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# OVERVIEW OF THE SEISMIC THREAT IN THE CENTRAL UNITED STATES

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## ABSTRACT

This paper summarizes geological, geophysical and seismological studies in two accepted and one candidate seismic zones in the central United States. The area was shaken by as many as 2,000 felt earthquakes in 1811-12, including four events greater than Magnitudes 7.0. These occurred before the area west of the Mississippi River was settled, so the intensity of shaking was not recorded over much of the affected region. Earthquakes in the central United States are felt over a much broader area than similar magnitude earthquakes in the western United States because of the low attenuation associated with undeformed Paleozoic age strata underlying the region. The New Madrid Seismic Zone (NMSZ) is believed to have been the source of the 1811-12 quakes and is the most studied source area in the central U.S. Some of the important structural features identified within this zone are summarized in this article, including the Reelfoot Fault scarp, Lake County Uplift, Crowley's Ridge, Blytheville Arch, Bootheel Lineament and the Crittenden County Fault Zone. In just the last few years a GPS measurement array has been established around the Reelfoot Fault, and a debate has emerged about the accuracy and implications of these measurements. In the Wabash Valley Seismic Zone (WVSZ) limited historical and instrument arrays suggests that although the recorded seismic activity is much lower than a plate boundary region, it is, nevertheless, anomalously high activity for an intraplate region. Recent paleoliquefaction studies in the WVSZ suggest that it has likely spawned large-magnitude earthquakes, though not with as great a magnitude or frequency as the NMSZ. The anomalous historic seismicity recorded in South Central Illinois is believed to be the reactivation of old basement faults or background noise, but paleoliquefaction studies indicate that large magnitude earthquakes may also emanate from this region. It has not been accepted as a credible seismic source zone, but may be at some time in the future, as more data is collected and synthesized.

## INTRODUCTION AND BACKGROUND

This paper is intended to summarize previous geophysical, geological and seismological studies in the in the Central U.S. focusing on active seismic sources in the upper Mississippi Embayment, Wabash Valley, and south central Illinois. Prior to 1973 most investigations related to earthquakes in the Central U.S. were minimal because no research monies were available. In 1973 The Nuclear Regulatory Commission (NRC) began funding research on seismic hazards when it began reviewing plans for construction of a thermal power plant in West Memphis, AR, across the Mississippi River from Memphis, TN. The proposed facility was only located 30 miles from assumed epicenter of the M 6.3 Marked Tree earthquake in 1843, along the southern end of the New Madrid Seismic Zone (NMSZ). At that time the U.S. Department of Energy (DOE) and the U.S. Geological Survey (USGS) began funding regional gravity and aeromagnetic surveys. In 1974 the USGS established a seismographic network to record and locate seismic activity in the NMSZ with increasing accuracy. In 1976, the NRC funded a multi-year six-state cooperative project to better assess the seismic-hazards posed to potential nuclear power plants. This project involved state agencies and universities and it began accumulating the scientific data and magnitude and frequency that are critical to developing a probabilistic hazard assessment for the central U.S. The balance of this article describes the development of seismic hazard data and the evolution of understanding of seismic hazards in the central USA that have occurred since serious monitoring and study began in 1973.

Two major seismic zones –New Madrid Seismic Zone and Wabash Valley Seismic Zone- are presently accepted to be likely source zones for large magnitude (> M 7.0) earthquakes in the central U.S. Most of the studies to date have focused on these two seismic zones, by geophysicists, seismologists, geologists, geological engineers, geotechnical engineers, and structural engineers. A third source zone, loosely termed the South Central Illinois Seismic Zone, was hypothesized because of its close proximity to St. Louis. It has exhibited relatively low micro-seismicity, but thought capable of fomenting moderate size earthquakes (up to M 6.0). The principal evidence for activity within these seismic zones comes from recent paloeliquefaction studies, which have been somewhat limited in geographic scope, because of limited funding and the paucity of suitable study sites, mostly along major water courses. The approximate areal extent of the three seismic source zones are shown in Figure 1.

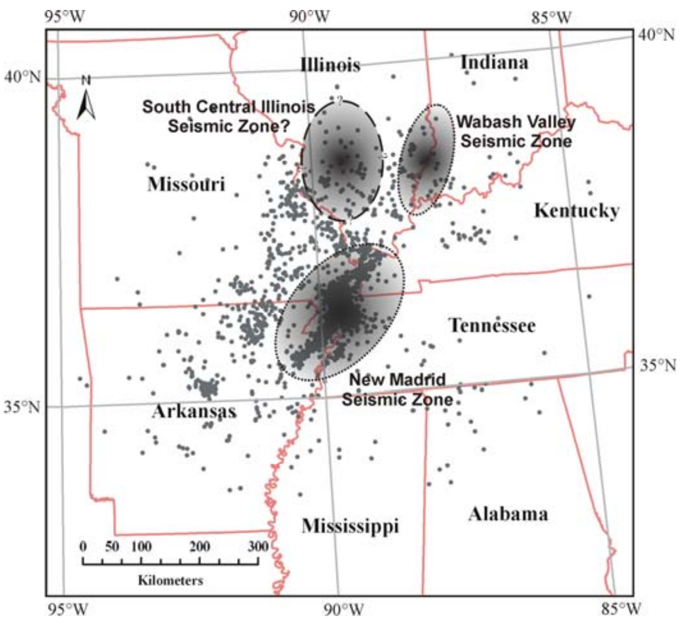


*Figure 1. Micro seismicity (magnitudes between 1 and 4) of the New Madrid Seismic Zone (from USGS). Dots represent the seismic activity recorded between 1974-2007. The ellipsoids are drawn based on this recent data, realizing that the only detailed arrays exist in the NMSZ. The limits of the proposed South Central Illinois Zone are arbitrary, because there is insufficient microseismic data to delineate the boundary of this source area.*

## THE NEW MADRID SEISMIC ZONE

### Structural and Geological Setting

The New Madrid Seismic Zone (NMSZ) is recognized for spawning historic earthquakes of significant magnitude, greater than M 6.0. It lies beneath the Upper Mississippi Embayment and extends from northeast Arkansas through southeast Missouri, western Tennessee, western Kentucky, and up into southern Illinois. The NMSZ is believed to be a failed midcontinetal rift. It is assumed to be a Southwest-Northeast trending basement graben, about 70 km-wide and 300 km-long, known as the Reelfoot Rift (Figure 3). The northeastern end of the rift is poorly defined because it merges with the Rough Creek Graben and other basement structures in southern Illinois (Boyd and Schumm, 1995). Structural relief on the rift is about 1.6 to 2.6 km (Hildenbrand et al., 1982). This graben is interpreted to have formed during an episode of continental rifting (crustal extension) that began in late Cambrian time, 523 to 505 million years ago (Hamilton, 1981). Magnetic data has revealed the presence of major positive magnetic anomalies along the flanks of the rift, interpreted to be mafic plutons (Hildenbrand et al., 1982; Hildenbrand, 1985).

