7

The New Madrid seismic zone of the Central United States

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Abstract

The central Mississippi River valley, within which the New Madrid seismic zone (NMSZ) lies, has undergone a history of Precambrian microplate accretion, Late Proterozoic Grenville orogenesis, Cambrian Reelfoot rifting, Late Paleozoic Ouachita/Appalachian orogenesis, Cretaceous passage above the Bermuda hotspot, and modest Cenozoic compression. Reelfoot Rift consists of northwest-striking Proterozoic and the northeast-striking Cambrian faults, which have undergone Neogene transpressive displacement that is apparently driven by the N60 °E to N80 °E S_{Hmax} of eastern North America. NMSZ earthquakes are occurring along five reactivated Reelfoot Rift faults, three of which are transpressive right-lateral strike-slip faults and two are reverse faults associated with compressional stepovers between the strike-slip faults. A number of models have been proposed for the NMSZ, but the model that best explains the Holocene onset of the seismic zone is the Mississippi River valley denudation model. In this model, Late Wisconsin entrenchment of the Mississippi River reduced the vertical stress, which reduced the normal stress across the Reelfoot Rift strike-slip faults and allowed them to slip. Quaternary displacement is not restricted to the NMSZ faults and occurs on many of the Reelfoot Rift and its outboard faults requiring an explanation for Quaternary faulting that encompasses a much larger area than the NMSZ. The denudation model appears to explain the wide distribution of low-displacement Quaternary faulting in the lower Mississippi River valley.

7.1 Introduction

The New Madrid seismic zone (NMSZ) is located in the central Mississippi River valley within the states of Missouri, Tennessee, and Arkansas (Figure 7.1) and is the most active

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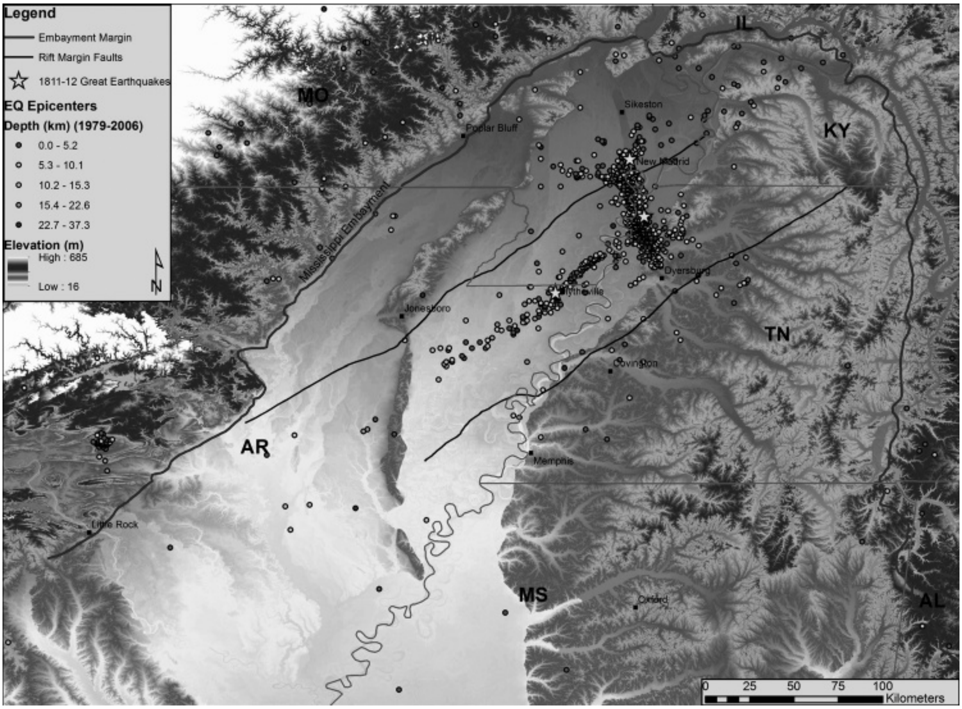

Figure 7.1 Small earthquakes recorded between 1979 and 2006 in the New Madrid seismic zone are illustrated in colored dots with the three largest 1811–1812 earthquakes marked with gold stars. Southern star, December 16, 1811; northern star, January 23, 1812; and central star, February 7, 1812. The earthquakes primarily occur within the underlying Reelfoot Rift, which is bound by the black lines (from Csontos *et al.*, 2008). For color version, see Plates section.

seismic zone of the Eastern United States. Microseismic activity (Chiu *et al.*, 1992; Mueller and Pujol, 2001) is occurring along reactivated basement faults within the Reelfoot Rift: a Cambrian aulacogen (Hildenbrand, 1985; Hildenbrand and Hendricks, 1995) (Figure 7.2). Although contemporary seismicity rarely exceeds **M** (moment magnitude) 4.0, the NMSZ has generated very large earthquakes; most recently during 1811–1812 when a minimum of four earthquakes (Hamilton and Johnston, 1990), estimated to have been in the mid **M** 7 range (Nuttli, 1973; Gomberg, 1993; Hough *et al.*, 2000; Mueller and Pujol, 2001; Hough and Page, 2011), occurred over a three-month period. The threat of this seismic zone to the United States has prompted numerous studies and expensive retrofitting, an example of which is the 276 million dollar retrofit of the Interstate 40 Bridge across the Mississippi River at Memphis. Debates continue as to the hazard posed by future New Madrid earthquakes (Stein, 2010). Many scientists argue that the late Holocene 500-year recurrence interval determined from NMSZ paleoseismic studies implies continuing hazard, whereas some of those studying GPS data argue that there is not enough strain currently accumulating to produce a very large earthquake in the near future. In this chapter I summarize the geological history of the NMSZ and its earthquakes.

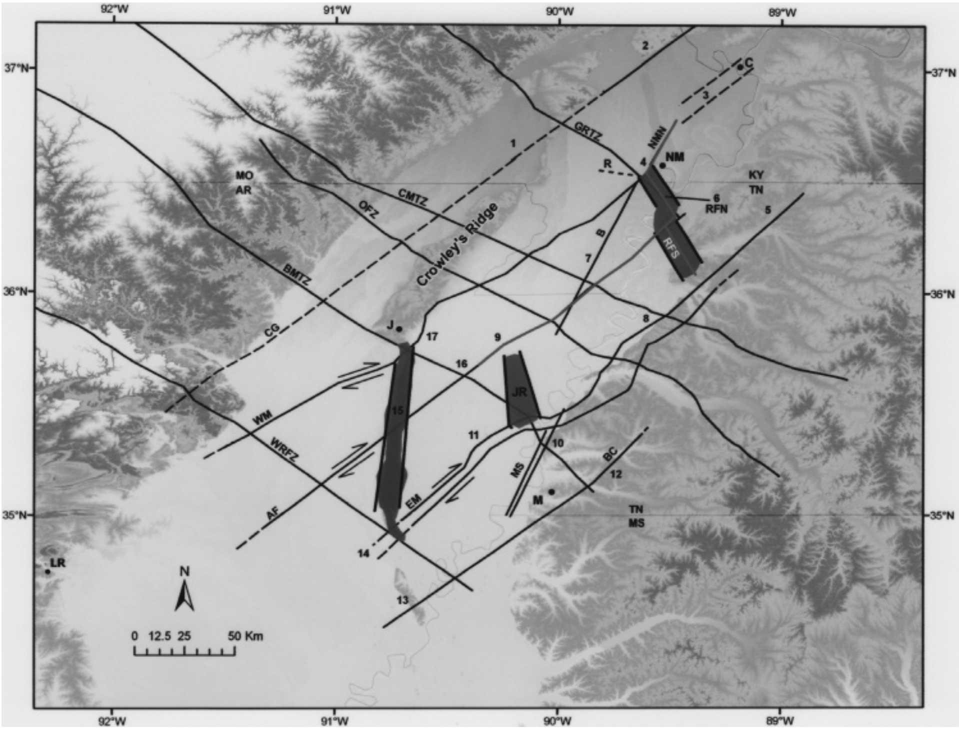

Figure 7.2 Reelfoot Rift faults and numbered locations of documented Quaternary faulting and liquefaction (from Van Arsdale and Cupples, 2013). Numbers correspond to numbers in Table 7.1. Right-lateral shear across the Reelfoot Rift is responsible for the New Madrid seismic zone earthquakes, which occur along the Axial (northeast of number 16), Reelfoot South, and Reelfoot North faults. Quaternary right-lateral shear on the rift faults is also causing uplift of the Lake County uplift/Reelfoot North fault (RFN), Joiner Ridge (JR), Charleston Uplift, the southern portion of Crowley's Ridge, and possibly the Meeman-Shelby fault. 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 (Cottonwood Grove 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, Tennessee; LR, Little Rock, Arkansas; NM, New Madrid, Missouri; C, Cairo, Illinois.

7.2 Geological history of the New Madrid seismic zone region

7.2.1 Precambrian

The NMSZ earthquakes are occurring beneath the flood plain of the central Mississippi River valley. To more fully understand this area it is instructive to review the regional geology and its history.

The Earth's crust beneath the Mississippi River valley has an average thickness of 42 km (Grollimund and Zoback, 2001). P-wave velocities and densities beneath the central valley reveal ~6 km of Mississippi Embayment sediments and Reelfoot rift-fill strata overlying basement (Ginzburg *et al*., 1983). Precambrian igneous and metamorphic rocks (6.2 km/s, 2.74 g/cm^3) of the upper crust extend from 6 to 17 km in depth. The lower crust varies in thickness and extends to depths of 39–46 km. Composition of the lower crust is speculative, but it is interpreted to be crystalline rocks of intermediate composition (6.6 km/s, 2.95 g/cm^3) (Stuart *et al*., 1997). The variable thickness of the lower crust is due to a rift pillow at the base of the lower crust (Mooney *et al*., 1983; Hildenbrand, 1985; Hildenbrand and Hendricks, 1995). Although not well constrained, the rift pillow rocks (7.3 km/s, 3.1 g/cm^3) are interpreted to be a quartz tholeiite intrusion or underplating that has been metamorphosed to garnet granulite. The pillow is proposed to have formed by mantle melt intrusions in the deep crust by a mantle plume during Cambrian rifting (Mooney *et al*., 1983; Hildenbrand, 1985; Pollitz *et al*., 2001), Appalachian orogeny (Hildenbrand and Hendricks, 1995), or during the Middle Cretaceous superplume event (Csontos, 2007). The top of the mantle (8 km/s, 3.3 g/cm^3) is at depths of 39–46 km.

