and Johnston, 1990; Johnston and Nava, 1990). Nearly two centuries ago, the population at risk in this area numbered in the thousands; today it is in the millions. Thus, understanding the 1811–1812 earthquakes and their possible recurrence is critical to evaluating the risk from future earthquakes in the central United States.

Reconciling geologic and geomorphic observations with faults inferred from the modern seismicity has been problematic. The modern seismicity of the New Madrid seismic zone defines three major trends: a southern 120-km-long trend striking N45°E; a 40-km-long, N35°E-striking trend north of the Kentucky Loop of the Mississippi River; and a N25°W transverse trend connecting the two northeast trends (Fig. 1). The focal mechanisms of the earthquakes in the two distinct northeast trends indicate that deformation is occurring predominantly on right-lateral strike-slip faults (Hermann and Canas, 1978; Hermann, 1979; Stauder, 1982; O'Connell et al., 1982; Andrews et al., 1985; Himes et al., 1988; Chiu, 1992), consistent with the current near east-west (N80°E) compressive stress field (Zoback, 1992). On the basis of focal mechanisms, surface and depth patterns of microseismicity (generally 3–15 km deep), and seismic-reflection data, the transverse zone of seismicity (N25°W) is interpreted to be complex, consisting of steep- to shallow-dipping normal, strike-slip, and thrust faults (Hamilton and Zoback, 1982; O'Connell et al., 1982; Nicholson et al., 1984; Himes et al., 1988; Chiu et al., 1992). Overall, the N25°W-trending transverse zone is interpreted to be a restraining stepover in a northeast-

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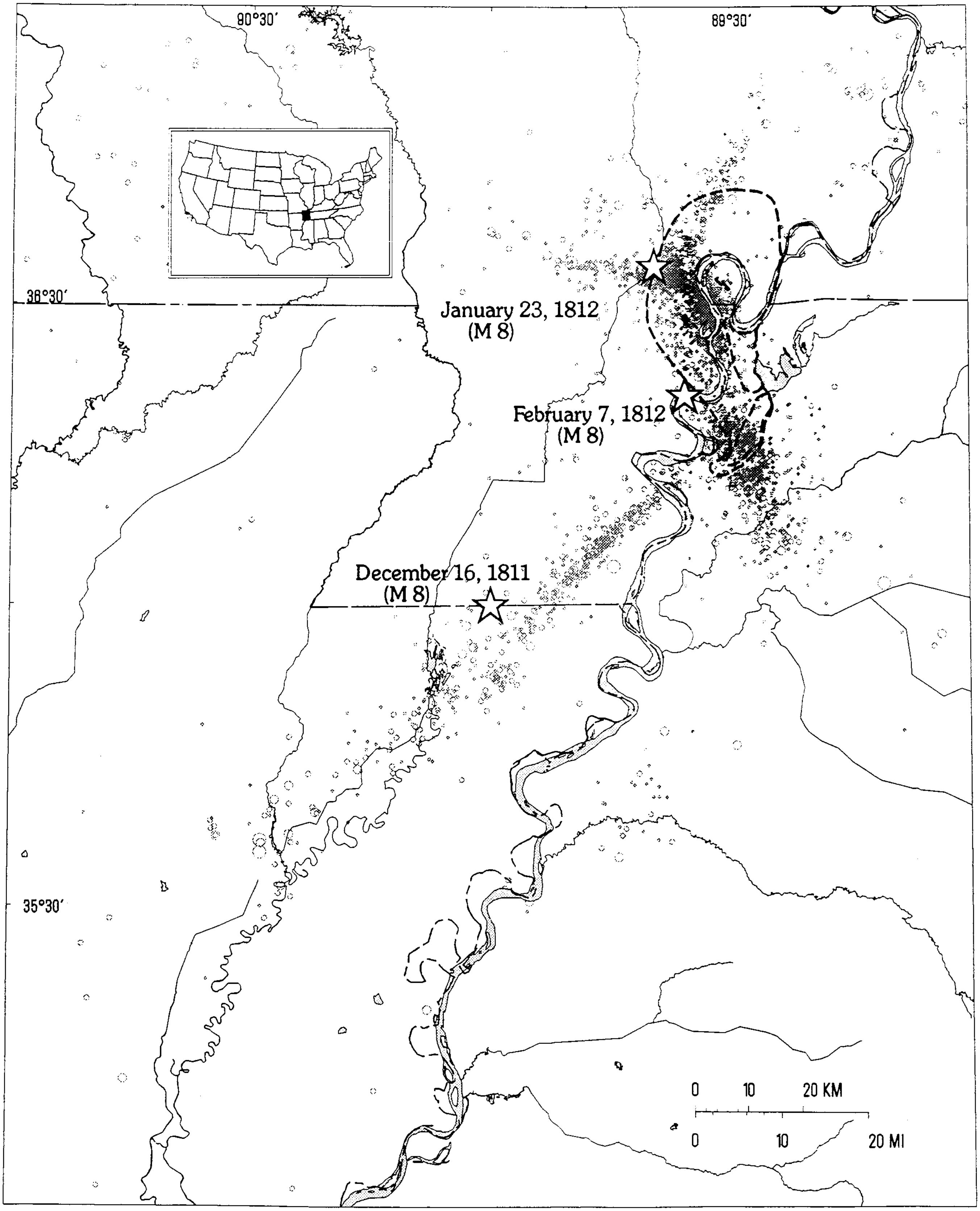


Figure 1. Regional map of the northern Mississippi Embayment and the New Madrid seismic zone (NMSZ). The Lake County uplift (Russ, 1982) is delineated by the heavy dashed black line. Circles indicate epicenters of earthquakes with M (moment magnitude) > 1.5 recorded between 1974 and 1991 (Taylor et al., 1991); size of circle corresponds to M. Epicenter distribution delineates the New Madrid seismic zone. Stars, dates, and estimated moment magnitudes indicate the approximate epicenters of the three major 1811–1812 New Madrid earthquakes (Johnston and Schweig, 1996).

trending, right-lateral, strike-slip fault system (Russ, 1982; Kelson et al., 1992). Three-dimensional boundary-element modeling of long-term deformation due to this hypothetical fault geometry reproduces the general pattern of uplifts (i.e., Lake County uplift) and subsidence (i.e., Reelfoot Lake) seen at the surface within this stepover zone (Gomberg and Ellis, 1994).

To link the surface geologic observations to deeper structures, we acquired new, and reinterpreted existing, high-resolution seismic reflection data in the Lake County uplift area (Figs. 1 and 2). By combining the structural interpretations derived from these data with evidence of near-surface tectonic deformation (geomorphologic mapping and historical accounts), and seismicity, we delineated several faults that probably ruptured during the February 7, 1812, earthquake. We interpret these faults as a north-northwest–trending thrust fault, at least 30 km long, and a series of subparallel, northeast-trending strike-slip faults.

SURFICIAL DEFORMATION WITHIN THE STEPOVER ZONE

The New Madrid seismic zone, descriptions of earthquake-induced waterfalls and rapids on the Mississippi River, and the formation of Reelfoot Lake have enticed scientists to examine the New Madrid, Missouri, area for surface ruptures from the 1811–1812 earthquake sequence and earlier events. Although extensive vegetation, lateral migration and erosion by the Mississippi River, agricultural land leveling (to increase drainage), and cultivation make it difficult to identify the subtle topographic features related to tectonic deformation, several prominent uplifts (topographic highs) and scarps have been identified (Usher, 1837; Fuller, 1912; Stearns, 1979; Russ, 1979, 1982; Kelson et al., 1992, 1994, 1996; Van Arsdale et al., 1991, 1994, 1995).

