EASTERN SECTION
SEISMOLOGICAL
RESEARCH LETTERS

Wagon Loads of Sand Blows in White County, Illinois

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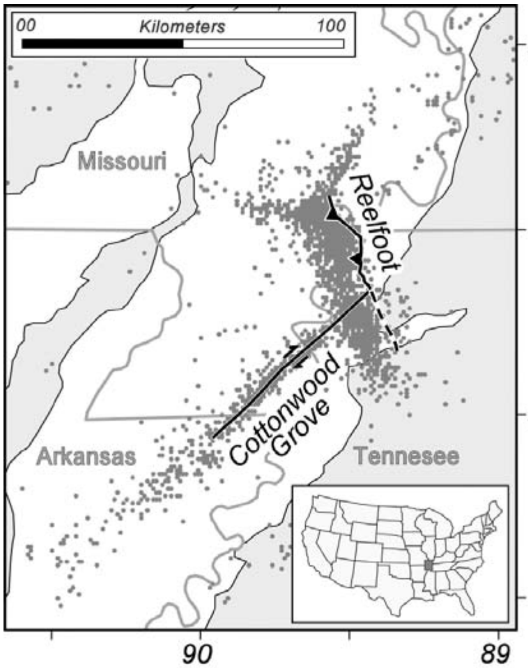
ABSTRACT

Several anecdotal accounts provide compelling evidence that liquefaction occurred at several sites in Illinois during the 1811–1812 New Madrid sequence, as much as 250 km north of the New Madrid seismic zone (NMSZ). At one Wabash Valley location, sand blows are still evident near Big Prairie, Illinois, a location described in a particularly detailed and precise historic account. This account includes descriptions of substantial liquefaction (sand blows) as well as a two-mile-long east-west-trending "crack" along which two feet of south-side-down displacement occurred. An offset can no longer be seen at this location, which has been extensively farmed and plowed for decades. Field reconnaissance verifies many of the details provided in the account, however. We conducted a seismic-reflection experiment at this location and observed a modest offset in the Paleozoic strata at this location. The offset is opposite to that described in the historic account, consistent with the hypothesis that large mid-continent earthquakes occur on faults reactivated in a Holocene stress regime different from the one in which they were formed. Only two explanations can account for these observations: Either large NMSZ events triggered substantial liquefaction at distances greater than hitherto realized, or at least one large "New Madrid" event occurred significantly north of the NMSZ. We explore these possibilities and conclude that, while neither one can be ruled out, several disparate lines of evidence suggest that the 23 January 1812 "New Madrid mainshock" occurred in White County, Illinois, near the location of the m_b 5.5 1968 southern Illinois earthquake and recent microearthquake activity.

REVISITING THE RUPTURE SCENARIO OF THE 1811–1812 SEQUENCE

The 1811–1812 New Madrid earthquake sequence included three well documented mainshocks that have been analyzed in considerable detail (*e.g.*, Nuttli, 1973; Penick, 1981; Street, 1982, 1984; Johnston, 1996b; Hough *et al.*, 2000; Bakun and Hopper, 2004). These events occurred at approximately 02:15 local time (LT) on 16 December 1811, around 09:00 LT on 23 January 1812, and approximately 03:45 LT on 7 February 1812 (henceforth NM1, NM2, and NM3, respectively). Based on a reanalysis of original felt reports, Hough *et al.* (2000) estimated M_w values of 7.2–7.3, 7.0, and 7.4–7.5, respectively. These magnitude estimates are consistent with results from geomorphic investigations (*e.g.*, Guccione *et al.*, 2002), scaling relationships (*e.g.*, Mueller and Pujol, 2001), forensic analysis of historic buildings that were and were not damaged during the sequence (Kochkin and Crandell, 2004), and comparisons of macroseismic effects with the 2001 M_w 7.6 Bhuj, India earthquake (Hough *et al.*, 2002). An additional large earthquake, the so-called "dawn aftershock", occurred near dawn on 16 December 1811 (hereinafter referred to as NM1-A; Johnston, 1996b; Hough and Martin, 2002).



