Improving the Earthquake Chronology for the St. Louis Region: Collaborative Research, M. Tuttle & Associates and Central Region Geologic Hazards Team, U.S. Geological Survey

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Ancient rift cause of very large earthquakes in the heartland of the United States

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The geologic record of paleoearthquakes reveals a surprising picture of fault behavior in the central United States. The famous 1811-1812 New Madrid earthquakes of magnitude 7 to 8 and several similar prehistoric events left there mark in the fertile soils of the Mississippi River in the form of earthquake-induced liquefaction features and ground failures, uplift and subsidence of large tracts of land, folding and faulting of river deposits, and abrupt changes to river channels (e.g., Tuttle et al., 2002 and 2005; Guccione et al., 2005; Holbrooke et al., 2006). In addition, evidence is accumulating for very large earthquakes outside the New Madrid seismic zone proper, but within the Reelfoot Rift, an ancient fault system embedded in the continental crust (Braile et al., 1997). Piecing together the paleoearthquake record, the New Madrid fault zone produced 1811-1812 type events every 500-1800 years during the past 4.5 ky and other faults of the Reelfoot Rift produced similar events during the past 60 ky (e.g., Cox et al., 2001; Harrison and Schultz, 2002; Tuttle et al., 2002 and 2006; Holbrooke et al., 2006). The picture that is emerging suggests that the locus of activity shifts from one part of the rift to another over the course of 5-15 ky. These findings have important implications for ancient rifts and earthquake forecasting in intraplate settings.

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The occurrence of very large (magnitude > 7) earthquakes in the New Madrid seismic zone (NMSZ) and surrounding region in the central United States far from a plate boundary is not accounted for by tectonic theory and remains a challenge for earth scientists to explain. It is widely accepted that the North American plate is under stress from tectonic forces related to the formation of new crust at the Mid-Atlantic Ridge, but very large earthquakes are expected to occur at the boundaries of the plate (where new crust forms or where plates collides or grinds past each other), not in the plate's interior. The 1811-1812 New Madrid sequence of earthquakes, including three very large shocks of moment magnitude (M, a measure of total energy released by an earthquake) greater than 7.5 (Johnston, 1996; Hough et al., 2000; Bakun and Hooper, 2004), in the lower Mississippi River valley, was thought to be a rare event (Figure 1). In recent years, however, geologists have unearthed evidence for prior sequences of very large earthquakes, or New Madrid-type events, in the NMSZ and surrounding region produced by reactivation of Reelfoot Rift faults.

The New Madrid seismic zone (NMSZ) has been the focus of many studies because it is the most seismically active region east of the Rocky Mountains and it produced the 1811-1812 New Madrid earthquakes (Street and Nuttli, 1984; Johnston and Schweig, 1996). The high rate of seismicity in the NMSZ has been explained by relatively high heat flow as well as weak upper mantle and lower crust that permit deformation in the upper crust at a rate faster than the surrounding region (Liu and Zoback, 1997). Primarily through the study of hundreds of sand blows (deposits resulting from earthquake-induced liquefaction and eruption of water and entrained sediment on the ground surface) across the region, the NMSZ is thought to have generated earthquakes of **M** > 7.5 in 2350 B.C., 900 A.D., and 1450 A.D. in addition to the earthquakes of 1811-1812 (Figure 1; Tuttle et al., 2002 and 2005). The sand blows that formed during the paleoearthquakes are similar in size and are distributed over a comparable area to those that formed in 1811-1812 indicating that they formed as a result of very large earthquakes centered in the NMSZ. In addition, many of the prehistoric sand blows, like the historic sand blows, are compound deposits that formed during multiple, closely timed earthquakes resulting from complex interactions of the New Madrid fault zone (Figure 2; Saucier, 1989; Tuttle et al., 2002). On the basis of the paleoliquefaction record, an average recurrence time of 500 years was estimated for New Madrid events during the past 1200 years (Tuttle et al., 1999).