The Lake County uplift is one of the more prominent examples of Quaternary-Holocene tectonic deformation within the New Madrid seismic zone (Fig. 1). It is approximately 23 km wide (east-west), 50 km long (north-south), and rises to a height of nearly 10 m above the Mississippi River flood plain. The Lake County uplift is a composite of several topographic and structural highs, including the Tiptonville dome (and associated Reelfoot scarp), and Ridgely Ridge (Fig. 3). Evidence of tectonic deformation within the uplift indicates that the majority of surface uplift can be no older than about 6 ka (Russ, 1979, 1982). The boundaries of the Lake County uplift are only approximately defined in places where relatively

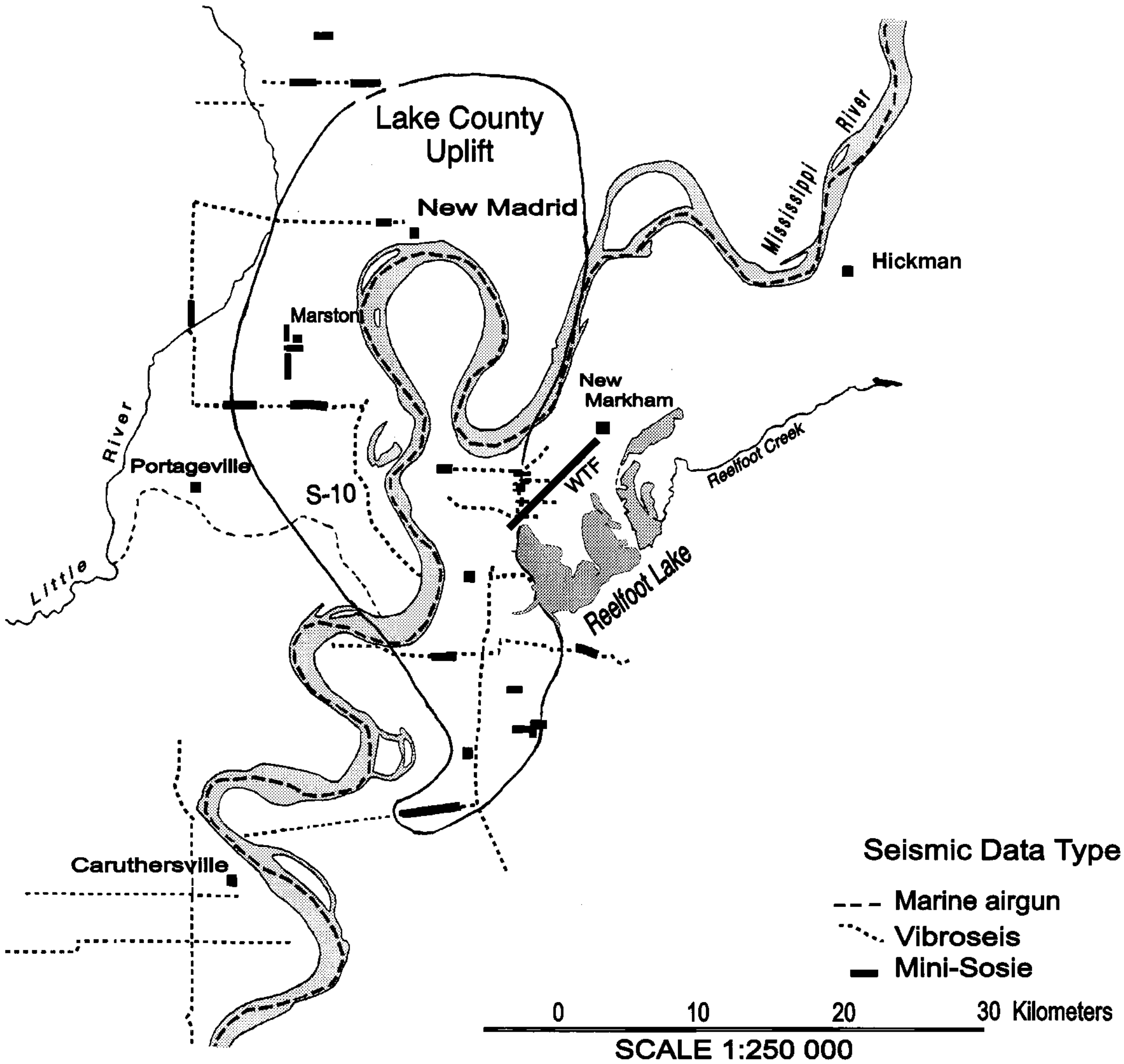


Figure 2. Location map showing the distribution and type (air gun, Mini-Sosie, and Vibroseis) of seismic reflection surveys in the New Madrid seismic zone. Base map is modified from Rhea and Wheeler (1994).

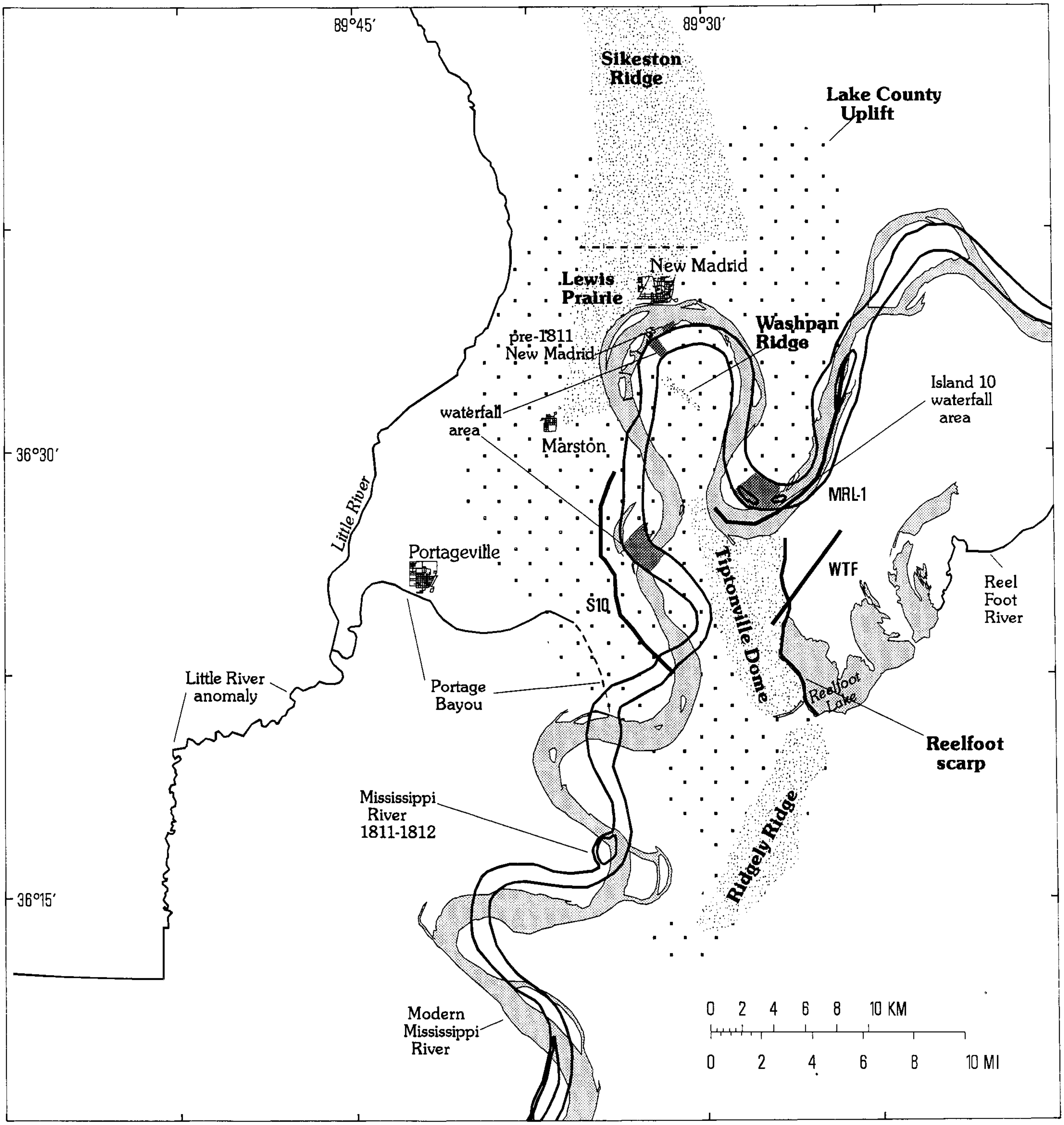


Figure 3. Map of geomorphic features and locations discussed in the text. Heavy black lines indicate the configuration of the Mississippi River at the time of the 1811–1812 earthquake events (Fisk, 1944). Location of the old (1811–1812) town site of New Madrid, Missouri, and the interpreted location of the February 7, 1812, earthquake-induced waterfalls are plotted with respect to the 1811–1812 Mississippi River configuration.

minor amounts of tectonic uplift have become indistinguishable from depositional and erosional relief (Stearns, 1979; Russ, 1982).