▲ **Figure 1.** Map of New Madrid Seismic zone with recent background seismicity (small circles) and major faults.

Johnston and Schweig (1996) explored rupture scenarios for the sequence and presented a preferred scenario that has generally been adopted in subsequent studies. In their interpretation, events NM1, NM2, and NM3 respectively ruptured the Cottonwood Grove Fault (the southern strike-slip limb of the NMSZ), the northern limb of the NMSZ, and the Reelfoot Fault (Figure 1). Johnston and Schweig (1996) suggested that NM1-A occurred on the northern end of the Cottonwood Fault; Hough and Martin (2002) concluded that it ruptured a segment of the Reelfoot Fault. The location of NM2 is based on three observations: an apparent northward shift in the strongest shaking, relative to the other principal events; the assumption that each of the three principal limbs of the NMSZ ruptured in one of the three principal mainshocks; and one eyewitness account of the severity of NM2 in the village of New Madrid. Johnston and Schweig (1996) acknowledged the scenario for NM2 to be the most speculative of the three events. Later studies have not shed new light on the rupture scenario of NM2, as they have done for the NM1 and NM3 scenarios.

In a recent study, Bakun and Hopper (2004) reexamined the locations and magnitudes of the principal New Madrid events using the method of Bakun and Wentworth (1997). This approach uses a grid-search method to find a location and magnitude that are most consistent with a set of intensity values, given an attenuation relationship established from instrumentally recorded earthquakes. Bakun and Hopper (2004) noted that the optimal location for NM2 is to the northeast of the NMSZ but rejected a Wabash Valley location based on the (supposed) failure of field studies to find 1811–1812 liquefaction features in this region.

The extent of the 1811–1812 New Madrid liquefaction zone has emerged as an open issue in recent years. As mapped traditionally, the zone where more than 1% of the ground is covered by sand blows extends no farther north than 37°N, about 20 km beyond the northern edge of the NMSZ as illuminated by microseismicity, and no farther south than approximately 35.4°N (Obermeier, 1989; Tuttle and Schweig, 1996). Cox *et al.* (2004), however, describe substantial liquefaction in Arkansas, approximately 175 km south of the NMSZ, that might have formed during either the 1811–1812 or the penultimate NMSZ sequence. The liquefaction field generated by the 2001 M_w 7.6 Bhuj, India earthquake extended as far as 240 km (Tuttle *et al.*, 2002); Hough *et al.* (2002) concluded that the magnitude of this event is a credible upper bound for the magnitude of the largest 1811–1812 event.

The primary purpose of this paper is to present detailed preliminary observations of a site in southern Illinois, within the Wabash Valley, where extensive liquefaction was in fact documented during the 1811–1812 sequence. Our observations also motivated us to reexamine the rupture scenario for NM2. To do so, we first revisit explicitly the fundamental starting assumption made by almost all previous investigations of 1811–1812 rupture scenarios: that the geometry of the principal faults in the NMSZ can be inferred from instrumentally recorded background seismicity (Johnston and Schweig, 1996; Mueller and Pujol, 2001), which is considered to represent a long-lived aftershock sequence from the 1811–1812 mainshocks. Although this assumption is commonly made, the existence of such long-lived aftershock sequences has been a matter of some debate. Two lines of evidence suggest that some aftershock sequences do persist for centuries. Using a model incorporating rate-and-state friction, Dieterich (1994) shows that the rate of aftershocks divided by the background seismicity rate is proportional to the mainshock stressing rate normalized by the long-term stress rate. This model is consistent with the observation that long-lived aftershock sequences are relatively common in intraplate regions (Ebel *et al.*, 2000), as intraplate earthquakes are generally thought to be associated with high stress-drop values (Scholz *et al.*, 1986) as well as low background stressing rates. As Stein and Newman (2004) showed, quantitative estimates of aftershock duration in low-strain-rate regions depend critically on parameters that are difficult to determine with precision, but with plausible choices of parameters for the New Madrid sequence, the method of Dieterich (1994) does predict sequences that last for several hundred years.