Drill hole data, exposures in the Ozark Uplands of southeastern Missouri, seismic reflection studies, and magnetic field studies suggests that during late Precambrian time (~543 Ma), the upper Mississippi Embayment area was a subareal landscape with 150 to 450 m of topographic relief, cut into Middle Proterozoic age granites and rhyolites (Buschbach and Schwalb, 1984). Sometime in the early to late Cambrian time (~505 Ma), northeast trending continental rifting began, which altered the landscape, forming the original Reelfoot Rift (Hildenbrand et al, 1982). Active rifting then ceased and the rift was filled with a 1 to 4 km sequence of marine clastic and carbonate sedimentary strata. During the Late Paleozoic time (~245 Ma), the region was uplifted, and several kilometers of sedimentary rock were eroded from the crest of the Pascola Arch (Stearns and Marcher, 1962) and this denudation probably continued until late Cretaceous time (~66 Ma) (McKeown, 1982). During Permian time (286-245 Ma), mafic igneous dikes and sills intruded the sedimentary rocks. Near the end of the Mesozoic, probably beginning in early to middle Cretaceous time (~144-105 Ma), regional subsidence recurred and a series of igneous intrusions were emplaced along the margins of the old rift; suggesting reactivation of the rift (Hildenbrand, 1982; Hildenbrand and Hendricks, 1995). During the late Cretaceous and continuing through the Eocene, subsidence resulted in development of the Mississippi Embayment. The embayment was filled with a southward-thickening wedge of predominantly clastic marine and continental sediments. In late Quaternary time and probably somewhat earlier, tremendous volumes of glacial melt-water from much of North America flowed down the proto Mississippi-Ohio River drainage system, through the northern embayment (Crone and Schweig, 1994; Van Arsdale, 2009). Braided streams that transported the meltwater deposited outwash sand and gravel in the embayment which is, typically, tens of meters thick in the New Madrid, MO area. During early Holocene time the Mississippi River changed from a braided stream to a meandering regime and began developing the modern meander belt we see today (Saucier, 1974). As the river meandered, fine-grained overbank sediment was deposited on the embayment's flood plains during annual spring floods, encompassing thousands of square kilometers in the modern river valley (Crone and Schweig, 1994; Van Arsdale, 2009). The Blytheville Arch extends northeast through the center of the Reelfoot Rift. It may have formed in response to tectonic activity near the end of the Paleozoic Era (Hamilton and Mooney, 1990). A simplified geologic cross-section of the Mississippi Embayment is presented in Figure 2. As much as 1-km of unconsolidated Cenozoic and Upper Cretaceous sedimentary strata fill the embayment. The underlying Paleozoic rocks include Upper Cambrian and Lower Ordovician carbonate rocks that are equivalent of the Knox-Arbuckle Mega Group, Upper Cambrian shales of the Elvins Group, Upper Cambrian dolomitic rocks of the Bonneterre Formation, and a thick sequence of Upper Cambrian clastic rocks (Figure 2).

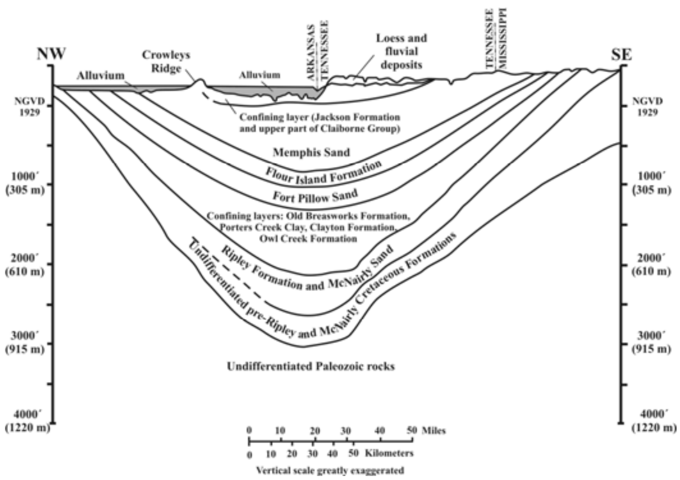


*Figure 2. Simplified Geologic cross-section of the Mississippi Embayment (after Brahana et al., 1987).*

There are a number of structural features believed to have formed in response to ongoing tectonism, even several features widely attributed to the earthquake sequence of 1811-12. These structural features include: the Reelfoot Fault scarp, Lake County Uplift, Crowley's Ridge, Blytheville Arch, Bootheel Lineament, and the Crittenden County Fault Zone. Some of these features are still being evaluated and their precise origin remains unresolved (Van Arsdale, 2009). These features are summarized below.

<u>Reelfoot fault scarp and Lake county uplift.</u> Individual faults in the NMSZ remain unidentified throughout much of the zone because they are not generally associated with recognizable surficial expressions. Most of these faults have been identified based on seismicity recorded since 1974 and recent geophysical investigations (mostly seismic and gravity-anomaly). The only recognized geomorphic feature on the surface likely produced by the tectonic activity is the Reelfoot Fault scarp and the uplifted natural levees along the Mississippi River (Schumm, 1986). The Reelfoot scarp is a topographic escarpment that extends south-southeastward from near the town of New Madrid, Missouri, along the western margin of Reelfoot Lake, to a point south of the lake (Crone and Schweig, 1994), which separates the Lake County Uplift and Reelfoot Lake Basin (Figure 3). Studies have shown that the Reelfoot scarp is about 32 km long, while the subjacent Reelfoot Fault may be as much as 70 km long (Van Arsdale et al. 1999; Crone and Schweig, 1994). The Reelfoot scarp is believed to be related to the formation of the Lake County Uplift, which includes the Tiptonville Dome and Ridgely Ridge features (Purser and Van Arsdale, 1998). It is believed to have formed or recently reactivated by the 7 February 1812 earthquakes, which is thought to have emanated from the Reelfoot Thrust (Mihills and Van Arsdale, 1999). Structures identified in exploratory trenches that cross the Reelfoot scarp suggests that it represents a monoclinal flexure, likely formed by uplift of adjacent Tiptonville Dome (Russ, 1982). The dome is an east-dipping monocline believed to be the surface expression of a fault-propagation fold associated with the underlying blind Reelfoot Thrust (Van Arsdale al. 1995a; Van Arsdale, 2000), which dips about 32° southwest. Recent studies have revealed as much as 9 m of structural relief along the modern scarp (Mueller et al., 1999). Russ (1982) concluded that most of the deformation on the Tiptonville Dome likely occurred during the last 2,000 years. Paleoseismic studies have suggested that the uplift may have occurred during at least three distinct earthquake sequences that have recently been dated; two prior to 1800 and that during 1811-12. Kelson et al. (1992, 1996) examined stratigraphic relations exposed in a trench across the Reelfoot scarp and, based on radiocarbon dates of scarp-derived colluvial deposits, concluded that the penultimate event occurred sometime between 1310 ±90 and 1540 ±90 AD, with a possible earlier event, prior to about 900 AD. Mueller and Pujol (2001) showed that the thrust is not strictly linear and suggested that the portion of the thrust, between 6- and 14- km depth, increases from between 25° and 31° to something between 42° and 75°, at the much shallower depths north of the Cottonwood Grove fault. Van Arsdale et al. (1998) found that 15 m of basal Quaternary deposits are displaced on the Reelfoot fault, increasing to 70 m, at the top of the Paleozoic strata, and the same stratigraphic units thicken on the downthrown side of the fault. This suggests that the Reelfoot fault has periodically been reactivated since the Paleozoic/Mesozoic interlude.

<u>Crowley's Ridge.</u> Crowley's Ridge is a linear elevated ridge that outcrops in the northwestern center of the Mississippi Embayment, extending 320 km from Helena, Arkansas, to Thebes, Illinois (Van Arsdale et al., 1995b). By all accounts it is an anomalous structural feature that remains largely unexplained, though Fisk (1944) was among the first to suggest that it is structurally controlled, uplifted by bounding faults on either side of the feature. Seismicity recorded since 1974 does not emanate from any portion of Crowley's Ridge, but well to the east of it (see figure 3). More recent work summarized by Van Arsdale et al. (1995b) presents additional evidence that Crowley's Ridge is structurally controlled. Since the imaged faults lie at the base of the ridge margins, the authors suggest that these features have been active during the Quaternary. The authors also feel that the faulting during Paleocene and Eocene is suggested by straigraphic correlations, such as marked thickening of the Midway and Wilcox Groups during Eocene time. During the interval between Paleozoic and Eocene time normal faulting appears to have elevated Crowley's Ridge 30 to 60 m, along the bounding faults originally postulated by Fisk (1944). Eocene or Pliocene-Pleistocene strata exposed along the Ridge appear to be displaced a maximum of ~7.5 m. Van Arsdale et al

(1995b) and Van Arsdale (2009) believes that most of the faulting in Crowley's Ridge is Tertiary and Wisconsin in age and that this deformation triggered some denudation of the Mississippi Valley.