Tiptonville dome (Fig. 3) is an asymmetrical north-northwest–trending topographic bulge and has the highest elevation within the Lake County uplift (approximately 10 m). Crosscutting geologic features exposed in trenches and local geomorphic history indicate that the majority of uplift associated with the Tiptonville dome is attributed to at least two major earthquake events between 2000 and 200 yr ago. (Russ, 1982; Kelson et al., 1992). Approximately 0.5 m of additional uplift on the northwest and southern lobes of the dome are attributed to the 1811–1812 earthquake sequence (Russ, 1982). The Reelfoot scarp, which forms the eastern side of the Tiptonville dome, is the topographic boundary between the dome and Reelfoot Lake basin. The scarp is interpreted to be a monoclinal flexure (fault-propagation fold) in late Holocene fluvial deposits above the up-dip projection of a southwest-dipping reverse fault (Reelfoot fault) (Kelson et al., 1992, 1994, 1996; Van Arsdale et al., 1994, 1995).

Ridgely Ridge is an elongate and symmetric northeast-trending topographic and structural high that forms the narrow “foot” area of the Lake County uplift (Fig. 3). Ridgely Ridge is interpreted to be an uplifted block between a series of northeast-trending strike-slip faults (Hamilton and Zoback, 1982; Russ, 1982; Stephenson et al., 1995). The maximum uplift on the ridge is approximately 6 m, none of which is attributed to the 1811–1812 earthquake events (Stearns, 1979; Russ, 1982). In discussing the timing of Ridgely Ridge deformation with respect to Tiptonville dome, Russ (1982), on the basis of the subdued physiography of Ridgely Ridge, crosscutting geologic features (i.e., Reelfoot scarp) and differences in soil profiles, noted that “the majority of the uplift is out of phase with and occurred earlier than the uplift of the dome.”

Other equally significant, although less prominent, topographic highs and/or surface features within the Lake County uplift that are inferred to be of tectonic origin include Washpan Ridge, located in the distinctive Kentucky Loop of the Mississippi River, and the Lewis Prairie area, which is the southernmost extension of Sikeston Ridge near New Madrid, Missouri (Fig. 3) (Stearns, 1979; Van Arsdale et al., 1994). Van Arsdale et al. (1994, 1995) suggested that Washpan Ridge, a narrow, northwest-trending topographic high, is a northwest continuation of the Reelfoot scarp. In addition, they suggested that the Reelfoot fault scarp extends to the northwest side of the Mississippi River (Lewis Prairie area, Fig. 3) near New Madrid, Missouri (Van Arsdale et al., 1994, 1995). Geologic evidence indicates that most of the Lake County uplift deformation occurred prior to the 1811–1812 events (Stearns, 1979; Russ, 1982). However, land grant survey maps published in 1785 show no Reelfoot Lake to the east of the Lake County uplift. Instead, these maps show scattered oxbow lakes and the Reel Foot River flowing directly into the Mississippi River (Glenn, 1933; Tennessee State Library and Archives, 1979; Van Arsdale et al., 1991; Stahle et al., 1992). Surface deformation associated with the February 7, 1812, earthquake, including uplift of the Tiptonville dome–Reelfoot scarp, down-warping by tectonic subsidence, sediment compaction from shaking, and/or faulting in the Reelfoot Lake basin, and sandblow deposit constriction of the Reel Foot River channel, formed the modern-day Reelfoot Lake (McGee, 1892; Fuller, 1912; Glenn, 1933; Penick, 1976; Stearns, 1979; Russ, 1982; Crone and Brockman, 1982; Van Arsdale et al., 1991; Stahle et al., 1992).

Earthquake-Induced Waterfalls: Extracting Facts From Folklore

Although there is abundant documentation describing the Lake County uplift surficial deformation (i.e., Tiptonville dome–Reelfoot scarp and Washpan Ridge) associated with the February 7, 1812, event, accounts of the earthquake-induced Mississippi River waterfalls and rapids have been largely treated as a curiosity by the scientific community. The existence and location of the earthquake-related waterfalls and rapids are geologically significant in that they represent additional evidence of surface rupture(s) in the New Madrid, Missouri, area. On the basis of historical records, Penick (1976) estimated that the 1812 waterfalls were similar to those currently on the Ohio River, which have a drop of 7 m over a distance of approximately 3 km. For this paper, the February 7, 1812, earthquake-induced waterfalls and rapids on the Mississippi River will be referred to hereafter simply as waterfalls.

The waterfalls apparently were short-lived phenomena. James Smith passed through the New Madrid area on February 18, 1812, and did not mention the waterfalls even though the primary purpose for his trip was to document navigational hazards caused by the earthquakes (Philadelphia Pennsylvania Gazette, March 18, 1812). The only documentation of their occurrence is from newspaper articles, letters, and folklore (Fuller, 1912; Penick, 1976). Penick (1976) collected, correlated, and analyzed the contemporary accounts that described the dramatic impact of the 1811–1812 New Madrid earthquakes on the people, topography, and the river in the New Madrid area.

The most detailed first-hand description of an earthquake-induced waterfall probably is that of Captain Mathias Speed. Speed recounted that as his two boats passed through the channel formed by Island Number 10,

> we were affrightened with the appearance of a dreadful rapid of falls in the river just below us; we were so far in the suck that it was impossible now to land—all hope of surviving was [sic] now lost and certain destruction appeared to await us! We . . . passed the rapids without injury, keeping our bow foremost, both boats being still lashed together. [Philadelphia Pennsylvania Gazette, March 18, 1812]

Unfortunately, the historical narratives of other earthquake-induced waterfalls are from anonymous second- or third-hand accounts. For example, a letter printed in the Bardstown Repository (no date) and referenced as “A Citizen of Kentucky” talks of “very dangerous falls . . . both above and below New Madrid.” Flint (1826) mentioned “A bursting of the earth just below the village of New Madrid, arrested the mighty stream in its course.” Alphonso Wetmore (1837), describing the fate of flatboats known to have cast off from their moorage at New Madrid following the first shock of the February 7, 1812, earthquake, noted that

> The current of the Mississippi . . . was driven back upon its source with the greatest velocity for several hours, in consequence of an elevation of its bed. But the noble river was not thus to be stayed in its course. Its waters came booming on, and over topped the barrier thus suddenly raised, carried everything before them with resistless power. Boats, then floating on its surface, shot down the declivity like an arrow from a bow, amid roaring billows and the wildest commotion.

After thorough examination of all of the narratives, Penick (1976) determined that the February 7, 1812, earthquake created waterfalls near Island Number 10 (Fig. 3) as well as falls approximately 0.7 km and 13 km downriver from New Madrid.

The exact location, size, and number of the temporary, earthquake-induced waterfalls will probably always be subject to debate (Flint, 1826; Hildreth, 1844; Dow, 1848; Lloyd, 1856; Owen, 1856; Lesieur, 1888; Fuller, 1912; Penick, 1976; Johnston, 1982; Russ, 1982; Shedlock et al., 1988; Shedlock, 1993; Fisher and Schumm, 1995). Herein, however, we add interpretations from seismic-reflection data to documented surficial deformation derived from geomorphic studies (trenching, coring, and leveling) and historical accounts and infer that notable riverbed deformation (waterfalls) occurred in at least three places as a result of the February 7, 1812 earthquake. These waterfall sites are located approximately 1 km and 12 km downriver and approximately 14 km upriver from the original New Madrid town site (Fig. 3).

INSTRUMENTALLY RECORDED SEISMICITY

Earthquakes recorded since 1974 in the New Madrid seismic zone define northeast- and northwest-trending fault zones (Fig. 1). Focal mechanisms of earthquakes in the axial (N45°E) and northeasterly (N35°E) trends of epicenters are primarily strike slip (Herrmann and Canas, 1978; Herrmann, 1979; Himes et al., 1988). A microearthquake study near Ridgely, Tennessee, shows that most of the earthquakes in the southern end of the transverse stepover zone (N25°W) of epicenters occur on a southwest-dipping, northwest-striking, reverse fault (Nicholson et al., 1984). Other studies have indicated a mix of strike-slip, normal, and reverse faulting in the transverse zone (Andrews et al., 1985).