Background NMSZ seismicity illuminates, in addition to the well constrained Cottonwood Grove and Reelfoot Faults, other linear features that may be associated with faulting (Figure 1). Das and Scholz (1981) demonstrate, however, that the pattern of static (Coulomb) stress change caused by mainshocks can result in regions of increased stress that correlate with off-fault aftershocks, where no primary mainshock rupture occurred. This result has been explored further, and tested at length, in the wake of the 1992 M_w 7.3 Landers, California sequence (*e.g.*, King *et al.*, 1994). Although aftershock distributions do not coincide perfectly with predicted stress change patterns, the theory typically accounts for the location of about 65%–85% of all aftershocks (King *et al.*, 1994; Hardebeck *et al.*, 1998). There is still debate regarding the extent to which aftershocks are controlled by static stress change, with, for example, some evidence that the dynamic stress changes associated with the passage of seismic waves are important as well (*e.g.*, Kilb *et al.*, 2000). Seeber and Armbruster (2000) show that, if one assumes that aftershocks of the 1992 M_w 7.3 Landers earthquake were triggered by static stress change, one can essentially invert the aftershock distribution to infer the pattern of mainshock rupture. This demonstrates that aftershock distributions reflect the mainshock stress changes well enough to be potentially useful for investigating mainshock rupture parameters. This presents a unique opportunity for historic earthquake studies: to use instrumental recordings of aftershocks to obtain quantitative constraints on preinstrumental mainshocks.

Focusing on the 1811–1812 sequence, Mueller *et al.* (2004) showed that ruptures on the Cottonwood Grove and Reelfoot Faults will generate off-fault lobes of increased Coulomb stress that coincide with the apparent minor fault limbs of the NMSZ. In particular, the northern limb of the NMSZ need not be associated with primary mainshock rupture. Moreover, a northern NMSZ location for NM2 does not appear to be consistent with the tenets of stress-change theories. (In the scenario presented by Mueller *et al.,* 2004, stress increases on the northern limb of the NMSZ after event NM3 occurs, but not after NM1 and NM1-A.) This work motivated a closer look at the historical accounts of NM2, to investigate whether written records might provide further clues to the location of this event.

In this paper we focus on a detailed analysis of accounts of NM2, including direct observations of effects from this earthquake. We also discuss several accounts of liquefaction in Illinois, including one that describes widespread liquefaction (sand blows) and ground disruption. Finally, we present results of a pilot seismic survey conducted in fall of 2003 to investigate the site further.

THE 23 JANUARY 1812 MAINSHOCK: “A WHOLE LOTTA SHAKIN’ GOIN’ ON”

Although NM2 was the only one of the three mainshocks to occur during waking hours, its intensity data set is the smallest of the three. This is generally attributed to the fact that the weather was unusually cold in the midcontinent during the month of January. Ice formed and slowed traffic on both the Ohio and Mississippi Rivers, thereby slowing the flow of information. For NM1 and NM3, some of the most valuable accounts are from boatmen who experienced the earthquakes firsthand. Hough *et al.* (2000) determined MMI values for 59 locations for NM2. This is smaller by a factor of almost 2 than the number of values available for NM1 (Hough *et al.*, 2000), although larger than the data set for NM1-A (Hough and Martin, 2002).