Crustal rocks of the southeastern United States formed as a complex of microplates and island arcs that were accreted during the Archean and Proterozoic (Figure 7.3). The major geological events of these times were the formation of the Superior Province (3.5–2.7 Ga), Penokean Province (1.89–1.83 Ga), Yavapai Province (1.78–1.72 Ga), Mazatzal Province (1.65 Ga), Eastern Granite–Rhyolite Province (1.47 Ga), Southern Granite–Rhyolite Province (1.37 Ga), and Midcontinent Rift system (1.1 Ga), and these provinces are bordered on the east and south by the Grenville Province (1.2–1.0 Ga) (Atekwana, 1996; Van Schmus *et al*., 1996, 2007; Tollo *et al*., 2004; Holm *et al*., 2007; Van Arsdale, 2009). Rocks of the Yavapai and Mazatzal Provinces (Geon 16 and 17 terranes of Figure 7.3) have a southwesterly grain and consist of metasedimentary, metaigneous, and basalt–rhyolite volcanic suites that were subsequently intruded by anorogenic granitic rocks of the Southern and Eastern Granite–Rhyolite provinces. The Mazatzal Province is bound on the east by the Eastern Granite–Rhyolite Province (EGRP), and the EGRP is generally accepted to be the basement rock of the NMSZ region. Seismic reflection data indicate widespread sub-horizontal reflectors, suggesting an interlayered sequence of rhyolites, granites, and mafic igneous rocks and/or sedimentary rocks within the EGRP (Van Schmus *et al*., 1993). Gravity and magnetic data suggest that the Mazatzal Province rocks may continue beneath the EGRP (Atekwana, 1996), whereas isotopic data (Van Schmus *et al*., 2007) indicate that Precambrian rocks younger than 1.6 Ga lie below the EGRP southeast of the heavy dashed line in Figure 7.3.

The Grenville Province bounds the eastern and southern flanks of the EGRP (Figure 7.3). This province formed by the collision of the North America craton first with island arcs and then with a continent to the east that is now buried beneath the Appalachian Mountains or was carried away during the late Proterozoic and early Paleozoic opening of the Iapetus Ocean (Rankin *et al*., 1993; Atekwana, 1996; Bartholomew and Hatcher, 2010). The Grenville orogeny culminated in the formation of a huge mountain range comparable to the Himalayas of today and also in the formation of the supercontinent of Rodinia. The western boundary of the Grenville Province, the Grenville Front, has been

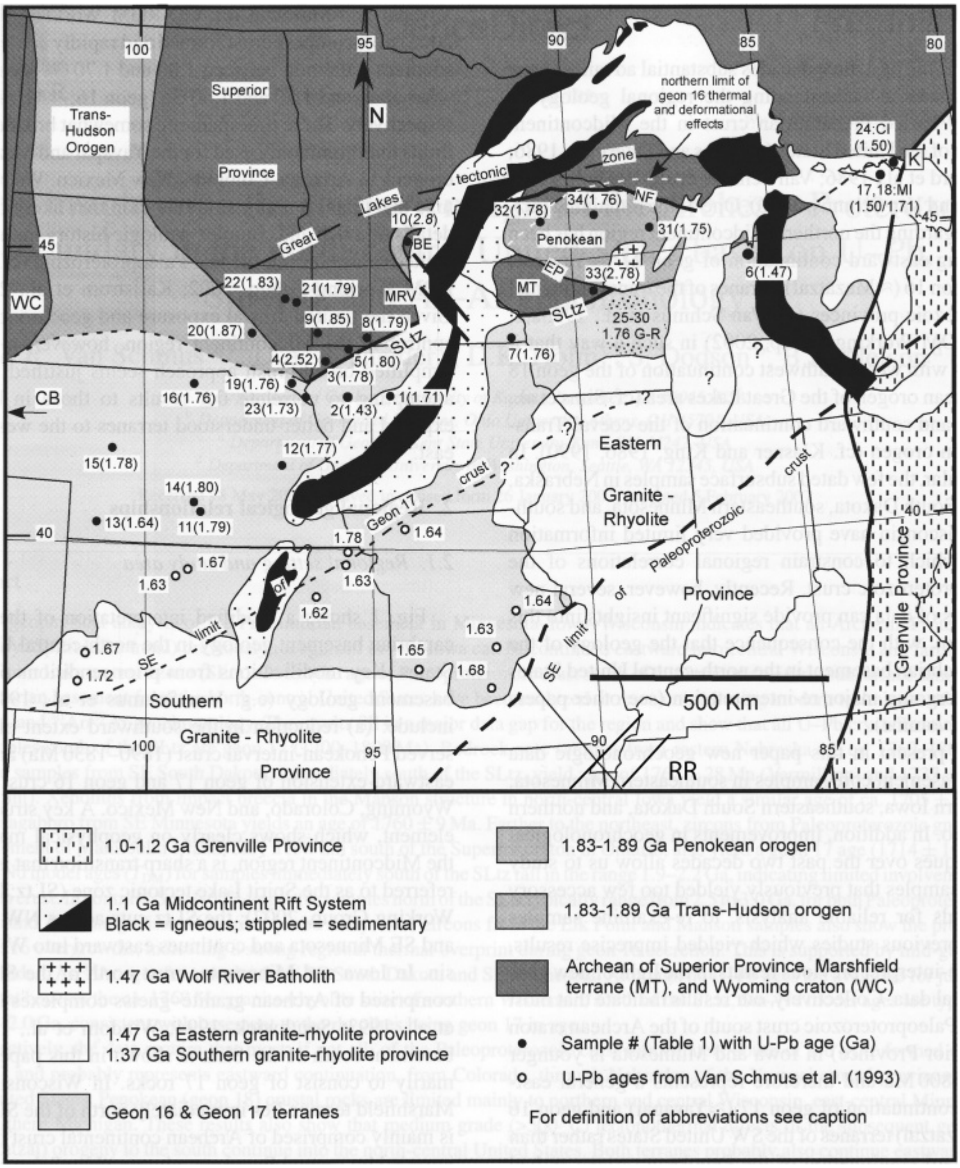

Figure 7.3 Precambrian geology of the northern Mississippi River valley (from Van Schmus *et al.*, 2007). BE, Becker Embayment; CB, Cheyenne Belt; CI, Croker Island complex; EP, Eau Pleine shear zone; G-R, granite-rhyolite province; K, Killarney magmatic complex; MI, Manitoulin Island; MRV, Minnesota River Valley terrane promontory; MT, Marshfield terrane; NF, Niagara Fault; SLtz, Spirit Lake tectonic zone; WC, Wyoming craton; RR, Reelfoot Rift.

traced primarily by gravity and magnetic data southerly through the United States, and the province's southwestern continuation has been mapped in Texas. However, it is not known where Grenville rocks exist beneath the southern United States, and in particular between southern Tennessee and its exposure in the Llano Uplift of central Texas, because there is insufficient drill-hole data in the southern United States. Culotta *et al*. (1990) have proposed that Grenville rocks underlie the NMSZ and Nelson and Zhang (1991) speculate that the western margin of the Grenville Front underlies and is responsible for the location of the Cambrian Reelfoot Rift. As the above survey of the literature indicates, the true nature of the Precambrian crust beneath the NMSZ is still an open question.

At the close of the Grenville orogeny, the Grenville Mountains extended along what is today the eastern seaboard and wrapped around the southern margin of the United States, just like the much younger 300 Ma old Appalachian–Ouachita Mountains (Van Arsdale, 2009; Bartholomew and Hatcher, 2010). Formation of the Grenville Mountains was the culmination of the collision of Laurentia (North America), Baltica (Europe), Amazonia (South America), and Kalahari (Africa) to form the supercontinent of Rodinia. Thus, during Rodinia time, the southeastern United States was a topographically high area located in the interior of Rodinia.

The Precambrian closed with the disassembly of Rodinia and the formation of a passive margin along the southern margin of the United States. More specifically, Thomas (1991, 1993) argues that the southern margin of the United States near the NMSZ area was formed by the Alabama–Oklahoma transform fault (Figure 7.4). If true, the continental shelf was sharply truncated, and immediately south of this transform fault (perhaps within as little as 25 km) was very deep water above an abyssal plain.

7.2.2 Paleozoic

Present-day NMSZ seismicity is occurring along reactivated faults of the Reelfoot Rift (Figures 7.1, 7.2, and Table 7.1). This rift formed during the Early or Middle Cambrian (520–500 Ma) as part of the Reelfoot Rift–Rough Creek graben–Rome Trough (Figure 7.4) in an abortive attempt to pull off a corner of Laurentia (United States) during the disassembly of Rodinia (Thomas, 1991). The southern end of the Reelfoot Rift was apparently the shelf edge at the Alabama–Oklahoma transform fault (Figure 7.4).

The Reelfoot Rift consists of fault-bounded blocks that were created by the intersection of Proterozoic (N$\sim$55°W) and Cambrian (N50°E) faults (Figure 7.2). North $\sim$55° west-trending faults that displace Paleozoic strata in southeastern Missouri (Anderson, 1979) and northeastern Arkansas (Haley *et al*., 1993) are interpreted to be reactivated faults of the Mazatzal terrane (Central Plains orogen) (McCracken, 1971). These reactivated Proterozoic faults (Cox, 1988) have been proposed to pass beneath the Mississippi River valley into western Tennessee (Figure 7.2) (Stark, 1997; Csontos *et al*., 2008). For example, the Grand River Tectonic Zone appears to continue beneath the Mississippi River valley as the Reelfoot fault (Csontos *et al*., 2008). During Cambrian rifting of Rodinia the N50°E-trending Reelfoot Rift formed and now underlies the Mississippi River valley in portions

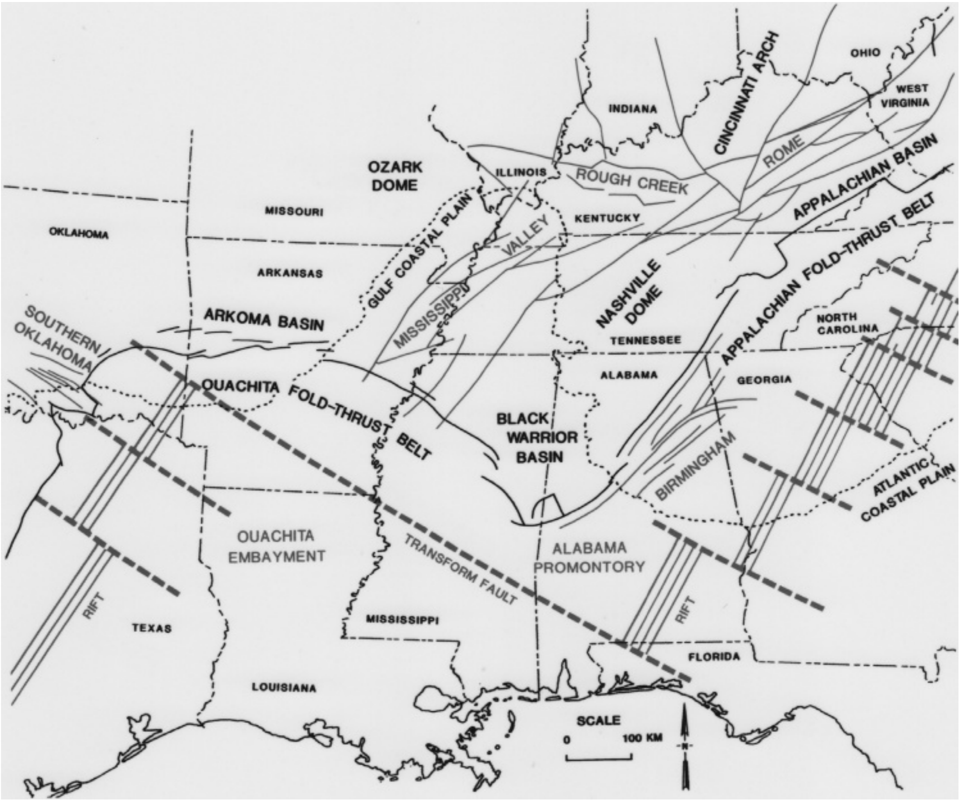

Figure 7.4 Late Precambrian–early Paleozoic transform faults (dashed lines), rifted continental margin (parallel straight lines), Cambrian basement fault systems (curved lines), and late Paleozoic orogenic belts and cratonic structures (modified from Thomas, 1988).

of Kentucky, Missouri, Arkansas, and Tennessee (Figure 7.4) (Erwin and McGinnis, 1975; Hildenbrand, 1985; Nelson and Zhang, 1991; Dart and Swolfs, 1998; Thomas, 2006; Csontos *et al.*, 2008). Superposition of the northwest- and northeast-trending faults resulted in the Reelfoot Rift consisting of sub-basin blocks.