Other types of studies within the New Madrid region largely corroborate the results of liquefaction studies. Folding and the formation of colluvial wedges (deposits that formed on the down-thrown side of fault scarps) above the Reelfoot fault correspond with the 900 A.D., 1450 A.D., and 1811-1812 New Madrid events (Figure 2; Russ et al., 1982; Kelson et al., 1996). Fault length-magnitude relations suggest that the 32-40 km long Reelfoot fault is capable of **M** 6.8-7.0 earthquakes (Kelson et al., 1996). Displacements along the Bootheel fault occurred in 900 A.D. and 1450 A.D. and suggest earthquake magnitudes of **M** > 7 (Guccione et al., 2005). Land-level changes and related effects occurred near Lake St. Francis in 2350 B.C. and 900 A.D., near Big Lake in 900 A.D., and near Reelfoot Lake in 1450 A.D. (Guccione et al., 2005). Northeast of the Reelfoot fault, the Mississippi River channel experienced abrupt changes to its morphology that correspond with the 2350 B.C., 900 A.D., and 1450 A.D. events (Holbrooke et al., 2006). In addition, a fourth earthquake has been proposed about 1000 B.C. from river channel data. Liquefaction features that formed about this time have been found at a couple of sites in the vicinity of Blytheville, Arkansas (Tuttle, 1999) and support the interpretation that there may have been another New Madrid earthquake about 3 ka. Taken together, the various types of data provide strong evidence that the New Madrid seismic zone produced sequences of very large earthquakes every 500-1800 years during the past 4.5 ka.

Studies outside the NMSZ proper also have found evidence for very large paleoearthquakes. These paleoearthquakes are associated with members of the Reelfoot Rift fault system (Figure 3). In western Tennessee, faulting of river deposits occurred about 10 ka (Cox et al., 2001). The northeast-oriented fault coincides with a 150-km-long lineament that is interpreted as the expression of the eastern Reelfoot Rift margin fault (ERMF). Based on the length of the lineament, it was proposed that the ERMF is capable of generating **M** > 7.5 earthquakes. Seismicity is spatially associated with the lineament and attributed to the ERMF (Chiu et al., 1997; Hough and Martin, 2002). New Madrid-size sand blows that formed 5.5 ka and 6.8 ka occur at the southwestern end of the ERMF near Marianna, Arkansas (Al-Shukri et al., 2005; Tuttle et al., 2006). One of the older sand blows is composed of five depositional units and probably formed as the result of a sequence of earthquakes. Some of the sand blows occur near and along lineaments that parallel the ERMF and the White River fault zone (WRFZ), one member of a family of northwest-oriented faults that pre-dates the Reelfoot Rift. The ERMF and WRFZ have been proposed as possible sources of repeated very large New Madrid-type events 5-7 ka (Tuttle at al., 2006).

In southeastern Missouri, several studies have focused on the Commerce fault system (CF), now thought to represent the western margin of the Reelfoot Rift (Figure 3). These studies found evidence of multiple episodes of liquefaction and faulting during the past 60 ky. Liquefaction features in the Western Lowlands formed during two earthquakes in the past 1.8 ky and two other earthquakes between 9-13.6 ka and 17-23 ka are attributed to a local source, probably the CF (Vaughn, 1994). In the Benton Hills, the English Hill fault, a member of the CF, is composed of a series of north-northeast oriented, through-going strike-slip faults that juxtaposes deposits of different ages (Palmer et al., 1997). Fault displacements occurred twice in the past 10 ky and between 25-35 ka and 50-60 ka (Harrison and Schultz, 2002). Similar observations were made to the southwest where the CF crosses the southeastern flank of Crowley's Ridge (Baldwin et al., 2005).

Studies of several faults of the northern end of the Reelfoot Rift in southern Illinois have found no evidence of faulting for at least 55-128 ky (Nelson et al., 1999; McBride et al., 2002). However, recent findings in western Kentucky of liquefaction features, including a sand blow that formed about 11.3 ka, suggest that a large earthquake induced liquefaction in this area about the same time as the ERMF ruptured in western Tennessee (Figure 4).