The most comprehensive published study of microseismicity in the New Madrid seismic zone located more than 700 earthquakes between late 1989 and late 1991 (Chiu et al., 1992). These results corroborated earlier findings of strike-slip faulting in the axial and northeast trends of epicenters. However, Chiu et al. (1992) determined that hypocenters in the transverse trend defined two southwest-dipping planes, the updip projections of which intersect or are near the eastern boundary of the Lake County uplift. They suggested that these two differently dipping planes (48°SW south of the intersection of the axial and transverse trends and 31° SW north of this intersection; Fig. 4) represented segmentation of an active fault. The dips Chiu et al. (1992) determined for these two faults are averages of the dips determined for multiple depth sections across each segment. We note here that the possible dip angles on the northern segment differed by as much as 20°. In particular, dip along the northwest segment of the transverse trend of seismicity is deepest at the northern end and shallows to the south.

There are observable density changes in seismicity and directional changes in the seismicity pattern within the northwest-trending alignment of epicenters (Fig. 1). Arrows X and Y (Fig. 4) bracket an area of lower seismic activity (lower density of epicenters) in the transverse trend. The X arrow roughly coincides with the gap between the southwest-trending Ridgely Ridge and the north-northwest–trending Tiptonville dome and the Y arrow projects along the northwest boundary of the Tiptonville dome (Fig. 4). Therefore, the area bracketed by arrows X and Y roughly correlates with the Tiptonville dome–Reelfoot scarp topographic high area where deformation related to the 1811–1812 events has been documented (Fuller, 1912; Russ, 1979, 1982; Kelson et al., 1992, 1994, 1996; Van Arsdale et al., 1994, 1995). The apparent changes in density between arrows X and Y suggest a change in lithologic composition, stress, or crustal structure in this segment of the seismogenic zone with respect to the rest of the transverse trend of epicenters. Arrow Y also points to a trend change in the seismicity pattern, from a northwest (below arrow Y, Fig. 4) to a more westerly alignment of epicenters (above arrow Y).

SEISMIC REFLECTION DATA

A number of high-resolution seismic reflection lines have been acquired in and adjacent to the Lake County uplift to define the subsurface geologic structure in the upper Mississippi Embayment (Fig. 2). Vibrosies lines (dotted on Fig. 2) were acquired in 1977, 1978, and 1979 and were generally described by Hamilton and Zoback (1982). Vibrosies lines S-10 (Fig. 2) and those that crossed the Cottenwood Grove and Ridgely faults southwest of Reelfoot Lake have been reprocessed and reinterpreted by the authors (Stephenson, 1995; and this paper). Shedlock et al. (1997) processed and interpreted 240 km of high resolution marine seismic data, acquired along the Mississippi River from Osceola, Arkansas, to Wickliffe, Kentucky, in 1981 (dashed line in Fig. 2); these data are being released as a CD-ROM. The section of these data included in this paper is published here for the first time. The Mini-Sosie high-resolution seismic reflection lines (black heavy lines in Fig. 2) were acquired by the authors during site specific surveys from 1990 to 1997. The majority of these lines (Fig. 2) have been published in previous reports by the authors (Odum et al., 1994, 1995; Stephenson et al., 1995). Line WTF, acquired by us in 1994, is newly released with this paper.

Within the Lake County uplift, maximum post-Paleozoic uplift is interpreted from seismic reflection data to be approximately 40 m beneath the Tiptonville dome (Crone and Brockman, 1982). The seismic-reflection data in this area show low structural relief (at most 40 m in the upper kilometer) with numerous undulations on the reflector surfaces that are in places difficult to correlate between nearby lines (Odum et al., 1994, 1995; Stephenson et al., 1995). In places these undulations appear to be the result of erosional and depositional processes, but in many cases they clearly are the result of tectonic deformation. Seismic-reflection data have proven effective for delineating structures such as the Cottonwood Grove, Ridgely, and unnamed (F1, Fig. 5) faults south of Reelfoot Lake (Zoback et al., 1980; Hamilton and Zoback, 1982; Shedlock and Harding, 1982; Stephenson et al., 1995) and fault(s) associated with the Reelfoot scarp and other structures north of Reelfoot Lake (Zoback, 1979; Sexton and Jones, 1986; Shedlock et al., 1988; Shedlock, 1993; Woolery et al., 1993, 1996).

High-resolution seismic-reflection profiles have also effectively imaged the Reelfoot fault (Fig. 6). A section of seismic data acquired on the Mississippi River (Fig. 7A) images approximately 40 m of apparent vertical displacement on the Paleozoic (P_z) and Cretaceous (K) reflectors across the Reelfoot fault. The Reelfoot fault is also imaged on the southwest end of Mini-Sosie seismic reflection profile WTF (Fig. 7B), acquired about 7 km south of, and roughly parallel, to the profile on the river (Fig. 6). The up-dip projection of the Reelfoot fault, inferred to be a southwest-dipping thrust fault, underlies an interpreted fault propagation fold, the Reelfoot scarp (Fig. 3) (Hamilton and Zoback, 1982; Sexton et al., 1982; Odum et al., 1994; Kelson et al., 1992, 1994; Van Arsdale et al., 1994, 1995; Woolery et al., 1996).

We interpret seismic-reflection profile S-10 (Figs. 2 and 5) to show two faults, which are characterized by disruption and abrupt vertical changes of Paleozoic, Cretaceous, and younger Tertiary reflectors (Fig. 8). On the basis of similar patterns of disrupted reflectors imaged on sections of Mississippi River reflection data subparallel to and 2 km northeast (Fig. 2) of profile S-10, we identified two steep-to-vertical, parallel-to-subparallel, northeast-trending faults across the Lake County uplift area (labeled F2 and F3, Fig. 5).

Fault F4 (Fig. 5) is imaged by both Mini-Sosie data (Odum et al., 1995) and airgun data collected along the Mississippi River. The southwest projection of this fault coincides with an interpreted splay (Shedlock et al., 1996) of the Bootheel lineament (Marple, 1989; Odum et al., 1995). Fault F5 is apparent on Vibroseis (Hamilton and Zoback, 1982), Mini-Sosie data (Odum et al., 1994, 1995), and airgun data (Shedlock et al., 1996, 1997).

We interpret a fault structure with about 20 m of apparent west-side-down displacement across the Cretaceous-Tertiary unconformity on the northeast end of the Mini-Sosie seismic reflection profile shown in Figure 7B (line drawing box II in Fig. 6). This fault zone is located about 4 km northeast of the Reelfoot scarp. We interpret a similar fault on the northeast end of the seismic-reflection profile shown in Figure 7A. On the basis of these seismic-reflection data, we interpret a north-south–trending, approximately 0.5–0.75-km-wide fault zone, herein named the New Markham fault (Fig. 5) after the nearby town of New Markham, Tennessee. The New Markham fault appears to have been active into the Quaternary Period, on the basis of reflection washout to the surface in Figure 7B and the deformed Quaternary reflectors in Figure 7A.

The faults interpreted from the seismic reflection data are consistent with a north-northwest–trending thrust fault or high-angle reverse fault in the center of the Lake County uplift, and several northeast-trending, right-lateral strike-slip faults at the southeast and central portion of the uplift.