A composite east–west COCORP deep reflection profile across the Reelfoot Rift ~50 km north of Memphis, Tennessee, reveals inward-dipping listric normal faults that form half-grabens along the southeast and northwest boundaries of the rift (Figure 7.5) (Nelson and Zhang, 1991). Inward-dipping reflections to 40 km depth indicate that extensional faulting may exist through the crust to the Moho. Extension across the rift is only ~17%; however, the amount of subsequent inversion shortening due to Appalachian/Ouachita orogeny compression is not known. Nelson and Zhang (1991) also identified northeast-trending faults within the rift: a steep east-dipping fault that projects up-section to the western margin of Crowley's Ridge, the steep west-dipping Axial fault (Cottonwood Grove

Table 7.1 *Reelfoot Rift Quaternary faulting and liquefaction locations designated with numbers in Figure 7.2 (from Van Arsdale and Cupples, 2013)*

Location/name	Structure	Deformation age	Source
1 Western Lowlands	Faulting and liquefaction	23,000–17,000 and 13,430–9,000 yr BP, AD 240–1020 and 1440–1540	Shoemaker *et al.*, 1997; Vaughn, 1994
2 Commerce fault	Faulting	60–50 ka, 35–25 ka, 5 ka, and 3,660 yr BP	Harrison *et al.*, 1999
3 Charleston Uplift	Faulting	<12 ka	Pryne *et al.*, 2013
4 New Madrid North fault	Faulting	Wisconsin	Baldwin *et al.*, 2005
5 Southeastern Reelfoot Rift margin	Faulting	Pleistocene	Cox *et al.*, 2006
6 New Madrid seismic zone	Faulting and liquefaction	2350 BC, AD 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 AD 1450	Guccione *et al.*, 2005
8 Southeastern Reelfoot Rift margin	Faulting	<20 ka	Cox *et al.*, 2006
9 Manila High	Faulting	11,500–5,400 yr BP, AD 1450 and 1811	Guccione *et al.*, 2000; Odum *et al.*, 2010
10 Southeastern Reelfoot Rift margin	Faulting	4,000–2,000 yr BP (2 events); <2000 yr BP	Cox *et al.*, 2013
11 Southeastern Reelfoot Rift margin	Faulting	Quaternary	Howe, 1985
12 Ellendale	Faulting	AD 400	Velasco *et al.*, 2005
13 Big Creek	Faulting	<27 ka	Harris & Sorrells, 2006
14 Marianna	Liquefaction	7,000–5,000 yr BP	Tuttle *et al.*, 2006
15 Crowley's Ridge	Faulting	Wisconsin	Van Arsdale *et al.*, 1995
16 Marked Tree High	Faulting	4,440–3,350 yr BP	Guccione, 2005
17 Northwestern Reelfoot Rift margin	Faulting	<19 ka	Van Arsdale *et al.*, 1995

fault) coincident with the Blytheville arch (Pratt *et al.*, 2012), and relatively minor faults. Howe (1985) interprets the Axial fault as a Cambrian half-graben fault that was inverted during the late Paleozoic Appalachian orogeny to form the Blytheville arch (Charlie's Ridge).

Although not radiometrically dated, the oldest sediments in the Reelfoot Rift are interpreted to be Early to Middle Cambrian (Johnson *et al.*, 1994). The sediments at the base of the rift consist of arkosic sandstones as much as 1 km thick overlain by shale, limestone, and dolomite with a cumulative thickness of 7 km. The deep arkosic sandstone

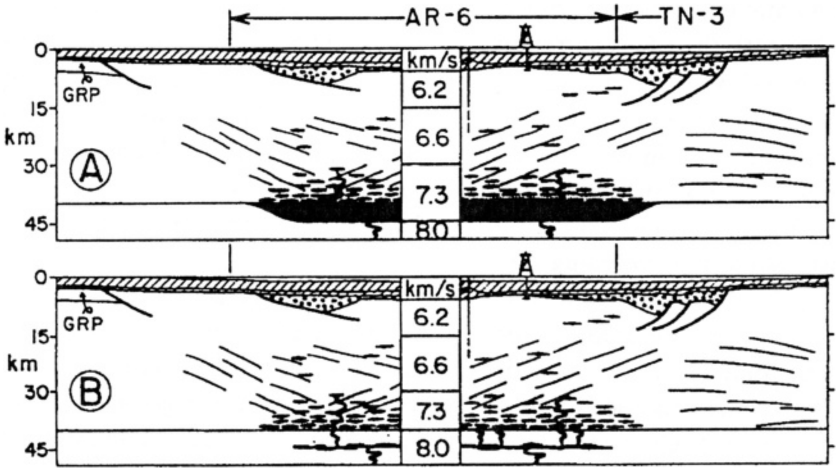

Figure 7.5 Two interpretations of a COCORP reflection line across the Reelfoot Rift located ~50 km north of Memphis, Tennessee. In (A) the 7.5 km/s velocity (black) at the base of the crust is interpreted to be a Cambrian magmatic underplate, whereas in (B) the 7.5 km/s velocity is interpreted to be magmatic sills injected into the pre-existing crust with no underplate (from Nelson and Zhang, 1991).

was deposited only within the down-dropped rift, and the detailed characteristics of these rocks remain a mystery because they have only been penetrated by a few oil exploration wells.

Subsidence of the Reelfoot Rift ceased by the end of deposition of the regionally extensive Knox Group, as revealed in the fact that the top of the Knox (470 Ma) is essentially flat across the rift margins. The NMSZ region experienced far-field effects of the Appalachian Taconic orogeny (480–450 Ma) and the Acadian orogeny (417–329 Ma) (Clendenin and Diehl, 1999) with some sediments shed westward off of the rising mountains reaching the NMSZ region. However, the Appalachian Allegheny orogeny (320–250 Ma) directly affected the NMSZ region. This orogeny resulted in the collision of North America with Europe, Africa, South America, and microcontinents to form the Appalachian–Ouachita mountain system. Appalachian Mountain thrust belt rocks continue westward beneath the Mississippi River valley and merge with the contiguous Ouachita Mountains. While formation of the Appalachian–Ouachita system was applying stress from the east and south, the Ancestral Rockies were also rising and thus applying stress from the west during the Carboniferous. The southern portion of the Reelfoot Rift was overthrust by Ouachita thrust sheets, while sediments accumulated over the rift in the Arkoma/Black Warrior foreland basin.

The Paleozoic closed with the Appalachian–Ouachita Mountain system forming a weld in the assembly of Pangea. This huge mountain system traversed the interior of Pangea resulting in drainage across the future United States flowing north and west off of the mountains (Dickinson and Gehrels, 2009).

7.2.3 Mesozoic

Pangea was torn apart during the Mesozoic, and southern North America began to separate with the initiation of the Gulf of Mexico in the Late Triassic (220 Ma). Disassembly of Pangea occurred primarily along the Appalachian–Ouachita Mountains, yet a portion of these mountains persisted and continued to control drainage across the Eastern United States until Late Cretaceous when the Mississippi Embayment formed.

The Mississippi Embayment formed as a consequence of the Central United States passing over the Bermuda hotspot during the mid-Cretaceous (Cox and Van Arsdale, 1997, 2002). Thermal heating and igneous intrusion of the crust by the hotspot caused uplift of the previously faulted Reelfoot Rift region to form the northeast-trending Mississippi Embayment arch. Erosion of the arch occurred and when the Central United States passed eastward off of the hotspot, the cooling crust subsided. Subsidence lowered the denuded crust below sea level and the Gulf of Mexico advanced up the axis of the subsided landscape, thus resulting in a regional unconformity wherein Late Cretaceous sediments locally lie on top of strata varying from Middle Cambrian shale in the northern embayment to Early Cretaceous limestone in the south. Hotspot uplift, erosion, and subsidence of the Mississippi Embayment arch included a segment of the Appalachian–Ouachita Mountains, which caused breaching of the mountains. Thus, drainage in the Central United States changed from north and west to south along the Mississippi Embayment axis to form the Mississippi River drainage system. The Bermuda hotspot is responsible for the Middle Cretaceous basalt and mafic intrusions in the NMSZ region, most of which were subsequently buried by the Late Cretaceous embayment sediments. Thus, the Reelfoot Rift and NMSZ underwent a significant thermal event during the Cretaceous.

The Early Cretaceous shelf margin is approximately coincident with the southern edge of the thick transitional crust in the northern Gulf of Mexico. This shelf margin was subsequently buried beneath a huge influx of Late Cretaceous clastic sediment. Sediment influx, primarily from the rising Rocky Mountains during the Laramide orogeny, and formation of the Mississippi River drainage system (Cox and Van Arsdale, 2002; Van Arsdale and Cox, 2007) were responsible for the seaward growth of the shoreline from southern Mississippi through eastern Texas. High Late Cretaceous sea level and subsidence of the Mississippi Embayment resulted in the Gulf of Mexico extending north into southern Illinois, thereby depositing approximately 500 m of Late Cretaceous sediments across the NMSZ. The Cretaceous ended with the Chicxulub impact occurring in the Yucatan Peninsula of Mexico immediately south of the Mississippi Embayment. What effect this impact may have had on the NMSZ is not known, but the Paleocene Clayton Formation at the K-T boundary in southeastern Missouri has been interpreted to be a megatsunami deposit (Campbell *et al.*, 2008).

7.2.4 Cenozoic

Subsidence of the Mississippi Embayment continued into Paleocene (65–55 Ma) Midway Group deposition. The overlying Paleocene Wilcox and Eocene (55–34 Ma) Claiborne

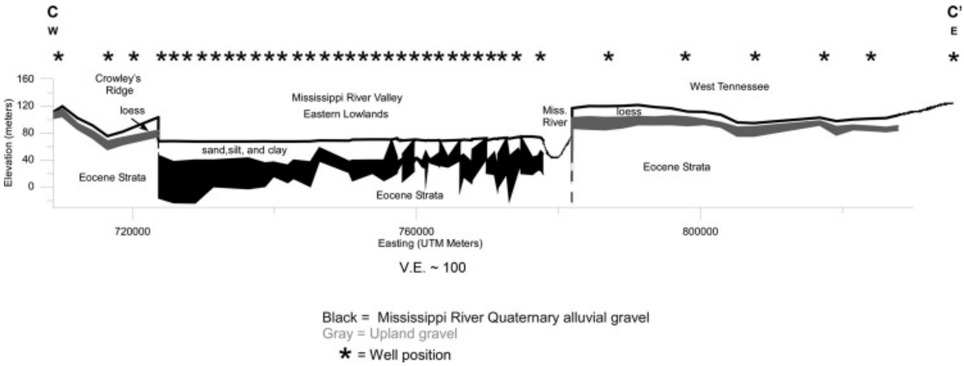

Figure 7.6 A west–east cross-section through the Mississippi River flood plain alluvium and the ancient Mississippi River flood plain sand and gravel (Upland gravel) located ~20 km north of Memphis in Figure 7.1 (from Van Arsdale *et al.*, 2007).

groups reflect alternating shallow marine, near shore, and fluvial environments as the Gulf of Mexico transgressed and regressed within the Mississippi Embayment. The last marine excursion into the Mississippi Embayment was during the Oligocene (34–24 Ma).