Piecing together paleoearthquake data from the various studies, it appears that different parts of the Reelfoot Rift were seismically active at different times during the past 60 ky (Figure 3). The Commerce fault in the Benton Hills of southeastern Missouri was active from 60-50 ka and 35-25 ka and then became active in the Western Lowlands to the southwest from 23-17 ka and 13.4-9 ka. Both portions of the CF are thought to have been active during the past 10 ky. The northern portion of ERMF spanning western Kentucky and Tennessee was active about 11-10 ka. Activity apparently shifted to the southern portion of the ERMF near Marianna, Arkansas from 6.8-5.5 ka and then about 4.5 ka moved to the NMFZ which remains active today.

Recently collected paleoearthquake data support the hypothesis that seismicity migrated across the greater New Madrid region during the past several 10s of thousands of years and most recently shifted to the NMFZ (McBride et al., 2002). More specifically, the data suggest that activity on the northern portions of the Commerce fault and the ERMF may have loaded the southern portions of those faults that later became active. Similarly, activity on the southern ERMF and possibly the WRFZ may have loaded the NMFS, which has been active for the past 4.5 ka. By inference, faults that currently are being loaded by activity on the NMFZ are likely to become active sometime in the next few thousand years.

The New Madrid region is underlain by faults of the northeast-oriented Reelfoot Rift system and an even older northwest-oriented system (Csontas et al., 2008). As demonstrated by numerical modeling, strain can be accommodated by displacements over a network of faults, such as that in the New Madrid region, with activity migrating across the network over time as a function of the strain rate (McKinnon, 2006). Recent estimates of strain across the New Madrid seismic zone from geodetic measurements vary from rates similar in magnitude to active plate boundaries (Smalley et al., 2005) to those with no statistical significance (Calais et al., 2005). The finding that New Madrid-type seismicity migrates from one part of the Reelfoot Rift to another suggests that deformation may be localized by the rift but distributed across multiple faults and over a much larger area than the New Madrid seismic zone, making it easier to reconcile possibly low strain rates.

Important implications of the paleoseismic findings are that faults within the Reelfoot Rift that have been quiet during the historic period may become active in the future and that other ancient rifts embedded in the North American plate may have the potential to produce very large earthquakes. With additional study of the geologic structures and tectonic forces controlling the location and periodicity of seismicity, it might be possible to better forecast where and when very large earthquakes are likely to occur in the future.

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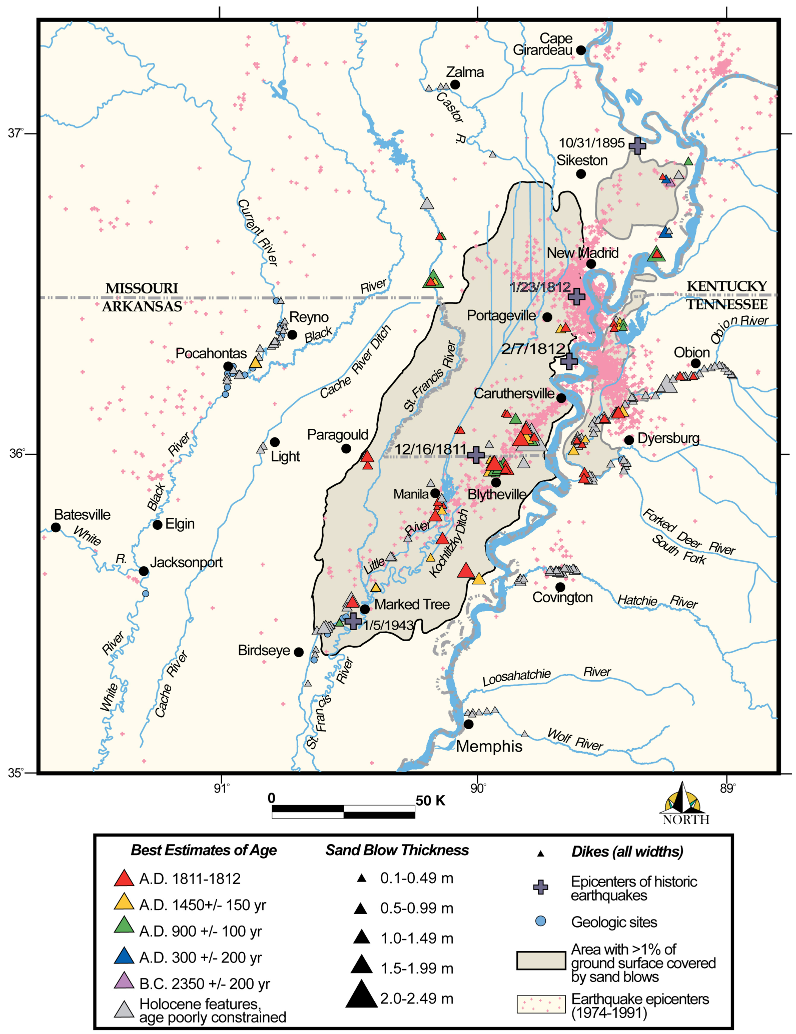