Blytheville Ach. The Blytheville arch was originally defined and mapped from seismic reflection profiles (Johnston and Schweig, 1996). In these signatures researchers identified a strong upwarp of Paleozoic strata within a 10–15 km wide zone that widens to the northeast. In this zone, flat-lying, continuous strata of Late Cretaceous and younger age strata overlies the upwarp. The rocks in the arch zone (Figures 3 and 4) also appear to be highly deformed and fractured, as inferred from low velocity and high attenuating seismic wave signatures. The Blytheville Arch extends along the axis of the Reelfoot Rift and the longest semi-continuous trend in post-1974 seismicity emanating from the NMSZ, which correlates with the Blytheville Arch along the axis of the rift (Crone et al., 1985; McKeown et al., 1990). Several mechanisms have been proposed for the formation of the Blytheville Arch, buts its origin remains unresolved. Crone et al., 1985 suggested that igneous intrusions might have caused the arch to form. Langenheim (1995) supports the intrusion mechanism by suggesting that nearly the entire arch is coincident with shallow intrusions. McKeown et al. (1990) argued that neither of these mechanisms would be correct because no folds or large reverse faults have been identified from the seismic reflection profiles and strata outside the rift appear undeformed. They proposed that the Blythville Arch was formed by diapiric movement, initiated by tensional stress normal to the Reelfoot Rift during the late Paleozoic, probably as a result of the Ouachita Orogeny (McKeown et al., 1990). One other structure that may have caused the Blytheville Arch to develop is a positive flower structure, a hypothesis favored by Johnston and Schweig (1996) and Crone et al. (1985). Johnston and Schweig (1996) suggested that the Blytheville Arch may have been formed during a period of transgressional strike-slip faulting along preexisting axial faults.

Bootheel Lineament. Another structural feature, named the Bootheel Lineament, was identified in the NMSZ in the early 1990s (Schweig and Marple, 1991; Schweig et al. 1992). These workers speculated that the 135 km long north-northeast oriented lineament is likely the surface expression of a coseismic strike-slip fault related to the 1811- 1812 earthquakes. Schweig and Marple's (1991) interpretation was based on a regression analysis considering the length of the fault, which is capable of spawning an earthquake of moment magnitude 7.6. The lineament does not coincide with any of the major trends in post-1974 seismicity, but intersects the southwestern arm of recorded seismicity (see Figures 3 and 5). They speculated this trend may be due to strain release or major reorientation caused by stress release on the NMSZ during the 1811-12 earthquake sequence.

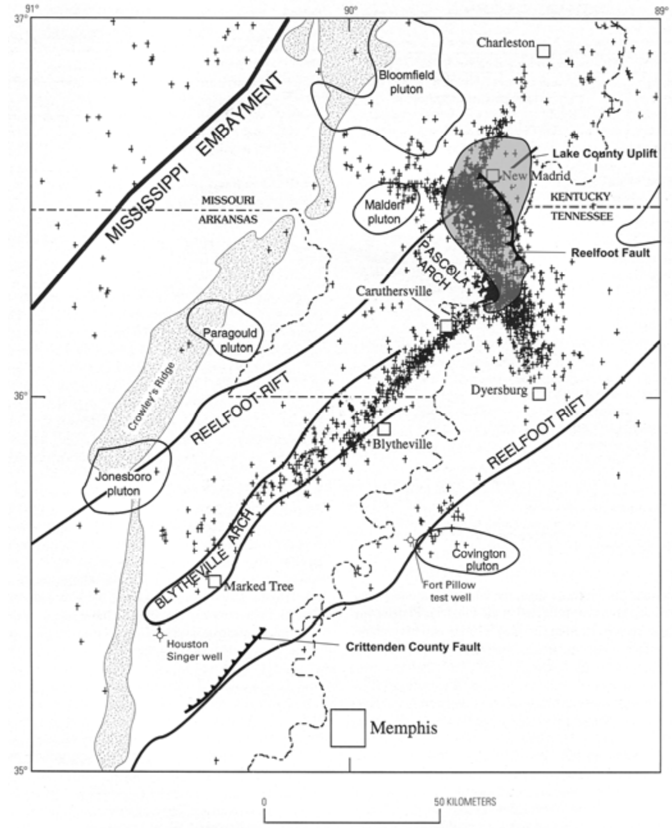


*Figure 3. Map showing the major tectonic features of the New Madrid Seismic Zone (Reelfoot Rift, igneous plutons, the Blytheville Arch, the Pascola Arch, Reelfoot Fault, and Lake County Uplift) and epicenters of microearthquakes in the upper Mississippi Embayment recorded after 1974 (modified from Shedlock and Johnston, 1994; Van Arsdale et al., 1995a/b).*

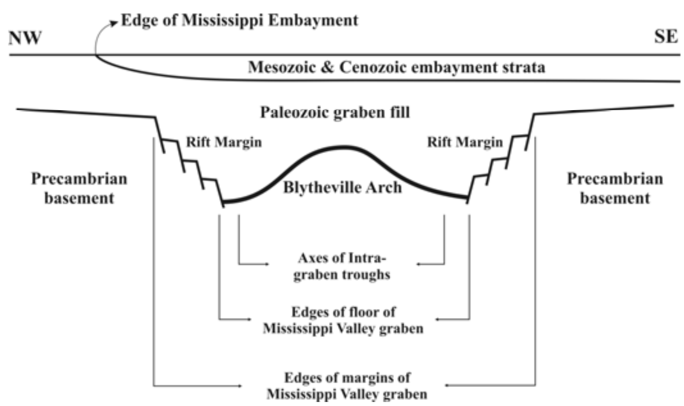


*Figure 4. Northwest-Southeast cross-section of the Reelfoot Rift and Blytheville Arch (modified from McKeown and Diehl, 1994).*

Crittenden County Fault Zone. The Crittenden County Fault is a 32-km long, northeast-trending, northwest dipping, down-to-the-southeast reverse fault (Luzietti et al., 1995) located near the southeast boundary of the Reelfoot Rift in northeastern Arkansas (Figure 3). On its southwest side the fault zone coincides with the rift margin, but towards the northeast it separates from the rift and diverges north as much as 4 km (Crone, 1992). The Crittenden County reverse fault displaces Cretaceous and Paleozoic rocks as much as 60 and 83 m, respectively (Luzietti et al., 1992). According to Crone (1992), this fault has experienced repeated episodes of movement throughout late Cretaceous and into the Tertiary. Luzietti et al. (1992, 1995) argued that this style of faulting is characteristic of compressional tectonics, while Crone (1992) interpreted that the ruptures in the Crittenden County Fault Zone are strands of graben-bounding normal faults that were reactivated as reverse faults from Late Cretaceous to middle-to-late Eocene time. Crone (1992) suggested a possible link between the Crittenden County Fault and the rift bounding faults with evidence of recurrent movement from late Cretaceous to late Eocene time, suggesting that this zone may be capable of generating large magnitude earthquakes, though with less frequency than longer segments. The unconformity displays significant lows east and west of the fault with relief up to 25 m. According to Mihills and Van Arsdale (1999), this relief could be the result of recent (Holocene age) subsidence.