During early Pliocene (5.5–4.5 Ma) the ancestral Mississippi River valley looked very much like it does today in the NMSZ region. A major river system flowed south within a vast flood plain that covered portions of the same states that the Mississippi River flood plain covers today. However, the Pliocene ancestral Mississippi River flowed at a higher elevation, perhaps as much as 100 m higher than today's Mississippi River (Van Arsdale *et al.*, 2007). Evidence for this high-level Pliocene river is the sand and gravel Upland Complex (Mississippi River terrace) discontinuously preserved on drainage divides east of the modern Mississippi River from western Kentucky to southern Louisiana and west of the Mississippi River on Crowley's Ridge in Arkansas (Figure 7.6) (Autin *et al.*, 1991; Saucier, 1994). The Upland Complex varies in thickness from 1 to 100 m primarily because it has an unconformable base and top. The Upland Complex overlays Eocene and Oligocene sediments and is overlain by Pleistocene (1.8 Ma–10 ka) loess (Clark *et al.*, 1989; Markewich *et al.*, 1998). This loess consists of up to five loess units that together reach a thickness of 30 m beneath Memphis, Tennessee.

Entrenchment of the ancestral Mississippi River valley began at ~4 Ma apparently due to growth of the Antarctic and Greenland ice sheets and resulting sea level decline. The valley has experienced a complex erosional and depositional Pleistocene history tied to the advance and retreat of perhaps 20 Laurentide ice sheets (Easterbrook, 1999). During the Pleistocene, the ancestral Mississippi River flowed down the Western Lowlands and the ancestral Ohio River flowed down the Eastern Lowlands and the two rivers merged south of Helena, Arkansas (Saucier, 1994; Van Arsdale *et al.*, 2007). During the Pleistocene their point of convergence jumped northward several times until reaching Cairo, Illinois, at 10 ka.

The Mississippi River valley has entrenched 100 m through Pliocene Upland Complex strata and is inset into Eocene strata (Figure 7.6) (Van Arsdale *et al*., 2007). This entrenchment occurred within the past ∼4 Ma.

7.3 The New Madrid seismic zone

7.3.1 The 1811–1812 earthquakes

Contemporary seismicity within the NMSZ primarily consists of small earthquakes occurring between the depths of 4 and 14 km (Figure 7.1) (Csontos and Van Arsdale, 2008). The earthquakes are occurring along a northeast trend from Marked Tree, Arkansas, to the southern end of Reelfoot Lake, Tennessee, where the seismicity merges with a broad band of earthquakes that lie along a northwest trend from Dyersburg, Tennessee, to New Madrid, Missouri. The seismicity trend continues northeast from New Madrid with a less well defined trend to the west from New Madrid towards Risco, Missouri.

During the winter months of 1811–1812 three very large mainshocks and one very large aftershock rocked the central Mississippi River valley (Johnston, 1996; Johnston and Schweig, 1996; Hough and Page, 2011). These earthquakes occurred at approximately 2:15 a.m. December 16, 1811, 8:15 a.m. December 16, 1811 (aftershock), 9 a.m. January 23, 1812, and at 3:45 a.m. February 7, 1812. Hough and Page (2011) believe that the December 16 mainshock occurred on the Axial fault, the large December 16 aftershock occurred on either the northern portion of the Axial fault or on the Reelfoot South fault, the January 23 mainshock occurred on either the New Madrid North fault or on a fault in southern Illinois, and that the February 7 mainshock occurred on the Reelfoot North fault (Figure 7.2). Shaking from the four principal events was felt at a number of locations along the eastern seaboard including Charleston, South Carolina, north to Quebec, Canada, at least as far west as the Kansas–Nebraska border, and south in New Orleans, Louisiana, encompassing an area of 500,000 km^2 (Penick, 1981; Johnston and Schweig, 1996). Few Europeans were living in the epicentral region during these earthquakes, with the largest town of New Madrid (now in Missouri) having a population of ∼400. Our best accounts of these earthquakes come from diaries kept by frontier people and boatmen who were on the Mississippi River at the time (Penick, 1981). Eyewitness accounts describe the banks of the Mississippi River caving, water sloshing out of the banks and returning with many downed trees, the river flowing upstream (probably a seiche), sand and water exploding 100 feet (30.5 m) into the air, ground fissures opening, landslides along the river bluffs, temporary damming of the river, temporary waterfalls (perhaps rapids), permanent land uplift (e.g., Lake County uplift) and subsidence (e.g., Reelfoot Lake), as well as severe ground shaking. As spectacular as these earthquakes must have been, there was no systematic compilation of the geological effects until Fuller (1912), who documented fissures, landslides (Jibson and Keefer, 1989), and liquefaction deposits (Obermeier, 1989) that were still evident in the landscape. One of Fuller's most compelling arguments for very large earthquakes was his work on the distribution of liquefaction deposits, mapped in detail by Tuttle *et al*.

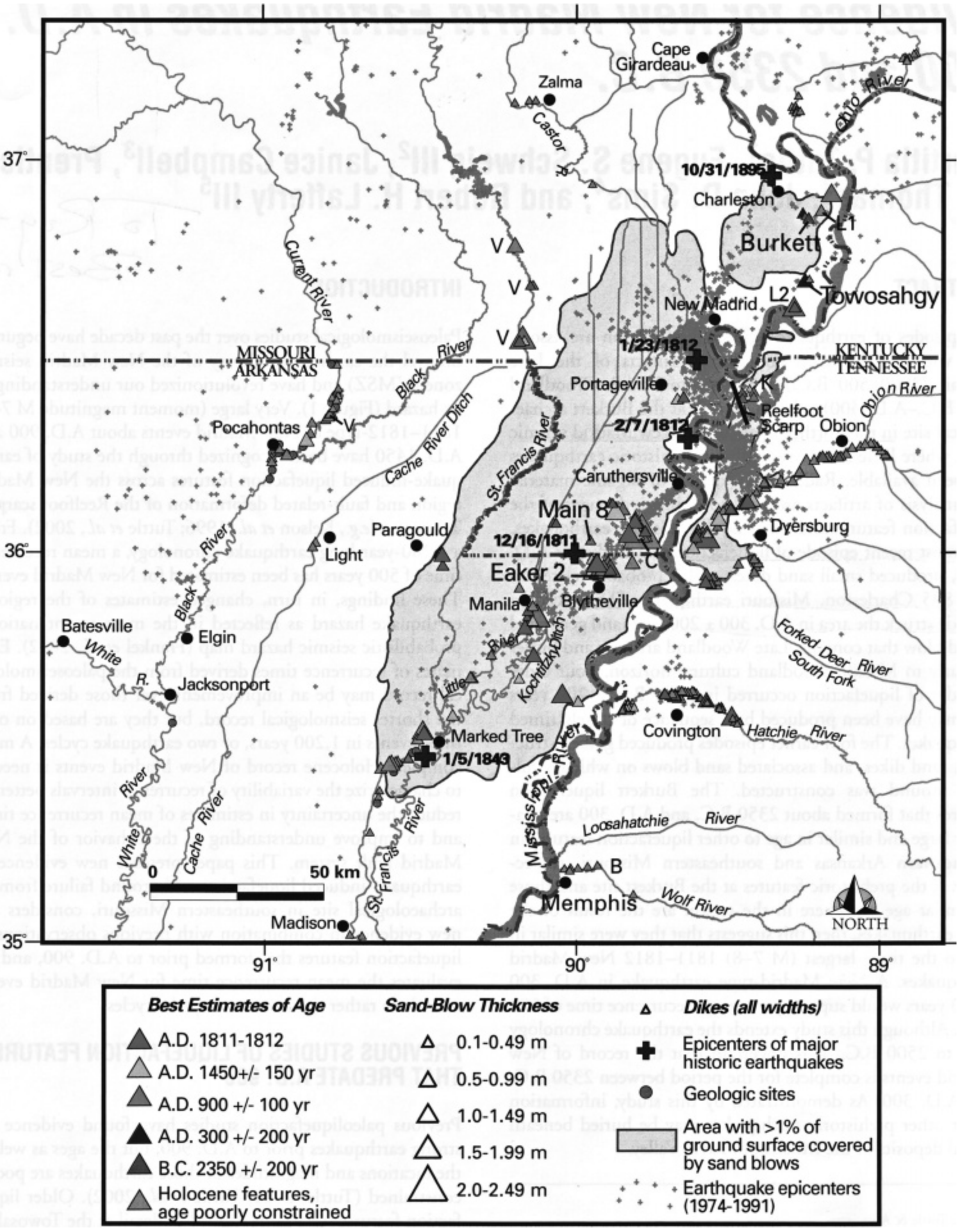

Figure 7.7 Map of earthquake liquefaction deposits in the New Madrid seismic zone region (from Tuttle *et al.*, 2005). For color version, see Plates section.

(2005) (Figure 7.7). Large aftershocks diminished after 1812 and the seismic threat was largely forgotten until the 1970s when the Mississippi River valley was evaluated for the construction of nuclear power plants. Installation of seismometers since the 1970s has clearly defined the NMSZ (Figure 7.1) (Chiu *et al*., 1992; Mueller and Pujol, 2001).

Magnitudes of the 1811–1812 earthquakes have been estimated from intensity data with maximum magnitude estimates having ranged from M 8.1 (Johnston, 1996; Johnston and Schweig, 1996) to low 7 magnitude (Gomberg, 1993; Newman *et al*., 1999; Hough *et al*., 2000).

7.3.2 Geological structure of the NMSZ

NMSZ earthquakes are generally believed to occur along reactivated, and commonly inverted, Cambrian Reelfoot Rift faults (Van Arsdale, 2009). In some cases faults are illuminated by seismic reflection data while in other cases earthquakes occur along planar surfaces that we interpret as fault planes. Specifically, the southern NMSZ seismicity arm is occurring along the Axial (Cottonwood Grove) fault (oriented 46°, 90°); earthquakes occurring along the central northwest-trending arm appear to define a southwest-dipping Reelfoot reverse fault that is divided into the Reelfoot South fault (150°, 44° SW) and Reelfoot North fault (167°, 30° SW), the Risco fault seismicity (92°, 82° N), and the New Madrid North fault seismicity (29°, 72° SE) (Csontos and Van Arsdale, 2008). Fault plane solutions indicate that the Axial and New Madrid North faults are right-lateral strike-slip faults, the Risco fault is a left-lateral strike-slip fault, and the Reelfoot fault is a thrust fault at depths of 4 to 14 km (Csontos and Van Arsdale, 2008). Seismic reflection data and fault modeling (Purser and Van Arsdale, 1998) reveal that the Reelfoot thrust fault steepens into a reverse fault with a southwest dip of 72° above 4 km (Figure 7.8) and Champion *et al*. (2001) model the Reelfoot fault above ∼500 m depth as a trishear fault propagation fold. The Reelfoot North fault has a hanging wall horst that is manifest at the ground surface as the Lake County Uplift with the Tiptonville dome culmination.