Figure 1 – Map of the New Madrid region showing inferred locations of large historic earthquakes (large gray crosses), modern seismicity (pink crosses), area of sand blows resulting from earthquake-induced liquefaction (tan area), and study sites of sand blows whose sizes and ages have been determined (triangles; see legend) (modified from Tuttle et al., 2005).

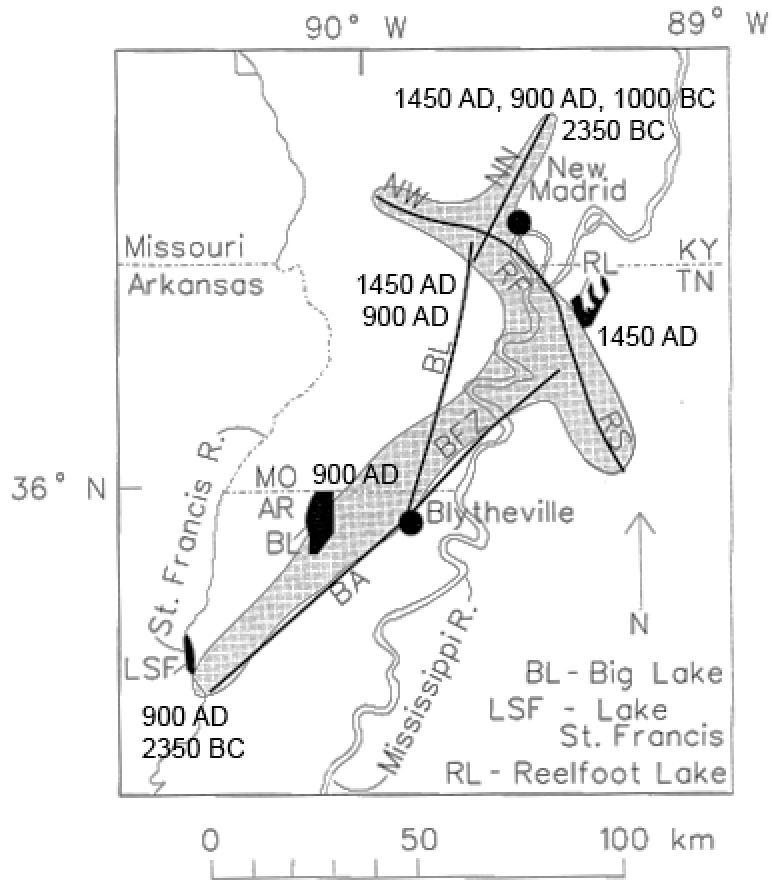

Figure 2 – Paleoearthquakes (shown by dates) associated with structures of the New Madrid fault zone (modified from Guccione et al., 2005; Johnston and Schweig, 1996). BA – Blytheville arch fault; BL – Bootheel lineament or fault; NW – New Madrid West fault; NN – New Madrid North fault; RF – Reelfoot fault; RS – Reelfoot South fault; LSF – Lake St. Francis; BL – Big Lake; RL – Reelfoot Lake.