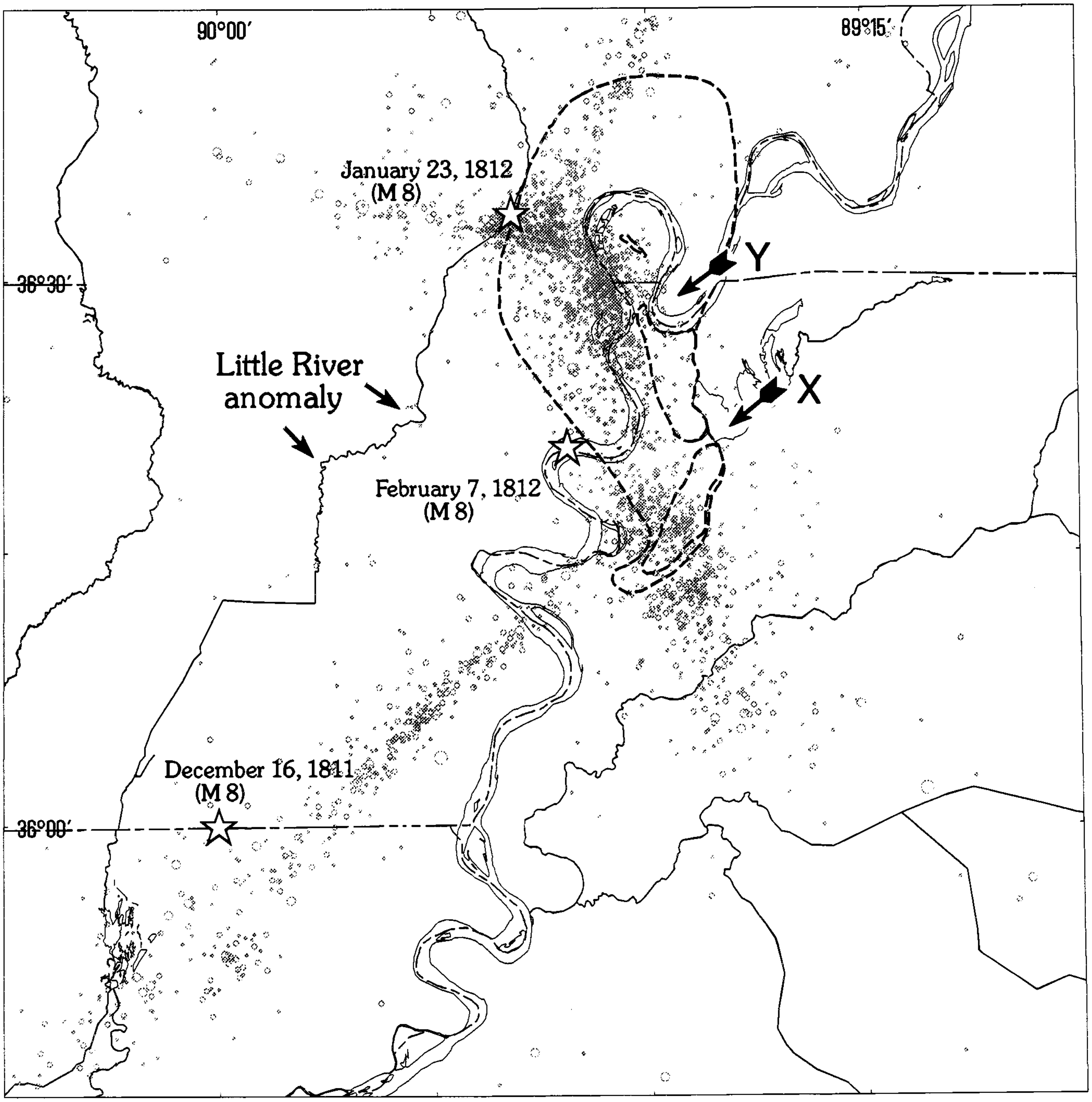


Figure 4. Regional map showing the outline of the Lake County uplift and epicenters within the New Madrid seismic zone. Circles indicate epicenters of earthquakes with M > 1.5, recorded between 1974 and 1991 (Taylor et al., 1991). The X and Y arrows bracket an area of lower epicenter density, which also correlates with the Tiptonville dome-Reelfoot scarp region documented to have undergone deformation related to the 1811–1812 events. Northwest of arrow Y, Chiu et al. (1992) found a 30° to 43° SW dipping plane of hypocenters. Between arrows X and Y, the dip shallows to as little as 20°SW. Southeast of arrow X, the dip steepens to an average of 48°SW.

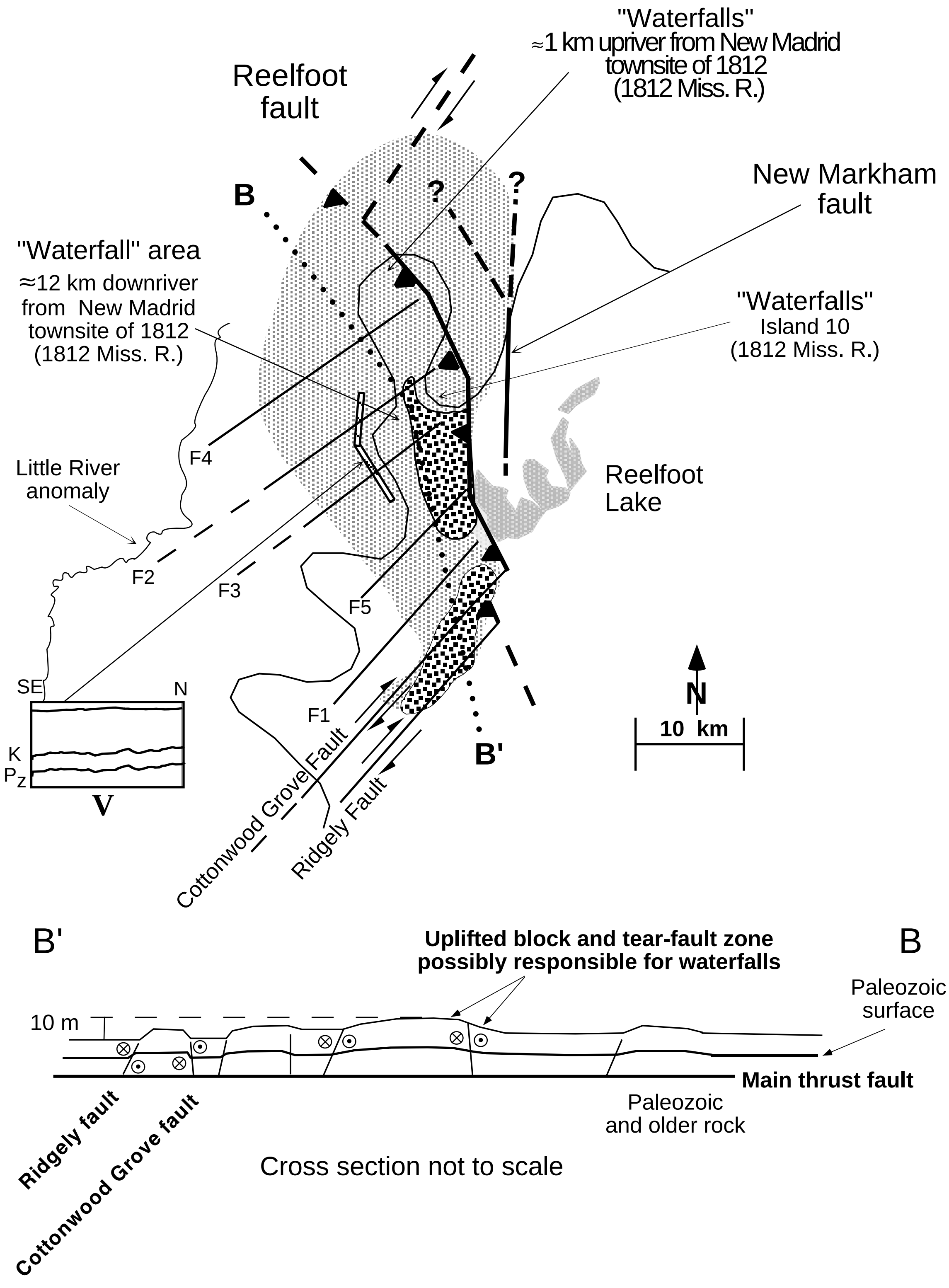


Figure 5. Schematic of the Reelfoot thrust fault (sheet) showing the inferred locations of the northeast-trending tear faults that act to partition the hanging wall of the thrust fault into parallel to subparallel blocks. Lines denoted F1 to F5 are faults. F1 is the unnamed fault delineated by Hamilton and Zoback (1982). F2 and F3 are determined by Vibroseis and airgun seismic reflection data. F4 is based on Mini-Sosie and airgun seismic reflection data. F5 is imaged by Vibroseis and Mini-Sosie seismic reflection data. The Cottonwood Grove and F1 faults lie within the Blytheville fault zone (Johnston and Schweig, 1996). Cross section B–B′ portrays the interaction between parallel to subparallel blocks.