<u>Seismicity</u>

The NMSZ dominates Central U.S seismicity and, according to Johnson and Nava (1990), has the highest seismic moment release rate of any seismic source zone in a stable continental region documented to that time (1990). The contemporary seismicity (1974-present) and deformation in the New Madrid region appears to be controlled by a regional stress field in which the maximum compressive stress is oriented approximately east-northeast-west-southwest. Historic seismicity of the region is summarized in Figure 5. Most of the active seismicity is concentrated in the northern embayment along a south-plunging trough of Cenozoic and upper Cretaceous age sedimentary rocks, which reach a depth of 1 km beneath Memphis, TN. Figure 5 also shows three principal trends of active seismicity in the NMSZ; two northeast-trending arms with a connecting northwest-trending arm. This pattern has been interpreted as a northeast-trending, right lateral strike-slip fault system with a compressional northwest-trending step-over zone (Bakun and Hopper, 2004). Since discrete faults are not expressed at the surface (with the exception of Reelfoot scarp), researchers have found it difficult to assign specific lengths for the entire zone. The zone of active seismicity extends from near Marked Tree, AR (on the southwest) to Charleston, MO (on the northeast); a distance of about 180 km, although diffuse seismicity extends over a slightly greater distance (Figure 5). A study by Johnston and Schweig (1996) identified seven candidate fault segments within the central fault system of the NMSZ: the Blytheville Arch (BA), Blytheville Fault Zone (BFZ), Bootheel Lineament (BL), New Madrid West (NW), New Madrid North (NN), Reelfoot Fault (RF), and Reelfoot South (RS), shown on Figure 5.

Some of the largest historic earthquakes in Central and Eastern North America occurred during the winter of 1811-1812. The 1811-1812 earthquake sequence had three main shocks and one large aftershock (the main shock of $M_w$ 7.6 on December 16, 1811 was followed by a strong aftershock of $M_w$ 7.0 later the same day [Hough and Martin, 2002]). Each of the main shocks were followed by ~15 aftershocks greater than $M_s$=6 and ~1600 aftershocks large enough to be felt over the three months following the initial event (Hamilton, 1981; Algermissen, 1983; Nuttli, 1987). The actual magnitudes of the 1811–1812 New Madrid events remain uncertain for a number of reasons. The 1811–12 earthquakes occurred before the region west of the Mississippi River was settled; so no credible intensity information was recorded west of the river, only east of it. Shaking intensity contours for the 1811-12 events are, therefore, sparse and inconsistent.

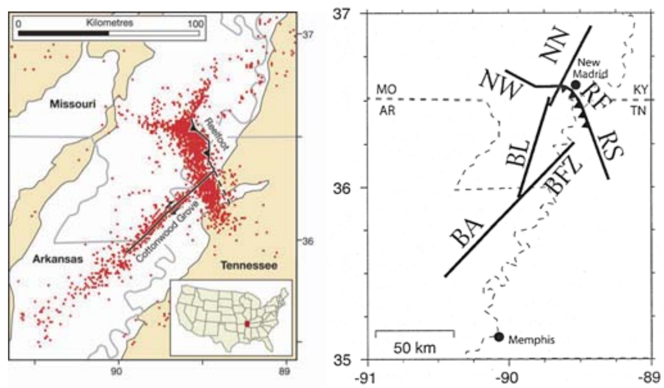


*Figure 5. The left figure: shows three principal trends of seismicity; two northeast-trending arms with a connecting northwest-trending arm. This pattern of seismicity has been interpreted as a northeast-trending, right lateral strike-slip fault system with a compressional northwest-trending step-over zone (Bakun and Hopper, 2004). Dots only represent seismic activity recorded between 1974-96. The right figure shows the fault segmentation of the NMSZ. The seven segments and their respective lengths are: Blytheville Arch (BA-70 km), Blytheville Fault Zone (BFZ-55 km), Bootheel Lineament (BL-70 km), New Madrid West (NW-40 km), New Madrid North (NN-60 km), Reelfoot Fault (RF-32 km), and Reelfoot South (RS-35 km) (from Bakun and Hopper, 2004). The Cottonwood Grove fault includes both the BA and BFZ segments.*

Another nagging uncertainty arises because of the low rate of seismic activity in the Central U.S. and brief duration of data collection (1974-present), as compared to other regions, like California. A third uncertainty arises out of the extreme impedance contrast between the underlying Paleozoic age bedrock and the unconsolidated alluvial soils filling present-day river channels. The impedance contrast between the Paleozoic age bedrock ($V_s$ = 3000 to 4000 m/sec) and Pleistocene age ($V_s$ = 175 to 275 m/sec) or Holocene age ($V_s$ = 150 to 200 m/sec) is quite severe as compared to other parts of the world. The impedance contrasts causes marked amplification of ground motion, especially of low amplitude, long period motions. The severe impedance contrasts in Holocene alluvium along river valleys likely resulted in an overestimation of the magnitude of the 1811–12 earthquakes because the early American communities were all situated along major river channels (Bakun and Hopper, 2004). Table 1 summarizes the range of estimated magnitudes for the 1811–12 earthquakes, proposed over the past ~30 years.

The locations of 1811–12 earthquakes have been resolved with a reasonable degree of agreement for the December 16, 1811 and February 7, 1812 events. Bakun et al. (2003) employed the limited isoseismal area constraint method (Bakun and Wentworth, 1997) to fix the locations of the 1811-12 main shock events in the NMSZ. The pair of December 16, 1811 earthquakes are believed to have occurred on the southern arm of seismicity associated with the Blytheville Arch (Johnson and Schweig, 1996; Muller, Hough, and Bilham, 2004). Johnston and Schweig (1996) outline two alternative geometries for the main rupture for this quake; either BA and BL, or BA and BFZ (see Figure 6). The February 7, 1812 $M_w$ 7.8 earthquake is generally believed to have occurred on the Reelfoot Fault (RF), possibly, including the New Madrid North (NN) or Reelfoot South (RS) segments. Mueller and Pujol (2001) stated that although the Reelfoot thrust is less than a third the length of the Cottonwood Grove fault (BA and BFZ), the area of the thrust is significantly larger because it has a much shallower dip, which varies from 30-75° along strike. This has the effect of increasing the amount of elastic strain energy stored within the ground mass surrounding the fault.

Table 1. Magnitude Estimates from Recent Studies. The magnitudes with stars are body magnitudes ($M_b$) while those without stars are moment magnitudes ($M_w$)

| | 16 December 1811 | 23 January 1812 | 7 February 1812 | 31 October 1895 |
|---|---|---|---|---|
| **Nuttli (1973)** | 7.2* | 7.1* | 7.4* | ----- |
| **Street (1982)** | 7.0* | 7.1* | 7.3* | ----- |
| **Stover and Coffman (1993)** | ----- | ----- | ----- | 5.9 |
| **Johnston (1996)** | 8.0 | 7.8 | 7.9 | 6.6 |
| **Hough et. al. (2000)** | 7.2-7.3 | 7.0 | 7.4-7.5 | ----- |
| **Mueller and Pujol (2001)** | ----- | ----- | 7.2-7.4 | ----- |
| **Bakun et. al. (2003)** | ----- | ----- | ----- | 6.0 |
| **Bakun and Hopper (2004)** | 7.6 | 7.5 | 7.8 | ----- |
| **Hough et al. (2005)** | ----- | 6.8 | ----- | ----- |

The January 23, 1812 earthquake has proven more difficult to constrain using the limited isoseismal area constraint method. Until recently, it was generally inferred to have occurred on the northern arm of the NMSZ, along segment NN (New Madrid north), according to Johnston and Schweig (1996); Tuttle, et al. (2002), and Cramer et al. (2005). Hough et al. (2000), Bakun and Hopper (2004), and Hough et al. (2005), have presented an alternative scenario for this rupture, in which New Madrid West (NW) is responsible, or possibly, the Wabash Valley Fault Zone (White County, IL), 220 km northeast of the NMSZ (and 378 km from the assumed epicenter for this event). A major problem with this interpretation is the physical evidence gleaned from recent paleoseismic studies within the NMSZ, which suggests four major events that date from 1811-12 (Tuttle, et al., 2002, Tuttle et al., 2005; Cramer et al., 2005). To date, liquefaction features triggered by the 1811-12 earthquakes have not been documented at distances greater than 240 km (Street and Nuttli, 1984; Johnston and Schweig, 1996; Tuttle et al., 2002). Figure 5 shows the approximate locations of historic quakes, based solely on reported intensities from inhabited areas.