Although seismically quiet in recent times there are two other faults with Quaternary displacement within the immediate NMSZ area. The 135 km long Bootheel fault is a transpressional right-lateral strike-slip fault with at least 13 m of strike-slip offset and ∼3 m of up-to-the-east displacement (Figure 7.2) (Guccione *et al*., 2005). Immediately northeast of the Lake County uplift is the New Markham fault. Odum *et al*. (1998) interpret the New Markham fault to be a near-surface continuation of the Reelfoot fault. However, the sense of displacement on this fault is up to the east, which is opposite to Reelfoot fault displacement. Van Arsdale *et al*. (1998) propose that the New Markham fault is a transpressive strike-slip fault with up-to-the-east reverse displacement. The Bootheel and New Markham faults may be linking faults (Wesnousky, 1988) that bypass the Reelfoot North fault stepover zone and may eventually “straighten out” the New Madrid shear zone (Schweig and Ellis, 1994; Van Arsdale *et al*., 1998).

Considering the regional tectonic setting it appears that the NMSZ is a right-lateral strike-slip fault system with two compressional left stepovers (Figure 7.2) (Csontos *et al*.,

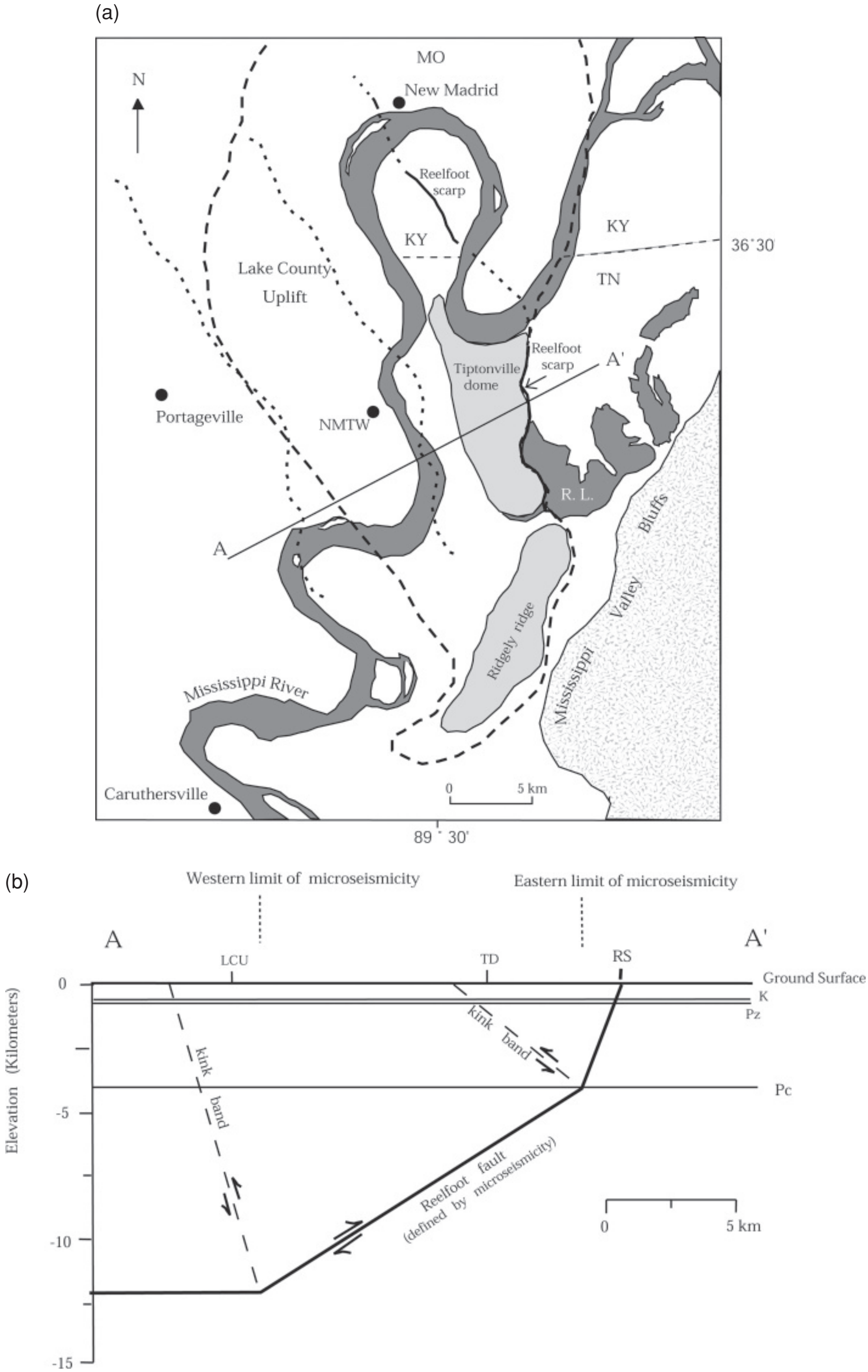

Figure 7.8 (a) The Lake County uplift and vicinity (from Purser and Van Arsdale, 1998). The dashed line marks the boundary of the Lake County uplift as defined by Russ (1982), and the dotted lines are kink bands (back thrusts) on the west side of the Tiptonville dome and Lake County uplift. Line A–A′ is the line of cross-section in B. RL, Reelfoot Lake. (b) Cross-section A–A′ with its kink bands (back thrusts). K, top of Cretaceous; Pz, top of Paleozoic; Pc, top of Precambrian; LCU, Lake County uplift western margin; TD, Tiptonville dome western margin; RS, Reelfoot scarp. No vertical exaggeration. Reverse fault displacement not visible at this scale.

2008). The major faults in the NMSZ are the southeastern Reelfoot Rift margin faults (Chiu *et al*., 1997), the Axial fault, the New Madrid North fault (northwest Reelfoot Rift margin), and the Reelfoot fault. The Reelfoot fault consists of two distinct segments: the Reelfoot South fault is a left stepover linking the southeastern Reelfoot Rift margin and the Axial fault, whereas the Reelfoot North fault is a left stepover linking the Axial fault with the New Madrid North fault (northwestern Reelfoot Rift margin). Northeast of New Madrid, Missouri, the northwestern Reelfoot Rift margin has 36 m of Quaternary displacement on the Charleston uplift (Figure 7.2) (Pryne *et al*., 2013).

The Commerce Geophysical Lineament is a very long basement feature (Figure 7.2) that may be an outlier fault of the Reelfoot Rift (Langenheim and Hildenbrand, 1997; Clendenin and Diehl, 1999; Van Arsdale and Cupples, 2013). Faulting in the Thebes Gap area of Missouri (Harrison *et al*., 1999) and Illinois (Nelson *et al*., 1997) reveals that at least this portion of the Commerce Geophysical Lineament (Commerce fault) is predominantly a right-lateral strike-slip fault that has been active throughout the Phanerozoic and has Quaternary movement. In the Western Lowlands (west of Crowley's Ridge) southwest of Thebes Gap, Vaughn (1994) has identified four paleoliquefaction deposits (23,000–17,000 yr BP, 13,430–9,000 yr BP, AD 240–1020, and AD 1440–1540) that may be due to prehistoric earthquakes on a north-northwest-trending fault underlying the St. Francis River (Figure 7.2).

Research also indicates Quaternary faulting east of the NMSZ (Parrish and Van Arsdale, 2004). Cox *et al*. (2001a) present evidence for Quaternary ground tilting based on analysis of drainage-basin asymmetry that they attribute to basement block tilting in southwestern Kentucky, western Tennessee, and northwestern Mississippi. Subsurface mapping of the Upland Complex in western Kentucky and Tennessee reveals Quaternary east–west normal faulting (Van Arsdale and Cupples, 2013). Faulting has also been mapped south of Memphis along the Big Creek fault zone (Spitz and Schumm, 1997; Harris and Sorrells, 2006; Harris, 2009), immediately west of Memphis along the Meeman–Shelby fault (Hao *et al*., 2013), and beneath Memphis that is Quaternary in age (Velasco *et al*., 2005; Martin, 2008; Van Arsdale *et al*., 2012).

Immediately north of New Madrid, Missouri, is Sikeston Ridge (Figure 7.1), which has been interpreted to be an erosional remnant of Pleistocene ancestral Mississippi River incision. Although there is no evidence of surface faulting along the margins of Sikeston Ridge, it is possible that Sikeston Ridge is an erosionally modified horst (Sexton, 1992; Csontos, 2007).

Regionally, we see other examples of compressional stepover zones within the Reelfoot Rift (Csontos *et al*., 2008). The southern portion of Crowley's Ridge is a fault-bounded block that has been interpreted to be a compressional stepover between the southeastern and northwestern Reelfoot Rift margins (Figure 7.2). A stepover origin has also been proposed for the sub-alluvial Joiner Ridge and its northwestern surface continuation of the Manila High (Odum *et al*., 2010).

The Reelfoot fault hanging wall horst, Joiner Ridge, the southern portion of Crowley's Ridge, and possibly Sikeston Ridge are nearly parallel uplifted blocks (Figures 7.1 and 7.2).

An obvious question is: what is controlling this structural pattern? It appears that these stepover zones are related to basement faults of the Reelfoot Rift. The Reelfoot fault extends between the rift margins, is divided into two segments by the Axial fault, and appears to overlie the Grand River tectonic zone (Csontos, 2007). Sikeston Ridge originates at the intersection of Reelfoot fault (Grand River tectonic zone) and the northwestern Reelfoot Rift margin; Joiner Ridge appears to be related to the intersection of the southeastern Reelfoot Rift margin and the Bolivar Mansfield tectonic zone; and the southern portion of Crowley's Ridge extends across the entire Reelfoot Rift, wherein the northern end originates at the Bolivar Mansfield tectonic zone/northwest margin of the Reelfoot Rift intersection and its southern end originates at the White River fault zone/southeastern margin of the Reelfoot Rift intersection. The relatively uniform spacing, parallelism, and the fact that the stepovers terminate at basement fault intersections suggest that the basement fault intersections are controlling the positions and orientations of the compressional stepovers (Talwani, 1999; Hildenbrand *et al.*, 2001; Gangopadhyay and Talwani, 2005; Van Arsdale, 2009).