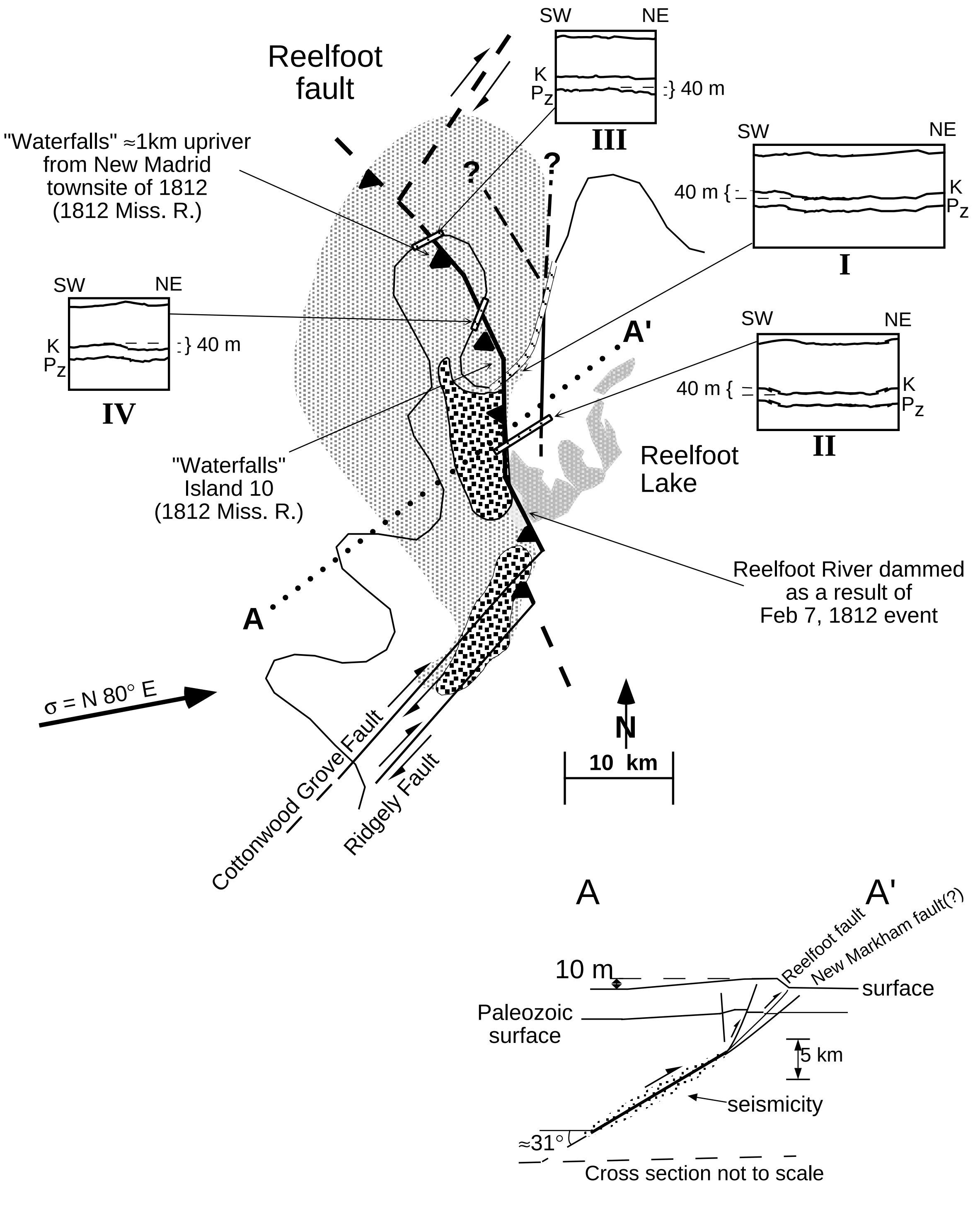
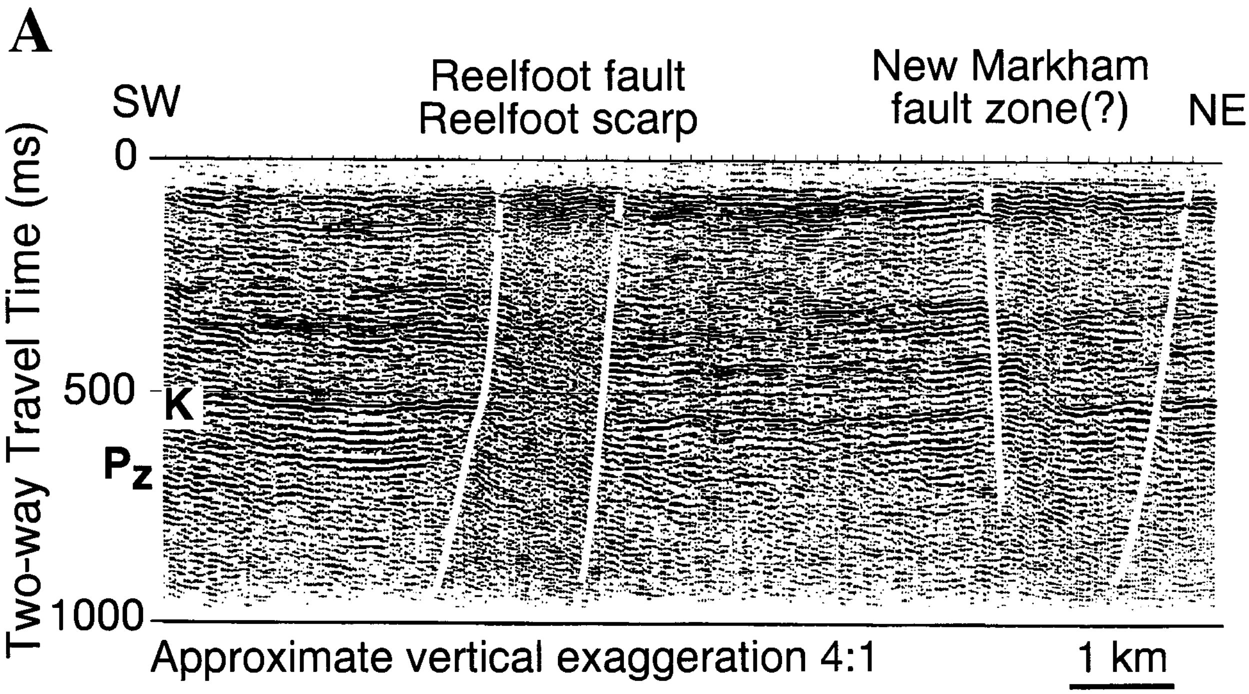


Figure 6. Major tectonic features of the Lake County uplift (LCU) area showing the inferred trace of the southwest-dipping Reelfoot thrust fault. Boxes I–IV are line drawings of seismic reflection data used to constrain trace of the Reelfoot thrust fault. Boxes I, III, and IV are based on data acquired along the Mississippi River (Shedlock et al., 1998); box II is based on Mini-Sosie data collected by the U.S. Geological Survey during 1994. Inferred waterfall locations are plotted with respect to the 1811–1812 Mississippi River course (see Figure 3). Cross section A–A′ depicts near-surface splaying of the thrust fault. The orientation of the current near east-west (N80°E) regional compressive stress field is from Zoback (1982). P_z—Paleozoic, K—Cretaceous.