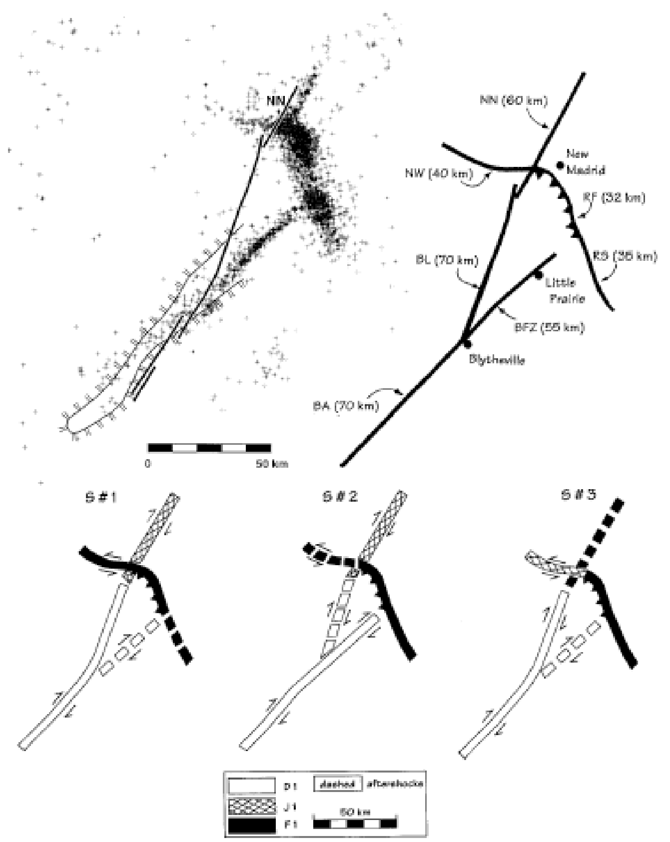


*Figure 6. Fault segmentation characterizing the NMSZ, showing possible fault rupture scenarios (S#1, S#2, S#3) for the 1811-1812 earthquakes, as defined by Johnston and Schweig (1996). The seven segments are identified in the text and the caption for Figure 3. D1 represents 16 December 1811, J1 represents 23 January 1812, and F1 represents 7 February 1812 earthquake sequences, using the seven fault segments. Based on historical and physical constraints, Johnston and Schweig (1996) stated that the D1 principal event must rupture BA, and the F1 principal event must rupture RF in all scenarios. S#1 was the favored scenario of the authors.*

Numerous paleoseismic investigations suggest that the largest 1811-1812 earthquakes were not unique in magnitude because paleoliquefaction features provide convincing physical evidence that no less than four similar size earthquake sequences have occurred over the last 2500 years, with an average recurrence of 500±300 years for the NMSZ events. Evidence was found for two historic earthquakes, similar in size and source zone of the 1811-12 events. These include an earthquake sequence that occurred 1450 ±150 years A.D. and another dated around 900 ±100 A.D (Tuttle and Schweig, 1995; Tuttle et al., 1999; Tuttle et al., 2002; Tuttle et al., 2005). Trenching studies in the Reelfoot Fault scarp have also shown that at least one sizable event (causing widespread liquefaction) likely occurred sometime between 1310 and 1540 A.D., and a possible earlier event, prior to 900 A.D (Russ 1982; Kelson et al. 1992, 1996). Saucier (1991) also reported paleoseismic evidence of a strong earthquake north of New Madrid, which likely occurred before 539 A.D. and weaker evidence for a younger event, occurring around 991 A.D. The oldest documented event associated with the modern Reelfoot Fault scarp appears to have occurred between 780 and 1000 A.D (Kelson et al. 1996). More recent studies (Smalley et al., 2005) concluded that the NMSZ is probably deforming at strain rates of 2.7 mm ± 1.6 $yr^{-1}$, which is on the same order of magnitude as measurements recorded on tectonic plate boundaries. These measurements are consistent with Tuttle et al. (2002), who suggested that the NMSZ produced earthquakes of M 7.6 or higher about once every 500 years. Mueller et al. (1999) calculated the strain rate on the Reelfoot Fault to be 6.1 ±0.7 mm/yr, based on the amount of Holocene deformation associated with the Lake County Uplift and the Reelfoot Fault scarp. The same study computed a slip rate of 1.8 to 2.2 mm/yr on the axial faults. However, other controversial GPS results are reported elsewhere (Newman et al., 1999). These researchers used a plate boundary model to interpret their GPS data and suggested that if the largest of the 1811-1812 shocks had been ~M 7, a recurrence interval of 500 years based on paleoseismologic evidence would agree reasonably well with their short-term GPS measurements. Conversely, if a ~M 8 is assigned to the largest shock of 1811-1812, this would suggest a recurrence interval exceeding 2500 years, which is not consistent with the paleoseismic data accumulated thus far. This interpretation was strongly debated (EOS, 2000; Tuttle et. al., 2002). EOS (2000) noted that Newman et al. (1999) used a plate boundary model instead of an intraplate model in developing their conclusions, which created some controversy regarding the validity of such assertions. Tuttle et al. (2002) also argued that the geodetic analysis Newman et al. (1999) used assumed an infinitely long, interplate fault zone and did not consider known physical characteristics of the NMSZ. Another recent study (Nemwan, 2007) argued that Smalley et al. (2005) reported the geodetic measurements as strain rates, differences between small motions at two sites divided by the distance between them. According to Newman (2007), reporting small motions as strains can be misleading, because very low rates of displacement rates can be quoted as very high strain rates, which can lead to incorrectly inferring high seismic risk. This researcher showed that depending on the change in measurement distance, strain rates decrease dramatically away from, and increase rapidly, very near the fault, therefore, reporting seismic hazard as strain rate can synthetically increase the seismic hazard. Another recent study (Rydelek, 2007) supported this argument by suggesting that the motions recorded over the past few years may be transient effects from the 1811-1812 earthquakes and thus, provide little direct inference about future earthquakes. To support this idea, Rydelek (2007) did a model calculation on the Reelfoot fault for a Mw=7.8 event. Rydelek reported the same order of strain rates in the vicinity of Reelfoot fault when postseismic relaxation is assumed, suggesting that the assumed high rate of strain in this region due to accumulation would be wrong, until further data and analysis verify that the calculations are not just a local effect of long-term postseismic relaxation. Because various studies yield diverse slip-rate estimates, the results of the studies are still open to considerable discussion; they remain unresolved and will likely be debated well into the future, until a sufficient body of consistent data has been collected and synthesized. The velocity issues will eventually be resolved because the precision of GPS velocity estimates increases with time, either shrinking the estimated motions closer to zero or show significant deformations once it climbs above recognized levels of uncertainties (Stein, 2007).

The October 31, 1895 Charleston, MO quake is the largest post-1812 event in the Mississippi Valley region. Structural damage and liquefaction were reported along a zone running from Bertrand, MO to Cairo, IL. The estimated moment magnitude of this event is between 6.6 (Johnston, 1996) and 6.0 (Bakun et al., 2003). The epicentral location of this event has traditionally been ascribed to the area around Charleston, MO, where the most significant ground failures were observed (Johnston 1996). Bakun et al. (2003) have advocated that the October 1895 earthquake may have been centered in southern Illinois, about 100 km north of Charleston, MO. However, given the size of the 1895 earthquake, it is more likely that the rupture occurred close to the significant ground failure observations near Charleston, MO (Cramer, 2006). Figure 7 shows the assumed location of 1895 earthquake from Wheeler et al. (2003) and Bakun et al. (2003). The magnitude estimates for this earthquake are summarized in Table 1.