7.3.3 Reelfoot fault segments

The Reelfoot fault consists of two fault segments with different strikes and dips based on earthquake foci locations. Between the depths of 4 and 14 km earthquake foci illuminate the Reelfoot North fault (167°, 30° SW) and the Reelfoot South fault (150°, 44° SW) (Csontos and Van Arsdale, 2008). In the upper 1 km, both faults have been imaged with seismic reflection data (Purser and Van Arsdale, 1998; Van Arsdale *et al.*, 1998) and dip 73° SW. It is believed that both faults retain the 73° SW dip to a depth of approximately 4 km (Figure 7.8) (Purser and Van Arsdale, 1998; Csontos and Van Arsdale, 2008). These two fault segments also differ at the ground surface. Whereas the Reelfoot North fault has a 10 m high monoclinal scarp, there is no surface scarp along the Reelfoot South fault (Van Arsdale *et al.*, 1999). Although there are subtle geological indicators that the Reelfoot South fault moved in 1812 (Van Arsdale *et al.*, 1999), the Pleistocene Hatchie River terraces of the Obion River (a west-flowing tributary of the Mississippi River) are essentially flat where they overlie the subsurface Reelfoot South fault. It should also be noted that the Reelfoot North fault monocline has its maximum height of 10 m at its mid-point near its intersection with the Mississippi River and the scarp height diminishes to zero north at New Madrid and south at the southeastern margin of Reelfoot Lake (Csontos and Van Arsdale, 2008). The uplift that has been occurring on the Reelfoot North fault over the past 2,600 years appears to be truncated by the New Madrid North fault (Western Reelfoot Rift margin) at its northern end and the Axial fault at its southern end, with no significant surface displacement on the Reelfoot South fault. A possible explanation for the absence of a scarp along the Reelfoot South fault may be that the blind reverse fault underlies a 50 m higher landscape and the fault has simply not propagated high enough to warp the ground surface (Van Arsdale *et al.*, 1999). It is also possible that the two faults are contiguous and are acting semi-independently or they are not continuous.

Absence of a scarp along the Reelfoot South fault and absence of displacement at the southern end of the Reelfoot North fault may indicate that the Reelfoot South fault did not rupture during the New Madrid earthquakes of 1811–1812 (Hough and Page, 2011). Alternatively, the February 1812 earthquake may have been the only rupture that has occurred along the full length of the Reelfoot fault during the Holocene.

7.3.4 Coseismic regional deformations

A number of landforms were formed or enhanced during the New Madrid earthquakes of 1811–1812 (Fuller, 1912; Mihills and Van Arsdale, 1999; Guccione, 2005; Csontos, 2007). Most obvious is the subsidence of Reelfoot Lake and uplift of the adjacent Lake County uplift (Fuller, 1912; Russ, 1982; Stahle *et al*., 1992). Uplift along the Blytheville arch in northeastern Arkansas and subsidence of the area immediately northwest of the arch occurred in 1811 and during prehistoric faulting events (Figure 7.2). To be more specific, uplift has been documented along the northwestern flank of the subcropping Blytheville arch at the Manila High (Guccione *et al*., 2000; Odum *et al*., 2001) and the Marked Tree High (Guccione, 2005). Uplift of the Manila High partially impounded the Little River to form the Big Lake sunkland, and uplift of the Marked Tree High partially impounded the St. Francis River to form the Lake St. Francis sunkland.

7.3.5 Seismicity and Reelfoot Rift faults

Only particular segments of the Reelfoot Rift faults are currently seismically active (Chiu *et al*., 1992, 1997) and/or have Holocene fault displacement. These include the Axial fault (Guccione, 2005), Reelfoot fault (Mueller and Pujol, 2001), New Madrid North fault (Baldwin *et al*., 2005), Commerce fault (Harrison *et al*., 1999), and the central segment of the southeastern Reelfoot Rift margin (Figure 7.2) (Cox *et al*., 2001b, 2006; Williams *et al*., 2001). Each of these seismically active segments is truncated by basement faults. The Reelfoot fault seismicity is truncated by the Reelfoot Rift margin faults, the Axial fault seismicity is truncated on its north by the Grand River tectonic zone and on its south by the Boliver Mansfield tectonic zone, the New Madrid North seismicity is truncated on its southern end by the Grand River tectonic zone with its northern end possibly truncated by the Charleston uplift, and there is Holocene displacement along the southeastern Reelfoot Rift margin between the Grand River tectonic zone and the Boliver Mansfield tectonic zone (Figure 7.2 and Table 7.1). Thus, it appears that (1) the Precambrian basement faults divide the basement into structural blocks (Figure 7.2), (2) basement fault intersections control near-surface faulting and geomorphology (e.g., southern Crowley's Ridge, Lake County uplift, and Joiner Ridge), and (3) active fault segment lengths are controlled by basement fault intersections. This suggests earthquake size may be controlled by the length of fault segments that bound the basement blocks of Figure 7.2.

Reelfoot Rift fault segments appear to have turned on and off through geological time. The Commerce fault segment of the Commerce Geophysical Lineament at Thebes Gap

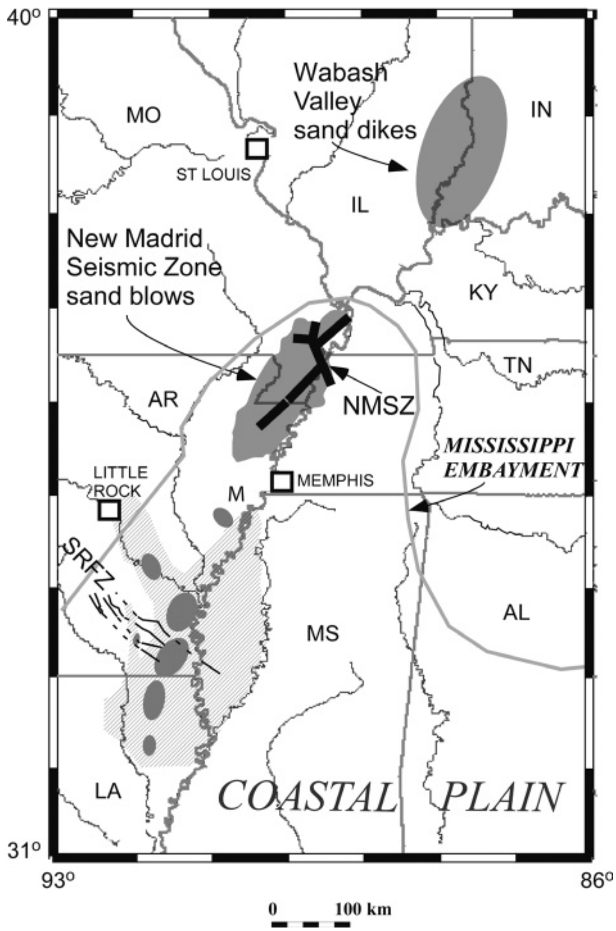

Figure 7.9 Seismically induced Quaternary liquefaction areas in NMSZ, Marianna (M) (Tuttle *et al.*, 2006), and southeastern Arkansas and northeastern Louisiana (from Cox *et al.*, 2010). SRFZ, Saline River fault zone.

(where the Mississippi River crosses Crowley's Ridge at the Missouri–Illinois border) is relatively seismically quiet now, but has experienced extensive Quaternary faulting (Harrison *et al.*, 1999; Harrison and Schultz, 2002). Similarly, the southeast Reelfoot Rift margin north of Dyersburg is seismically quiet, but at Union City, Tennessee, there is a west-facing fault scarp that reveals Pleistocene faulting of this portion of the rift margin (Figure 7.2) (Cox *et al.*, 2001b, 2006). Sikeston Ridge, the southern portion of Crowley's Ridge (Spitz and Schumm, 1997; Van Arsdale *et al.*, 1995), and Joiner Ridge are seismically quiet but their bounding faults may have been active during the Pleistocene. Seventy-five kilometers southwest of Memphis, Tennessee, near the town of Marianna, Arkansas, is an area of low seismicity that has major earthquake liquefaction that occurred between 5,000 and 7,000 years ago (Figure 7.9) (Al-Shukri *et al.*, 2005; Tuttle *et al.*, 2006).

Movement on one of the southeastern Reelfoot Rift margin faults is believed responsible for the Marianna liquefaction. Further southwest near Monticello, Arkansas, but still within the projection of the Reelfoot Rift, Cox *et al*. (2000) have identified Holocene faulting and earthquake liquefaction (Cox *et al*., 2004) along the northwest-trending Saline River fault zone (Figure 7.9). Although this area is also underlain by the Ouachita–Appalachian thrust belt, Cox *et al*. (2000) and Cox (2010) believe that the northwest-trending basement fault responsible for this Quaternary faulting is the Alabama–Oklahoma transform fault (Figure 7.4) – the probable southern terminus of the Reelfoot Rift.

7.3.6 New Madrid seismic zone fault activation models

Various models have been proposed to explain the NMSZ. Gomberg and Ellis (1994) numerically model far-field (plate tectonic scale) and locally derived driving strains for the NMSZ faults. Applying elastic dislocation theory Tavakoli *et al*. (2010) model the NMSZ as a 240 km long transpressional flower structure with the principal fault being a right-lateral shear zone rooted in the lower crust that is located along the axis of the Reelfoot Rift (Axial fault). The driving mechanism for the Tavkoli *et al*. model is a drag force at the base of the North American plate. Pratt (2012) combines an analog sandbox model and computer models of a restraining stepover within a N28°E-trending right-lateral shear zone to analyze the NMSZ (Figure 7.10). Deformation displayed in Figure 7.10 is the predicted map view of surface displacements caused by three N47°E upper-crustal faults above a N28°E lower crustal shear zone under a uniform N70°E regional compression. The driving mechanism for the Pratt model is the horizontal N60°E to N80°E maximum compressive stress due to ridge push. Van Arsdale and Cupples (2013) believe that ridge push and/or basal drag is the driving force, but using hundreds of well logs they show that Quaternary right-lateral shear extends across the entire Reelfoot Rift to include the outboard Commerce and Big Creek faults (Figure 7.11). This shear has produced east–west-trending normal faults and north–south-trending compressional stepovers.

Within the Reelfoot Rift region of the Eastern United States are the seismically quiet Rough Creek graben, Rome Trough, Mid Continent Rift, and Southern Oklahoma aulacogen (Figure 7.4). This raises the fundamental questions: why is the Reelfoot Rift seismically active when its neighbors are not, and why does activity within the Reelfoot Rift migrate among different faults during the Quaternary? A number of contributing factors have been cited, some of which are unique to the Reelfoot Rift. Two of these factors are (1) the Reelfoot Rift faults have broken completely through the crust (Nelson and Zhang, 1991; Bartholomew and Van Arsdale, 2012), and (2) these faults are favorably oriented to experience shear in the regional stress field (Zoback and Zoback, 1989; Ellis, 1994; Heidbach *et al*., 2008). Regionally, a N60°E to N80°E horizontal maximum compressive stress is due to the plate driving force of ridge push (Zoback, 1992; Richardson, 1992) and/or basal drag from lower mantle flow (Liu and Bird, 2002).