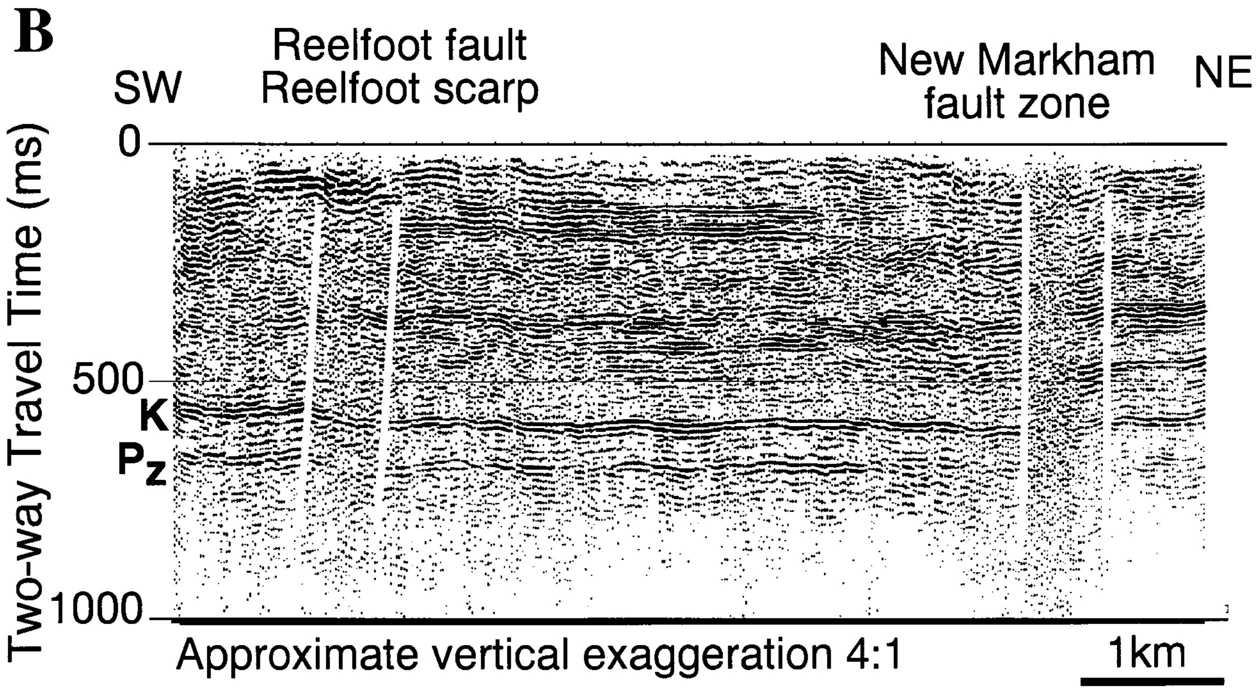


Figure 7. (A) Portion of Mississippi River seismic reflection line (Shedlock et al., 1997). These data, collected along the river in the vicinity of the Tiptonville dome (Box I, Fig. 6), image the Reelfoot fault and the newly identified "New Markham" fault. (B) U.S. Geological Survey Mini-Sosie line subparallel to and approximately 7 km south of the river data shown in A (box II, Fig. 6). Profile images the Reelfoot fault and the New Markham fault, which displays approximately 25 m of east-side-up displacement. Reflector (P_z) represents the Paleozoic-Cretaceous unconformity and reflector (K) represents the Cretaceous-Tertiary unconformity.

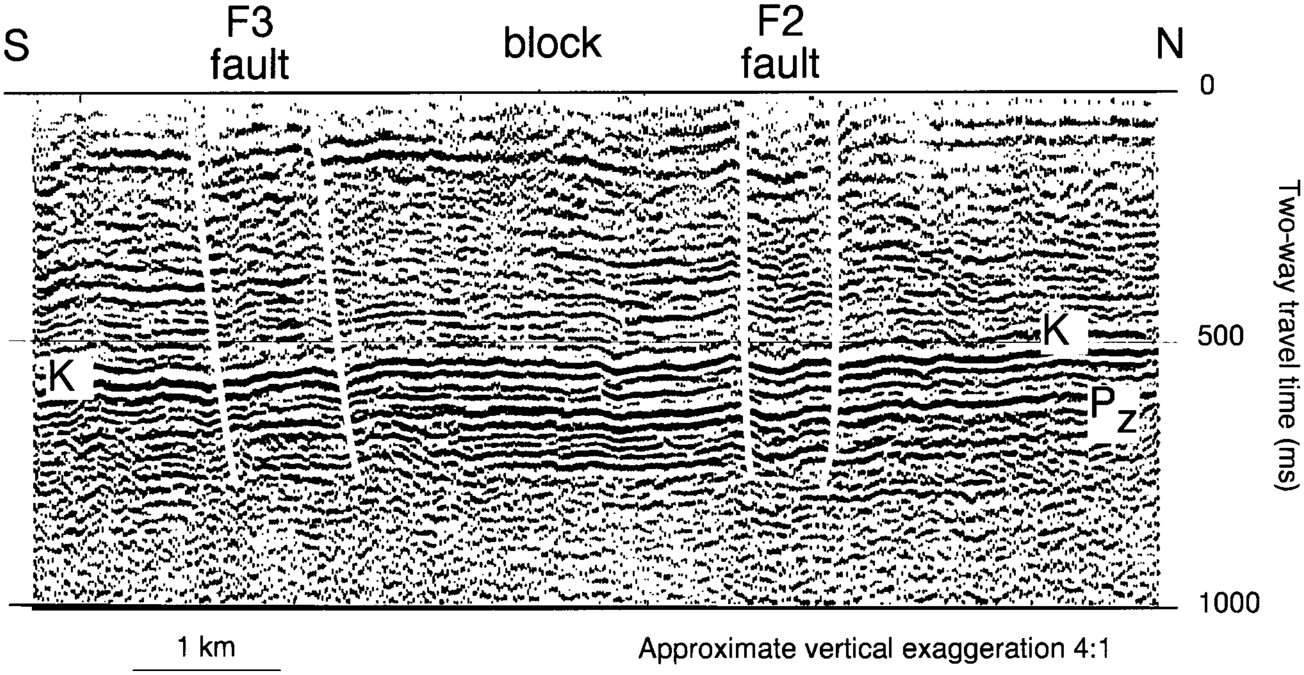


Figure 8. Vibroseis seismic reflection profile S-10 (Hamilton and Zoback, 1982), acquired south of 36.5°N on the west side of the Mississippi River (Figs. 2 and 3). Data are reinterpreted to show two fault zones. Reflector (P_z) represents the Paleozoic-Cretaceous unconformity; reflector K represents the Cretaceous-Tertiary unconformity.

TECTONIC MODEL FOR NEW MADRID AREA DEFORMATION

On the basis of the pattern and timing of the surficial deformation observed within the Lake County uplift, the historical accounts of waterfall locations, the geology and geomorphology of the region, and the structural features identified from seismic reflection data, we describe the tectonics beneath the Lake County uplift and the New Madrid area. We infer that the major deformation within the New Madrid seismic zone stepover consists of two primary components; a north-northwest trending thrust fault (the Reelfoot fault), and a series of northeast-trending faults that partition the hanging wall of the thrust fault into subparallel blocks.

Reelfoot Thrust Fault

We suggest that the Reelfoot fault trace is at least 30 km long, extending from south of Reelfoot Lake (Purser et al., 1996) to the Mississippi River in the vicinity of New Madrid, Missouri (note deformation on box III, Fig. 6), thus nearly tripling its originally mapped length of 11 km. This inferred extension of the Reelfoot fault trace to the north-northwest is based on faults interpreted from seismic reflection data (line drawing boxes I through IV in Fig. 6). This inferred trace of the Reelfoot fault intersects the 1811–1812 Mississippi River course at historically reported locations of earthquake-induced waterfalls about 1 km downriver from the old New Madrid town site and in the Island No. 10 area (Figs. 3 and 6). Van Arsdale et al. (1994, 1995) independently corroborated this extension of the Reelfoot fault by showing that the east side of Washpan Ridge is a Reelfoot scarp-type flexure of tectonic origin. In addition, evidence of a tectonic scarp on the north side of the modern Mississippi River suggests the continuation of the thrust fault trace into the Lewis Prairie area, west of New Madrid, Missouri (Fig. 3) (Van Arsdale et al., 1994, 1995).

Northeast-Trending Partitioning Faults

The structural architecture surrounding the Mississippi Embayment exhibits major northeast-trending right-lateral strike-slip faulting and north-to-northeast secondary deformation, documented by mapping of bedrock exposures (Clendenin et al., 1993; Harrison and Schulz, 1994), high-resolution aeromagnetic and gravity data (Hildenbrand and Hendricks, 1995), and seismicity (Nicholson et al., 1984). On the basis of seismic reflection data (Hamilton and Zoback, 1982; Stephenson et al., 1995), the Cottonwood Grove and Ridgely faults are interpreted to be vertical, northeast-trending faults that locally exhibit right-lateral movement with a small component of oblique motion. These northeast-trending faults at the southern end of the Lake County uplift, including fault F1 (Fig. 5), are apparently part of a zone of near-vertical faults that project along the southwest trend of the modern New Madrid seismic zone (the Blytheville fault zone of Johnston and Schweig, 1995). Ridgely Ridge, the southernmost topographic high within the Lake Country uplift, is interpreted to be an uplifted block (horst) between the Cottonwood Grove and Ridgely faults (Hamilton and Zoback, 1982; Nicholson et al., 1984; Stephenson et al., 1995). We interpret faults F2, F3, F4, and F5 (Fig. 5) to be near-vertical, northeast-trending, strike-slip faults having some oblique slip. We infer that these northeast-trending faults are tear faults that have acted in the near surface to partition the hanging wall of the low-angle Reelfoot thrust fault into subparallel blocks that have undergone differential, but predominantly horizontal, displacement during episodes of faulting (cross section B–B′, Fig. 5).