## THE WABASH VALLEY SEISMIC ZONE

### Structural and Geologic Setting

The Wabash Valley Seismic Zone (WVSZ) is located along the southern border of Illinois and Indiana within a spoon-shaped depression known as the Illinois Basin (Figure 6). The Illinois Basin is bounded on the east by the Kankakee and Cincinnati Arch, on the west by the Ozark Dome and Mississippi River Arch, on the north by the Wisconsin Arch, and on the south by the Mississippi Embayment (Nelson, 1995). Two major elements characterize the basin: a broad southwestward-plunging cratonic depression which extends across central Illinois and southwestern Indiana; and a rift system covering southern-most part of the basin (Kolata and Hildenbrand, 1997). The Wabash Valley fault system (WVFS) is the name that has been given to a linear northeast-southwest-trending band of 90 km long and 50 km wide (René and Stanonis, 1995) narrow graben structures that lies within in the Illinois Basin. Similar to the NMSZ (with the exception of the Reelfoot fault), the surface expressions of the Wabash Valley faults are covered by late Tertiary and Quaternary age unconsolidated sediments. The faults were initially recognized by the oil and gas industry when they tried to correlate structure and stratigraphy using exploratory wells and geophysical imaging (Bristol and Treworgy, 1979; René and Stanonis, 1995; Bear et al., 1997; Hildenbrand and Ravat, 1997; Woolery, 2005). These efforts characterized a series of high angle normal fault and strike-slip faults with trends between N15°E and N50°E. These faults offset the Pennsylvanian and older units with vertical offsets of as much as 145 m along the faults (Nelson, 1995; Bristol and Treworgy, 1979). Some workers have suggested that the WVFS may be a northward extension of the Reelfoot Rift (Sexton et al., 1986). However, Bear et al. (1997) concluded that the fault displacements of the WVFS actually decrease southward, in the direction of the NMSZ. These researchers suggested Cambrian age fault movement followed by strike-slip displacements along the major features during the balance of the Paleozoic. There are some other fault systems in close proximity to both the WVFS and NMFS. Included in these systems are: the Rough Creek-Shawneetown fault system to the south and the Cottage Grove fault system to the southwest (see Figure 6). The Rough Creek-Shawneetown fault system is a graben system which appears to be an eastward extension, or branch, of the Reelfoot Rift, which trends westward and curves sharply southwestward at its western terminus. It is bounded by large normal faulting (which ended by late Cambrian) to reverse faulting (which initiated during post-Pennsylvanian), shifting back to normal (extensional) faulting during early Mesozoic time. Displacements reach 2500 meters on the major faults. The Cottage Grove fault system consists of right-lateral strike-slip faults, with maximum lengths of only 22 km.  Post-Pennsylvanian horizontal displacements of these faults varies between several and hundreds of meters (Nelson, 1995).

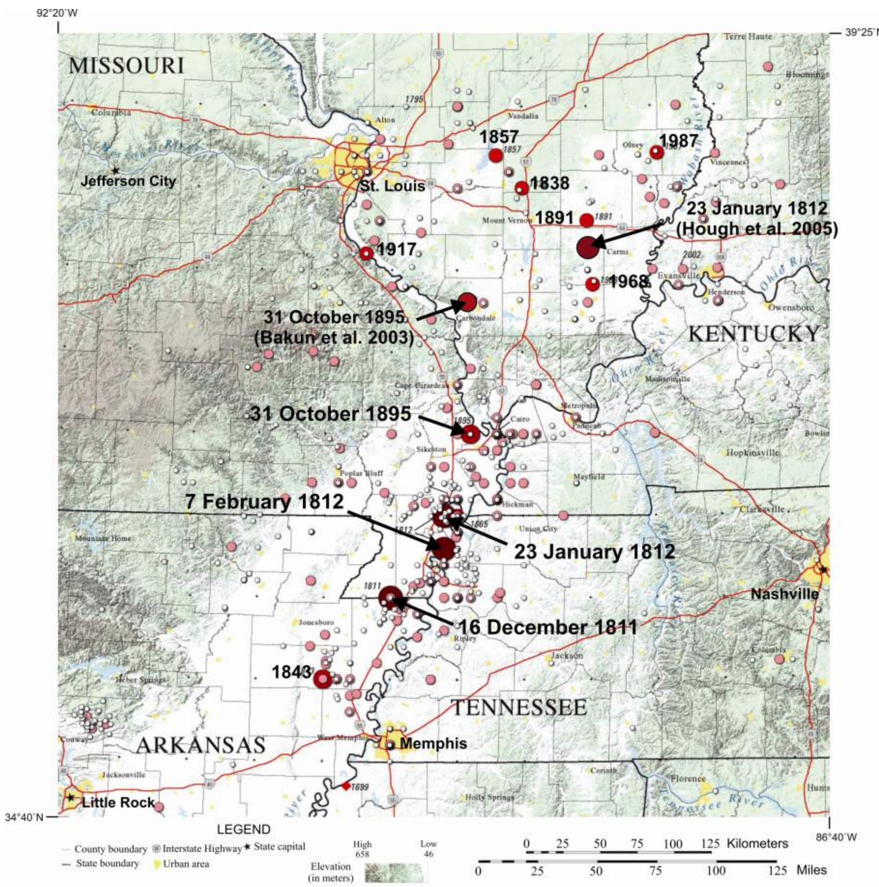


*Figure 7.  Location of historic earthquakes (modified from Wheeler, 2003). The diameter of the circles represent epicenters of historic earthquakes, with increasing magnitude. The circles with specific dates are those events with magnitude greater than 5.0, while the three main shocks from 1811-12 and M 6+ event of 1895 are identified separately. Alternative epicentral locations are also shown on the figure for 23 January 1812 (Hough et al. 2005) and 31 October 1895 (Bakun et al. 2003).*

The tectonic history of the Illinois Basin is summarized by Kolata and Hildenbrand (1997). During late Precambrian (~543 million years past-myp) to Middle Cambrian (~525 myp) the super continent broke up in response to extensional forces, forming a series of listric faults that bound the grabens in the Reelfoot Rift and Rough Creek Graben, a process that continued through late Cambrian time (~505 myp). Between late Cambrian and late Middle Ordovician (~470 myp), thermal subsidence and isostasy appear to have been the primary mechanisms controlling development of the proto-Illinois Basin. The Mississippian (~360-320 myp) and Pennsylvanian (~320-286 myp) periods witnessed the uplift of domes and arches, and far-field stress transmission from the Paleozoic Alleghenian and Ouachita orogenic belts (Craddock et al., 1993) which included high-angle faulting, forced folds, and reverse faulting in the Rough Creek Graben, and reverse faulting and strike-slip faulting in the Cottage Grove Fault System. This stress also caused widespread intrusion of ultrabasic magma in the Reelfoot Rift near its intersection with the Rough Creek Graben (Kolata and Hildenbrand, 1997). After this period of compression, during early Permian (~286 myp) the break-up of Pangea initiated, changing the stress field of the area and reactivating the faults within and adjacent to the rift.

## Seismicity

The WVSZ is the second most active source zone dominating Central U. S. seismicity. Historic and instrumental records suggest that, although the seismic rate is much lower than a typical plate boundary region, activity is by no means "zero." During historic occupation (post 1800) no moderate or large earthquakes have been felt in the WVFS. The diffuse seismicity pattern (see Figure 5) of southern Indiana and Illinois includes at least eight earthquakes exceeding M 4.5 during the last two centuries (Bakun and Hopper, 2004). The contemporary seismicity and deformation in the Wabash Valley region appears to be influenced by a regional stress field where the maximum compressive stress is oriented approximately east-northeast-west-southwest.