A third factor argued by a number of authors is that the rift pillow in the base of the crust beneath the Reelfoot Rift causes a local stress concentration. Grana and Richardson

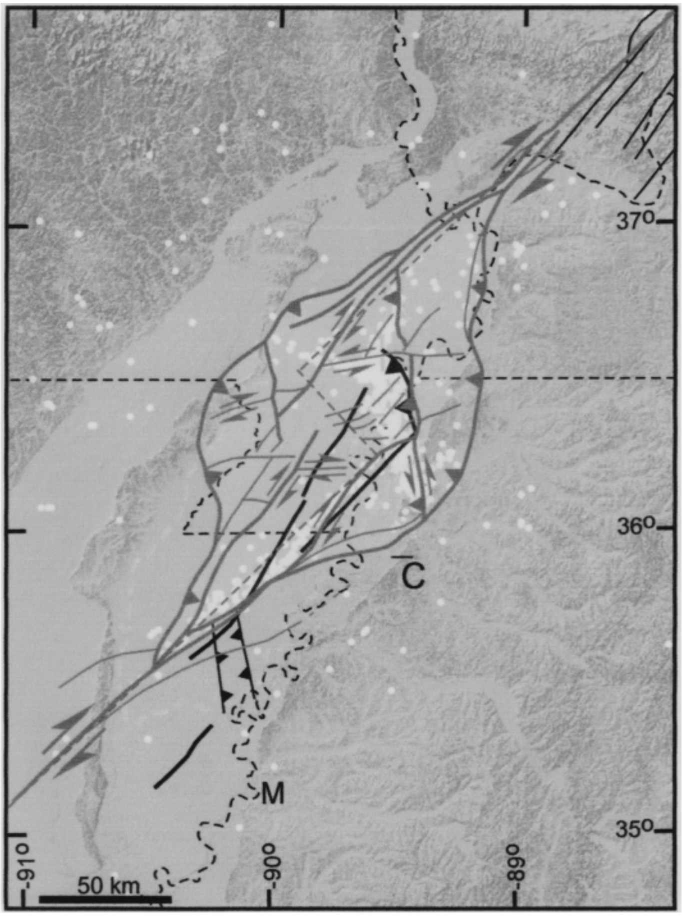

Figure 7.10 Model of the NMSZ combining sandbox analog and computer modeling (from Pratt, 2012). Map view of predicted surface displacements caused by three N47°E upper-crustal faults above a N28°E lower-crustal shear zone under a uniform N70°E regional compression. Seismicity shown as white dots. M, Memphis, Tennessee.

(1996) argue that body forces acting on the rift pillow contribute to the present-day stress field, whereas Stuart *et al*. (1997) suggest that slip along a subhorizontal detachment fault near the domed top of the rift pillow creates a stress concentration in the upper crust above the rift pillow dome. Pollitz *et al*. (2001) propose that sudden weakening caused by Wisconsin deglaciation caused the rift pillow to start sinking, which in turn initiated a downward pull, leading to Reelfoot thrust faulting. Although the rift pillow has been cited as a factor in causing the NMSZ, as discussed above, the rift pillow's age is in question. The apex of the rift pillow underlies the "bull's-eye" of the Cambrian–Upper Cretaceous unconformity beneath the NMSZ. (See the top of the Paleozoic animation at www.geosociety.org/pubs/ft2009.htm [Csontos *et al*., 2008; Van Arsdale, 2009]). It seems unlikely that this superposition is a coincidence, and this Cretaceous unconformity pattern

(a)

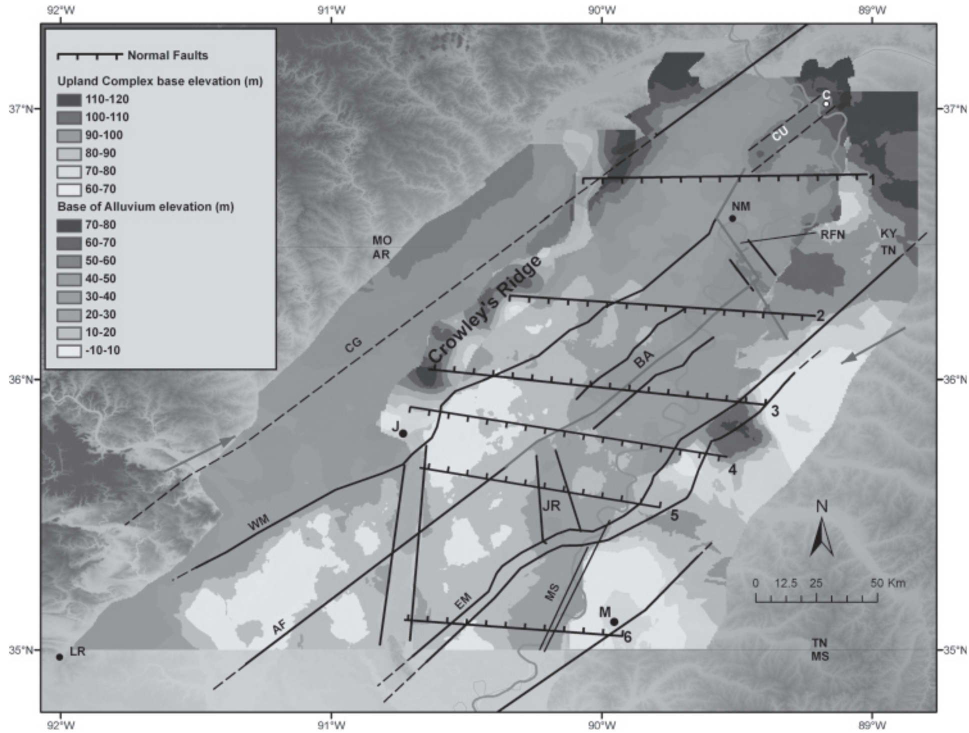

Figure 7.11 (a) Reelfoot Rift and its outboard faults (from Van Arsdale and Cupples, 2013). Right-lateral simple shear is occurring along the N45°E basement faults driven by the regional horizontal maximum compressive stress (red arrows). The resulting strain field has caused north-striking compressional uplifts bound by black fault lines (e.g., Joiner ridge) and the late Pliocene to perhaps Holocene west-striking normal faults with barbs on the down-dropped side. CG, Commerce geophysical lineament/fault; WM, northwestern Reelfoot Rift margin; AF, Axial fault (Cottonwood Grove 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, Arkansas; C, Cairo, Illinois; NM, New Madrid, Missouri; M, Memphis, Tennessee. For color version, see Plates section.

strongly suggests that the Reelfoot Rift pillow was either intruded or reactivated during mid Cretaceous (Grana and Richardson, 1996; Csontos *et al.*, 2008).

A fourth possible contributing factor for the contemporary faulting may be that the Reelfoot Rift faults have been intermittently active since the mid Cretaceous. When the central Mississippi River valley passed over the Bermuda hotspot, the Reelfoot Rift was heated and uplifted 3 km as part of the Mississippi Embayment arch (Cox and Van Arsdale, 1997, 2002) and the rift faults were probably reactivated to accommodate the uplift. Subsequent Late Cretaceous cooling subsidence of the Mississippi Embayment that occurred after passing off the hotspot continued at least through the Paleocene, which may have kept the Reelfoot Rift faults active during the Paleogene (e.g., Van Arsdale *et al.*, 1995; Luzietti

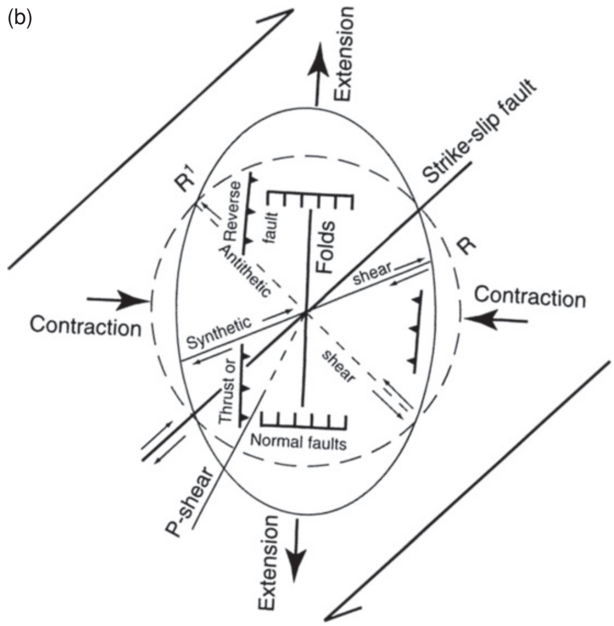

Figure 7.11 (b) The strain ellipse illustrates the nature and orientation of structures that form within an area undergoing right-lateral simple shear (map view). Local east–west compression results in north-striking folds and reverse faults and local north–south extension results in east-striking normal faults as seen in (a) (from Keller and Pinter, 2002).

et al., 1995). Neogene movement has been documented on the Crittenden County fault (Luzetti *et al*., 1995), the Reelfoot fault (Kelson *et al*., 1996; Van Arsdale, 2000), Axial fault (Guccione, 2005), Bootheel fault (Guccione *et al*., 2005), New Madrid North fault (Baldwin *et al*., 2005; Pryne *et al*., 2013), bounding faults of Crowley's Ridge (Van Arsdale *et al*., 1995), the Commerce fault (Harrison *et al*., 1999), and the southeastern Reelfoot Rift margin faults (Cox *et al*., 2006) (Figure 7.2 and Table 7.1). Thus, the Reelfoot Rift is unique among its neighboring rifts in that although the total amount of displacement on individual Reelfoot Rift faults has been small (e.g., 70 m on the Reelfoot fault since the Cretaceous) many of the rift faults (perhaps all) have experienced Cenozoic movement.

The fifth reason, which is also unique to the Reelfoot Rift, is that the very large Mississippi River passes directly over the NMSZ and most of the rift. Van Arsdale *et al*. (2007) have discussed the late Pliocene through Holocene erosional history of the central Mississippi River valley that they believe may be tied to the late Holocene onset of the NMSZ, which is discussed below.

7.3.7 Earthquake recurrence

Paleoseismologic investigations have revealed a recurrence interval of approximately 500 years for large NMSZ earthquakes over the past ~1,700 years (Kelson *et al*., 1996;

Tuttle *et al*., 2002). Trenches excavated across the Reelfoot scarp (monocline) identify three earthquakes (Russ, 1982; Kelson *et al*., 1996) and regional paleoliquefaction studies identify five earthquake sequences, including 1811–1812, that have occurred within the last ~4,300 years (AD 1811–1812, 1450 ± 150, 900 ± 100, 300 ± 200, and 2350 BC ± 200 years) (Tuttle *et al*., 2002, 2005). Straightening of the Mississippi River upstream from the Lake County Uplift at approximately AD 900 and between 2244 and 1620 BC has been interpreted by Holbrook *et al*. (2006) to be due to uplift of the Reelfoot fault across the course of the river, which further supports the paleoliquefaction dates of AD 900 and 2350 BC. Paleoliquefaction data also indicate that the AD 1450, AD 900, and 2350 BC earthquake periods had multiple earthquakes within a short period of time like the 1811–1812 sequence (Tuttle *et al*., 2002, 2005).

The maximum structural amplitude of the Reelfoot scarp is ~11 m, which has occurred within the last 2,600 years (Champion *et al.,* 2001; Carlson and Guccione, 2010). At depth beneath the Reelfoot scarp, the unconformity at the base of the Holocene alluvium is displaced 16 m, top of the Eocene Wilcox Group 31 m, top of the Paleocene Midway Group 42 m, top of Cretaceous 63 m, and top of Paleozoic 73 m. The Reelfoot fault has moved 16 m in the past 10,000 years with 11 m occurring in the past 2,600 years, implying a slip rate of 1.8 mm/yr throughout the entire Holocene and 6.2 mm/yr over the past 2,600 years (Van Arsdale, 2000). In subsequent studies of the Reelfoot scarp, a late Holocene slip rate of 3.9 ± 1 mm/yr was interpreted by Champion *et al*. (2001), while Carlson and Guccione (2010) estimate a late Holocene slip rate of 13 mm/yr calculated from the AD 1450 and 1812 faulting events. The subsurface fault displacement history (Sexton and Jones, 1986; Van Arsdale, 2000; Champion *et al*., 2001) further indicates that the Reelfoot fault turns on and off through time. This raises the question: what caused the fault to become active during the Holocene?