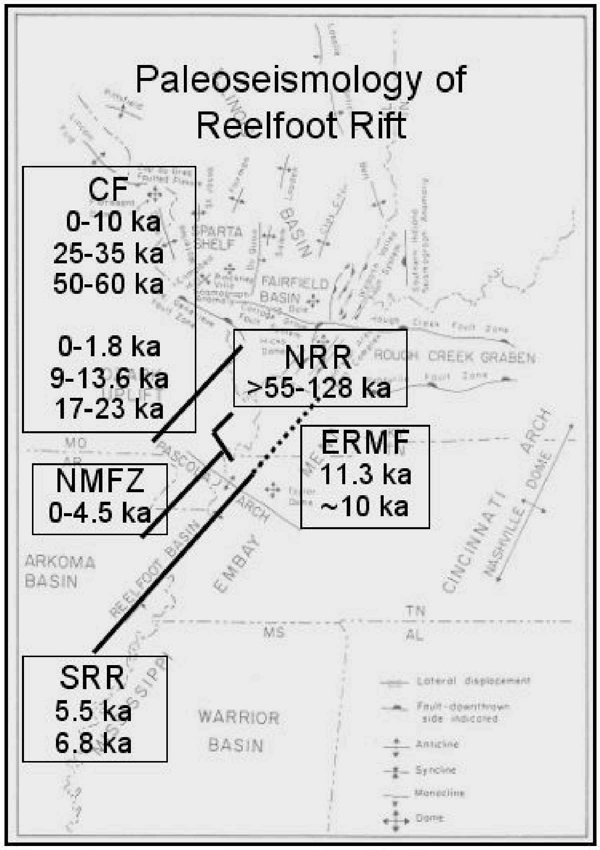

Figure 3 – Summary of paleoearthquake activity associated with different portions of the Reelfoot Rift. NMFZ – New Madrid fault zone; ERMF – Eastern Reelfoot Rift Margin fault; CF – Commerce fault; RR – Reelfoot Rift. Background map from Schwalb (1982).

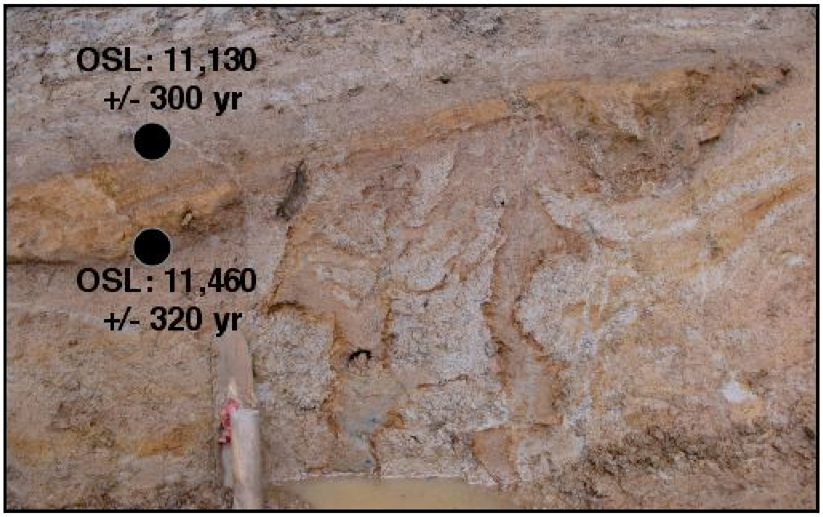

Figure 4 – Very weathered sand blow and feeder dikes among other liquefaction features found in western Kentucky. Dating by optically stimulated luminescence (black circles show sample locations) indicates that sand blow formed about 11.3 ka. Local fault of the Reelfoot Rift, possibly an extension of the ERMF, is the most likely source of the causative earthquake. Photograph by M. Tuttle.