Some controversies remain regarding the boundary of the southern part of the region, where the Reelfoot Rift meets the Rough Creek Graben. According to Wheeler (1997), the Reelfoot Rift makes an angle of 30 to 40 degrees with the maximum horizontal stress ($SH_{max}$), promoting the strike-slip faulting. This would help explain why the Rough Creek Graben exhibits less seismicity (it parallels the maximum horizontal stress field). Historic seismicity of the region is summarized in Figures 5 and 7. Candidate active westward dipping thrust faults from seismic reflection profiles and recent paleoliquefaction studies in this region suggests that the WVSZ is capable of triggering repeated large-magnitude earthquakes, between M 7.0 and 7.8 (McBride, 1997; McBride et al 2002a; McBride et al 2002b), and has spawned repeated earthquakes over the last 10,000 years (Obermeier, 1998; Munson et al., 1997). Some of the proposed paleoquakes are described in the following paragraphs and their interpreted magnitudes are compared in Table 2.

Most workers feel that the largest paleoearthquake emanating from the WVSZ was the Vincennes-Bridgeport earthquake, which occurred 6,011 ± 200 yr BP (Obermeier, 1998). The magnitude of this earthquake estimates ranges between M 7.1 and 7.8 (see table 2) based on various methods explained previously. The recent study using magnitude-bound method estimates a magnitude of M 7.3 for this earthquake. However, Street et al. (2005) argued that the relationship assumed for these estimations should be the original Ambraseys Curve and that when this was applied to the same data, they determined a noticeably lower magnitude, of M 7.1.

The next largest earthquake that has been identified is the Skelton-Mt Carmel earthquake. This earthquake has been dated at 12,000 ± 1000 yr BP (Hajic et al., 1995, Munson et al., 1997 and Obermeier, 1998). The moment magnitude estimates of this event vary between M 6.7 and 7.4. The third largest earthquake event identified is known as the Vallonia earthquake. This earthquake is thought to have occurred in East Fork Valley, about 100 km east of the Wabash River. The date of this event is about 3,900 ±250 yr BP. The estimated moment magnitude of the Vallonia quake is between M 6.3 and 7.1. The largest prehistoric quake identified and dated within the WVSZ is the Martinsville-Waverly earthquake. This earthquake probably centered about 30-50 km southwest of what is now Indianapolis, and 5 km southwest of Waverly (Munson et al, 1997). Radiocarbon and archeological relations at two sites in this area bracket the age of the disturbance between 8,500 and 3,500 yr BP. This magnitude of this quake has been estimated between M 6.2 and 6.9.

The magnitudes of these paleoearthquakes have been estimated by various workers based on a suite of approaches, such as magnitude-bound, cyclic stress, and energy stress methods, and are summarized for comparison in Table 2. The interpreted locations of these earthquakes are shown in Figure 8. Considerable evidence also suggests that smaller magnitude earthquakes also occurred in the region. On 18 April 2008 a M5.2 earthquake centered near Mt. Carmel, Illinois was felt more than 500 km away, and 35 aftershocks were recorded on the Advanced National Seismic System (ANSS) detection array (Herrmann et al., 2008; Yang et al., 2009). The fault rupture occurred along a nearly vertical left-lateral strike-slip fault striking WNW-ESE. On 18 June 2002 an M4.6 quake rattled the Evansville, IN area (Eagar et al., 2006) about 46 km SSE of Mt. Carmel. In June 1987 a M 5.1 event occurred a few miles east of Olny, IL, about 27 km north of the 2008 Mt. Carmel epicenter. 40 years earlier a similar size quake emanated from Dale, also in southeastern Illinois. It was estimated to have a body wave magnitude $M_b$5.3 (Gordon et al., 1970) and surface magnitude ($M_s$) 5.2 (Stauder and Nuttli, 1970). It caused moderate damage in the near-field area and minor damage as far away as Chicago and St Louis. Figure 8 presents the assumed epicentral locations for historic earthquakes with magnitudes > 5.0.

Table 2. Magnitude Estimates from Recent Studies for Wabash Valley Earthquakes

| | Vincenes-Bridgeport earthquake | Skelton-Mt. Carmel earthquake | Vallonia earthquake | Martinsville-Waverly earthquake | Mt. Carmel earthquake (April 18, 2008) |
|---|---|---|---|---|---|
| **Obermeier et al., 1993** | M 7.8 | M 7.2 | M 6.9 | M 6.8 | |
| **Pond, 1996** | M 7.7 | M 7.4 | M 6.7 | M 6.9 | |
| **Munson et al., 1997** | M 7.5 | M 7.1-7.2 | M 6.9 | M 6.8-6.9 | |
| **Pond and Martin, 1997** | M 7.8 | M 7.3 | M 7.1 | M 6.9 | |
| **Street et al., 2004** | M 7.1 | M 6.6 | M 6.3 | M 6.2 | |
| **Olson et al., 2005** | M 7.3 | M 6.7 | M 6.3 | M 6.2 | |
| **Herrmann et al., 2008** | | | | | M 5.2 |

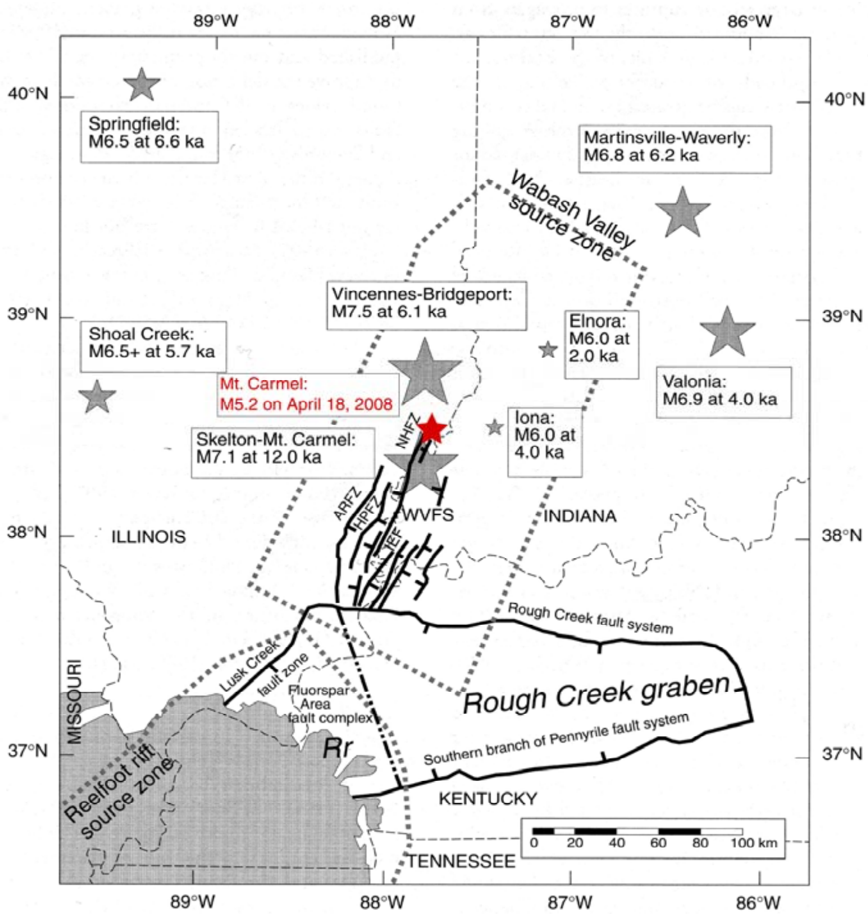


*Figure 8. Structural map showing the relation between the Rough Creek Graben, Wabash Valley Fault Zone and Reelfoot Rift Seismic Zone (modified from Wheeler and Cramer, 2002). Stars represent the interpreted historic epicenters of some of the large earthquakes occurred in the region. The magnitude estimates of these quakes are based on the studies by Herrmann et al., 2008; Munson et al., 1997; Obermeier, 1998; McNulty and Obermeier, 1999 and Tuttle et al., 1999. The four faults of the north-northeast striking Wabash Valley Fault System are: the Albion-Ridgway fault zone (ARFZ), Herald-Phillipstown fault zone (HPFZ), New Harmony fault zone (NHFZ), and the Inman East Fault (IEF).*