7.3.8 Proposed Holocene triggering mechanisms of the NMSZ

Kenner and Segall (2000) model the NMSZ as having an elastic lithosphere with a weak lower-crustal zone and show that a prolonged sequence of large earthquakes can result from a local perturbation of the stress field by changes in thermal state, pore pressure, or most likely recession of the Laurentian ice sheet 14,000 years ago. Grollimund and Zoback (2001) proposed that glacial unloading north of the NMSZ increased seismic strain rates in the NMSZ at the end of the Wisconsin; however, Wu and Johnston (2000) previously argued that glacial unloading is unlikely to have triggered the large earthquakes in New Madrid. A problem with having the Wisconsin ice sheet retreat cause the onset of Holocene seismicity in the NMSZ is that there have been perhaps as many as 20 ice sheet advances and retreats during the Pleistocene (Easterbrook, 1999), yet there has been only 31 m of displacement on the Reelfoot fault since the Eocene. There appears to have been something unique about the late Wisconsin or early Holocene that initiated the Holocene reactivation of the NMSZ.

Schweig and Ellis (1994) speculate that the NMSZ may have initiated between 11 and 3 Ma due to a change in North American plate motion and consequent rotation of the stress field that resulted in higher resolved shear stress on the Reelfoot Rift faults. However, this model raises the question of why other Eastern United States rifts have not also been reactivated. The model also does not account for the Holocene initiation of seismicity within the NMSZ and surrounding Reelfoot Rift. More recently Forte *et al*. (2007) argue that contemporary descent of the Farallon slab in the lower mantle beneath the Central United States is responsible for New Madrid seismicity. In the Forte *et al*. model, downwelling mantle flow, viscously coupled to the ancient Farallon slab, is the driving mechanism. However, their calculated S_{Hmax} in the NMSZ appears to be of the same magnitude and direction as much of the Midcontinent Rift System where there is no seismicity or evidence of Quaternary faulting.

Liu and Zoback (1997) relate New Madrid faulting to local high heat flow and local differences in lithospheric strength. McKenna *et al*. (2007) refute the existence of the proposed heat flow anomaly and conclude that there is no fundamental difference in lithospheric strength between the NMSZ and the surrounding area. Even if subsequent research should support local high heat flow in the NMSZ, there is no apparent reason why heat flow should have increased during the Quaternary.

Excess fluid pressure in the NMSZ due to regional groundwater flow has been proposed to explain its seismicity (McKeown and Diehl, 1994). High pore pressure would reduce the normal stress across the faults and promote faulting. However, the Holocene groundwater flow pattern in the NMSZ appears to have been in existence since the formation of the Mississippi Embayment in the Late Cretaceous and thus this model does not provide an explanation as to why faulting turned on during the Holocene.

Van Arsdale *et al*. (2007) have discussed the late Pliocene through Pleistocene erosional history of the central Mississippi River valley, which they suggest may be tied to the late Holocene onset of NMSZ activity. The ancestral Mississippi/Ohio River system used to flow south across this region at an elevation that was 100 m higher than today's Mississippi River (Figure 7.6). Entrenchment of the ancestral Mississippi/Ohio River system started at ~4 Ma with the most recent 6 m of entrenchment occurring between 12,000 and 10,000 years ago (Calais *et al*., 2010). Calais *et al*. (2010) argue that this most recent entrenchment reduced the vertical stress, which reduced the horizontal stress that kept the NMSZ faults locked. In this model, the erosion between 12–10 ka reactivated the stressed NMSZ faults.

The Calais *et al*. (2010) model provides both an explanation for the onset of the NMSZ and for the onset of the formation of the Lake County Uplift. Denudation of the Mississippi River valley at the end of the Pleistocene caused right-lateral slip on the Axial and New Madrid North faults thereby causing uplift of the Lake County Uplift compressional stepover. As discussed above, Sikeston Ridge, Joiner Ridge, and the southern portion of Crowley's Ridge may also be compressional stepovers. If indeed these are all compressional stepovers then they could all be a consequence of right-lateral shear across the Reelfoot Rift that occurred as the valley was denuded over the past ~4 Ma. The denudation-driven model provides a mechanism to distribute minor displacement among Reelfoot Rift faults at different times within the Quaternary since denudation would have occurred at different times and different locations in the Mississippi valley. This model is supported by the fact that Crowley's Ridge is older than 18,000 years; Sikeston Ridge is younger than 18,000 years; the Lake County Uplift has come up within the last 2,600 years; and both Joiner Ridge and the Charleston Uplift are apparent at the base of the Mississippi River alluvium (Csontos *et al.*, 2008; Odum *et al.*, 2010; Pryne *et al.*, 2013) but have not yet emerged as topographic ridges.

7.3.9 Is elastic strain energy accumulating in the Reelfoot Rift faults

Paleoseismologic trench studies indicate that the Reelfoot North fault has ruptured three times (Russ, 1979; Kelson *et al.*, 1996; Champion *et al.*, 2001) and paleoliquefaction identifies four large earthquake sequences over the past 1,700 years (Tuttle *et al.*, 2002) implying an earthquake recurrence interval of $\sim$500 years. A $\sim$500-year recurrence interval for **M** $>$ 7.5 earthquakes is inconsistent with the rate of **M** $\sim$6 earthquakes since 1812. Two earthquakes estimated to be in the low **M** 6 range have occurred in the NMSZ, one in 1843 near Marked Tree, Arkansas, and the second in 1895 near Charleston, Missouri (Hopper and Algermissen, 1980; Guccione, 2005). If even one of the 1811–1812 earthquakes was **M** 7.5 then, based on the Gutenberg–Richter frequency–magnitude relationship, there should have been four **M** $\sim$6.5 earthquakes in the NMSZ since 1812 (Atkinson *et al.*, 2000). A more significant problem with a continuing short recurrence interval is that GPS measurements reveal very low strain rates (0.2 $\pm$ 2.4 mm/yr) in the NMSZ (Newman *et al.*, 1999; Calais *et al.*, 2005; Stein, 2010). At these strain rates it would take $\sim$10,000 years to accumulate sufficient strain energy to generate a **M** 7 earthquake (Stein, 2010). These arguments suggest that the 1811–1812 earthquakes were in the low **M** 7 range (Hough *et al.*, 2000; Mueller and Pujol, 2001; Hough and Page, 2011). An alternative explanation is that the NMSZ turns on for a brief period of geological time and turns off for very long periods of geological time and that we are at or near the end of a cluster of faulting/seismic activity (Coppersmith, 1988; Van Arsdale, 2000).

The denudation model by Van Arsdale *et al.* (2007) and Calais *et al.* (2010) appears to provide an explanation that fits both the geological and historical records. In the denudation model, normal stress on the Reelfoot Rift faults is reduced due to erosion of sediment from above the NMSZ faults, thereby increasing the ratio of shear stress to normal stress and allowing favorably oriented faults to slip. The reduction in normal stress is controlled by the erosional history of the Mississippi River. Once a certain threshold of erosion is passed then the critical shear stress/normal stress ratio is exceeded and faulting occurs. If this is indeed the driving mechanism, it would occur as a burst of faulting (seismic) activity separated by perhaps millions of years of quiescence until another erosional period occurs. Additionally, we expect that in the case of a basement rift and large river system there would be minor fault displacement over a large area within short geological time. It is possible that this mechanism has been active in the deep geological past of the Reelfoot Rift. I now consider the history of the Reelfoot North fault.

There has been 16 m of Quaternary displacement, 15 m of post-Wilcox/pre-Quaternary displacement, 11 m of Wilcox displacement, 21 m of Midway displacement, and 10 m of Late Cretaceous displacement on the Reelfoot North fault (Van Arsdale, 2000). Based on these displacements and estimates of their respective time frames one can calculate a Late Cretaceous slip rate of 0.0007 mm/yr, Paleocene slip rate of 0.002 mm/yr, Wilcox Group slip rate of 0.001 mm/yr, post-Wilcox/pre-Holocene slip rate of 0.0003 mm/yr, and a Holocene slip rate of 1.8 mm/yr. If we spread the 16 m of Holocene displacement over the entire time frame of the Paleocene, then we would have a slip rate of 0.001 mm/yr. Secondly, the magnitudes of the slip for these time periods separated by unconformities are similar. This similarity implies that perhaps any single cluster of activity may not exceed ~20 m of fault displacement on the Reelfoot North fault. From either perspective it appears that since the plate tectonic setting of the NMSZ has not changed substantially since essentially the Cretaceous, we should expect uniform behavior over time. However, this does not get the NMSZ off the hook. If the Reelfoot North fault can slip as much as 20 m during the current cycle then there may be 9 more meters of slip before this fault shuts down perhaps for millions of years.

7.4 Conclusions

Earthquakes on the NMSZ occur along faults within the Cambrian Reelfoot Rift that appear to have cut across northwest-striking Proterozoic faults (Figures 7.1 and 7.2). At a more regional scale the Commerce Geophysical lineament and the Big Creek fault zone (Figure 7.11) are interpreted to be outboard faults of the rift. Right-lateral shear across the Reelfoot Rift is causing right-lateral displacement along the Southeastern Reelfoot Rift margin faults, Axial fault, and New Madrid North fault, and reverse displacement on the Reelfoot North and Reelfoot South faults. Thus, there are three strike-slip faults and two left stepovers that are currently seismically active. There is also evidence of Quaternary faulting along portions of the Southeastern Reelfoot Rift margin faults, Big Creek fault, the Commerce Geophysical lineament, the Bootheel fault, the New Markham fault, Crowley's Ridge, the Saline River fault zone, Joiner Ridge, and the Meeman–Shelby fault (Figure 7.2 and Table 7.1). In effect, the Reelfoot Rift is a Cambrian structure that has been active over much of its area within the Quaternary. Proposed explanations for the driving force for the faulting and resultant earthquakes include a sinking rift pillow, ridge push, a subducting Farallon slab, local weakening of the crust, excess pore-fluid pressure, glacial isostatic adjustment, and erosional unloading. The absence of significant Neogene deformation in the region requires Quaternary onset of the most recent episode of deformation and the paleoseismic record indicates that faulting began in the NMSZ during the Holocene. Holocene reactivation of the NMSZ faults has been attributed to local stress perturbation due to melting of the Wisconsin ice sheet, a change in North American plate motion, or a reduction in normal stress across strained faults due to denudation by the Mississippi River. The denudation model explains the Holocene onset of the NMSZ and, I believe, also provides the most satisfactory explanation as to the cause, distribution, displacement magnitude, and timing of Quaternary faulting of the Reelfoot Rift faults throughout the lower Mississippi River valley. Quaternary incision of the Mississippi River system locally diminishes the stress on the faults produced by ridge push and releases the stored elastic strain energy at different times and different locations, thereby turning Reelfoot Rift faults on and off with relatively minor total Quaternary displacement occurring on individual faults.

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