The differential displacement between adjacent blocks is exemplified by the distribution of surficial deformation credited to the 1811–1812 events. For example, Ridgely Ridge underwent no documented uplift, even though the southeast lobe of the Tiptonville dome, just 3 km north of Ridgely Ridge, underwent at least 0.5 m of uplift (Stearns, 1979; Russ, 1982; Kelson et al., 1994). This additional uplift of the southeastern lobe of the

Tiptonville dome–Reelfoot scarp, accompanied by suspected subsidence to the east of the scarp, is theorized to be responsible for the formation of Reelfoot Lake following the February 7, 1812, earthquake (Fuller, 1912; Stearns, 1979; Russ, 1982; Stahle et al., 1992). The Cottonwood Grove fault and/or fault F1 just to the northwest (Fig. 5), may have acted to decouple or isolate the Ridgely Ridge block from the northeast-moving Tiptonville dome block(s). In addition, we believe that the 1812 earthquake-induced waterfalls about 14 km upriver (Island No. 10 area) and about 1 km downriver from the old New Madrid town site were the result of Mississippi River blockage (Reelfoot scarp–Washpan Ridge flexure) and riverbed deformation (fissuring, liquefaction, and sand blows) caused in part by the northeast thrusting of the Reelfoot fault and possible surface accommodation along fault F3.

The waterfalls located approximately 12 km down river from the old New Madrid town site (Fig. 3) may have been caused in part by riverbed uplift associated with the northeast-trending thrust movement of the Reelfoot fault and, in part, by riverbed deformation related to tear faults F2 and F3 (Fig. 5). Russ (1982) also concluded that surficial uplift and riverbed disruption occurred in the waterfall area approximately 12 km down river from the old New Madrid town site. Russ (1982) and Fischer and Schumm (1995) identified an anomalous steepening of the natural levee gradient along an 11-km-long section of the modern Mississippi River beginning at a point approximately 7 km down river from the old town of New Madrid. Russ (1982) attributed the steepened gradient to tectonic deformation associated with the uplift of the Tiptonville dome and noted that historical accounts mentioned an earthquake-induced waterfall within this area. On the basis of the direction of slope change and restricted length of the anomaly, Russ (1982) calculated that as much as 2 m of surficial uplift was possible. The suggestion that the Mississippi River has yet to reach hydraulic equilibrium through this section, as evidenced by an anomalously convex-upward low-water reference plane profile, suggests continued and/or recent uplift and deformation (Russ, 1982; Fischer and Schumm, 1995).

Further evidence that documents the timing of movement on the aforementioned Tiptonville block area is found in historical narratives. Prior to the 1811–1812 earthquakes, cargo-laden keelboats traveled from the Mississippi River past the town of Portageville, to the Little River by way of the Portage Bayou (Fig. 3) (Broadhead, 1902). Passage through this natural channel was impossible following the earthquakes because uplift on the western margin of the Tiptonville dome apparently caused the channel to drain (Broadhead, 1902; Penick, 1976).

The Little River (Fig. 3) flows southward past New Madrid, Missouri, in a meander belt channel that is 1.6 to 2.4 km wide; near Portageville, Missouri (Fig. 3), the river course abruptly deflects to a N40°–50°E trend, occupies a 0.4 km meander belt channel for a distance of 10 km, then turns due south in a 4.0-km-wide meander belt channel (Fischer and Schumm, 1995). Regional maps by Ross (1765) document that this anomalous river trend existed prior to the 1811–1812 earthquakes. We note that the orientation of the aforementioned section of the Little River aligns with the locations of two of the 1812 waterfalls (Fig. 3) and interpreted fault F2 (Fig. 5). Thus, we speculate that the river course deflection and change in meander belt width may be structurally controlled by block uplift associated with movement of northeast-trending faults.

The instrumentally recorded seismicity in the New Madrid seismic zone also provides evidence of northeast-trending tear faults. The observable density changes in seismicity and directional changes in the seismicity pattern within the northwest-trending alignment of epicenters also are parallel to or coincident with geomorphic and/or seismic-reflection evidence of subsurface faulting.

Arrow X (Fig. 4), which separates the more shallowly dipping (31°SW) buried thrust fault from the more steeply dipping (48°SW) fault to the southeast (Chiu et al., 1992), aligns with the axial trend of seismicity and the Blytheville fault zone. Arrow Y projects along the trend of tear fault F2 and the trace of the Little River anomaly (Fig. 4). Fault F3 is within the area of decreased seismicity between arrows X and Y, but separates the more seismically active northwestern third of this area from the least active southeastern portion (Fig. 4). Thus, a series of northeast-trending faults may separate the Reelfoot thrust fault into segments that exhibit different rates of present-day seismicity.

We offer two possible explanations for the decrease in epicentral density between fault F2 and faults in the Blytheville fault zone (Fig. 4). Recent deformation involving the northeast movement of block(s) beneath the central part of the Lake County uplift, including the 1811–1812 earthquake sequence, may have reduced stresses along this segment of the partitioned thrust fault, resulting in a lower level of current seismicity. Alternately, the seismicity density decrease may correspond to a locked segment of the thrust fault that releases only after significant stress builds up. Given the higher concentration of contemporary seismicity throughout the rest of the New Madrid seismic zone, the latter explanation is more likely.

New Markham Fault

The Reelfoot fault imaged in the shallow subsurface beneath the Reelfoot scarp and Washpan Ridge flexures lies to the west of the up-dip projection of the northeast-trending thrust fault defined by hypocenters in the transverse stepover segment of the modern New Madrid seismic zone (cross section A–A′, Fig. 6) (Chiu et al., 1992). The linear surface projection of this approximately 31° southwest-dipping thrust fault coincides with the location of the New Markham fault trace (cross section A–A′, Fig. 6). Lack of observable surface expression on the New Markham fault, such as a west-facing scarp, suggests that this fault may have (1) accommodated predominantly pre-Holocene vertical deformation; (2) surface deformation in the form of subtle downwarping; and/or (3) had its surface expression obliterated by Mississippi River erosion. We interpret the New Markham fault to be oriented north-south, with down-to-the-west displacement. The relation of the New Markham fault to deeper structures, including the Reelfoot fault, is unclear. It is possible that the New Markham fault is part of a larger thrust sheet, and its trace may bend to the northwest (Fig. 6). Alternately, the New Markham fault may be an older structure that has been reactivated by motion on the thrust fault.

SUMMARY

By integrating geomorphic evidence, historical narratives, and reinterpretation of existing and newly acquired seismic-reflection data, we have developed a tectonic model that is consistent with surficial deformation associated with the February 7, 1812, New Madrid earthquake. The deformation is explained by differential movement within the hanging wall of the shallowing Reelfoot thrust fault. We infer that northeast-trending tear faults have acted in the near surface to partition the hanging wall of the southwest-dipping thrust fault into subparallel blocks that have undergone differential displacement during episodes of Holocene, and possibly older, faulting (cross section B–B′, Fig. 5). Furthermore, differential northeast-directed movement of shallow thrust block(s) resulted in surficial uplift (Tiptonville dome–Reelfoot scarp and Washpan Ridge), riverbed blockage and deformation at locations that are coincident with the historical accounts of waterfalls approximately 1 km downriver and 14 km upriver from the old town site of New Madrid, Missouri. Additionally, we infer that the movement of the same block(s) that resulted in the approximately 0.5 m of uplift on the northern lobe of the Tiptonville dome–Reelfoot scarp area caused uplift and riverbed deformation (fissuring, liquefaction, and sand blow geysers) in the area of historically reported waterfalls approximately 12 km downriver from the old town site of New Madrid, Missouri.

Our partitioned Reelfoot thrust fault is consistent with all of the features associated with the 1811–1812 earthquake sequence, with faults identified in seismic-reflection data, with the topography of the Lake County uplift (including the underlying left-stepping, right-lateral, strike-slip faults (Gomberg and Ellis, 1994), and with regional seismicity patterns. We speculate that some of the northeast-trending tear faults in our model could be as long as 40 km, are deep seated, may define the most recently active margins of the thrust fault, and are structurally related to changes in the seismicity pattern within the New Madrid seismic zone (Fig. 4).

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