POSSIBLE SEISMIC ZONE IN SOUTH CENTRAL ILLINOIS

Paleoliquefaction data and basement faults have been identified in seismic-reflection data collected and synthesized in south Central Illinois (Su and McBride, 1999). These data suggest this region is capable of generating earthquakes with a maximum possible moment magnitude between M 6 and 7, nucleating in the Paleozoic age basement. This area has spawned two strong mid-Holocene events, known as the Springfield and Shoal Creek earthquakes, which have been identified in recent paleoliquefaction studies (McNulty and Obermeier, 1999). These investigators documented at least one moderate-size earthquake (M 6.2 to 6.8) and, probably, a second smaller event (~M 5.5) in the Springfield, IL region, between 5,900 and 7,400 yr BP. The same study also documented evidence of paleoliquefaction caused by another strong earthquake (Shoal Creek), believed to have occurred in southwest Illinois sometime around 4,520 BC ± 160 yr (McNulty and Obermeier, 1999). McNulty and Obermier (1999) believe that these earthquakes almost certainly exceeded M 6.0, but site enhancement effects caused by the severe impedance contrast between the Paleozoic basement and unconsolidated Quaternary-Holocene cover might also account for the scale of the observed paleoliquefaction features (Bauer, 2008). Tuttle et al. (1999) studied paleoliquefaction features in the St Louis area and identified at least two generations of Holocene age earthquakes were probably responsible for these features. Tuttle (1999) feels that the most recent liquefaction features probably formed during the 1811-1812 New Madrid events, while older paleoliquefaction features likely formed during the mid-Holocene earthquake, around 4,520 BC ± 160 yr. In addition, sand dikes along the Meramec River in St. Louis appear to be prehistoric, but post-date older features dated at 13,210 yrs before present. Tuttle (1999) suggested that possible paleoearthquake sources include the Valmeyer and Waterloo-Dupo anticlines; Du Quoin monocline; Centralia, St Louis, New Madrid faults, and an unidentified source near Shoal Creek. Figure 1 shows an arbitrarily drawn areal extent of the possible South Central Illinois Seismic Zone.
The seismicity in the St Louis area is generally believed to emanate from reactivation of old basement faults (Tuttle et al. 1999). Figure 1 shows recent microseismic (M 1-4) activity in the region while Figure 9 shows the principal structural features and locations of the assumed epicenters of earthquakes in this region (EGC, 2006).

SUMMARY AND CONCLUSIONS

A recent study (Cox et al., 2007) identified three sand blow fields in Arkansas as far as 200 to 250 km away from the New Madrid Seismic Zone. These sand blows may not be distal liquefaction features associated with earthquakes emanating from the New Madrid Seismic Zone, but could be associated with moderate size earthquakes on local faults, such as: the Saline River Fault Zone and/or Arkansas River Fault Zone, with probable moment magnitudes between 5.8 and 6.1. In this article, structural, geological and seismic characteristics of two definite seismic zones (New Madrid and Wabash Valley) and a candidate seismic zone (South Central Illinois) have been described and the key studies performed to date in these zones have been summarized. As more data is collected and evaluated in the American Midwest, a better understanding of the various seismic zones and their inter-relationships will hopefully emerge.

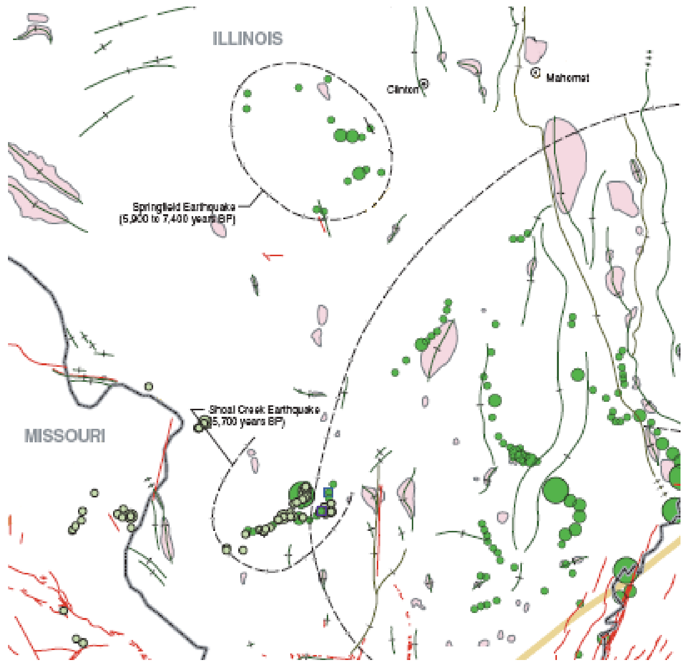


*Figure 9. Map showing bedrock structures, dome structures, liquefaction features, and likely paleoearthquake epicenters in south central Illinois (Exelon Generation Co., 2006).*

Catchings and Mooney (1991) indicated that the seismogenic crust in the New Madrid Region attenuates seismic energy only about 25% as effectively as the crust in the Western United States. The low energy attenuation in the Midwest allows damaging shear waves to travel much farther in the Central United States, so the quakes are felt over a much broader area than similar earthquakes in the western United States (Nuttli, 1979; Atkinson and Beresnev, 2002). Though less frequent than quakes along plate boundaries, a moderate magnitude earthquake (> M 6.0) could have devastating impacts on the Midwest, where pipeline and transportation corridors are obliged to cross thick sequences of unconsolidated valley fill between unfractured Paleozoic and Precambrian age basement rocks.
No small measure of controversy will abate in regards to the origins of the various seismic zones in the foreseeable future, due to the paucity of outcrops and research funding for assessing seismic risk in the Midwestern USA. The short period of observation and collection of microseismicity (~35 years) is much too short to draw any significant conclusions, other than the fact that the area exhibits anomalously high

seismicity at present, in comparison to adjacent regions of the continental U.S.

During the past decade a much better picture has emerged concerning the local geologic factors tending to control seismic site response, and the magnitudes of most of the historic earthquakes in the central U.S. have been lowered, accordingly. Some uncertainties will likely persist in regards to assigning energy centers for some of the historic earthquakes, in large part because of the asymmetry of reported shaking intensities, which emanated from sparsely populated hamlets along alluvial valleys of major rivers, along the Mississippi and Ohio River Valleys. A third controversy emanates from the results of the GPS measurements, which can be interpreted as either as the accumulation of accreting crustal strain preparatory to a future quake, or as post 1811-12 sequence relaxation (USGS, 2009).

In the most recent assessment (USGS, 2002; 2009) the USGS has assuaged that the probability of a repeat of 1811-1812 events, with moment magnitudes between 7.5 and 8.0, emanating from the NMSZ within next 50 years is 7–10%; and the probability of an $M_w$ 6.0 and greater event within next 50 years is between 25 and 40%. The later figure represents a very high likelihood of occurrence in the foreseeable future.

As more paleoseismic, seismic, geologic, recurrence frequency data, and GPS measurements have been amassed for the Central U.S., and with additional data, collected over decades instead of months, many of the issues described in this paper may be resolved. However, the tectonic issues and their implications for the seismic hazard and public policies attached thereto, will likely remain embroiled in debate until a damaging earthquake strikes the region.

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