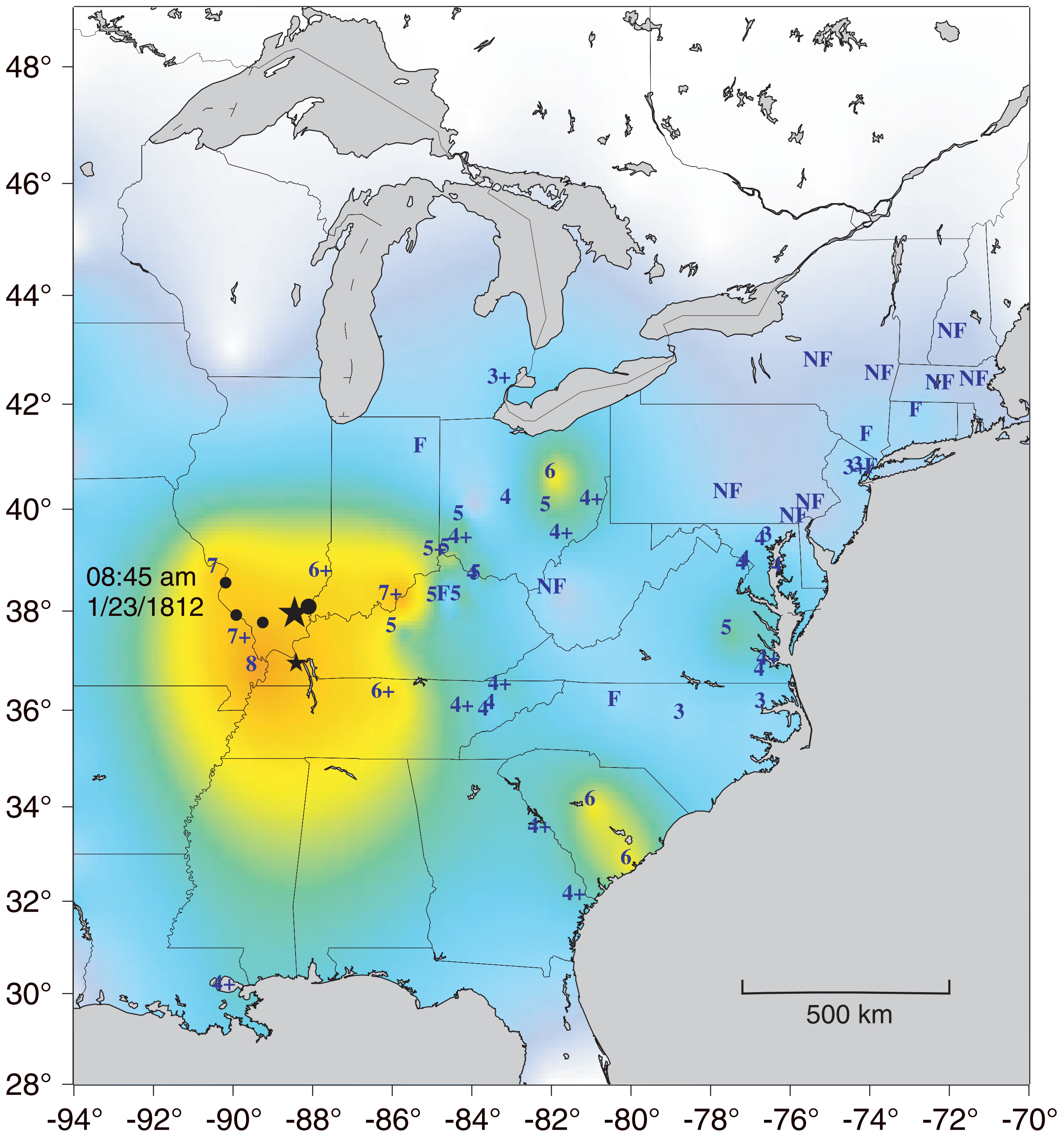
To map out the shaking distribution we employ a simple mathematical approach whereby the data are contoured using a continuous-curvature gridding algorithm. A uniform grid of estimated intensity values, $I(x,y)$, is determined by solving the equation

$$\left(1-T\right)\cdot L\left(L\left(I\right)\right)+T\cdot L\left(I\right)=0\ , \tag{1}$$

where T is a tension factor between 0 and 1, and L indicates the Laplacian operator (the divergence of the gradient; see Wessel and Smith, 1991, and online *GMT* documentation at `http://gmt.soest.hawaii.edu/gmt/doc/html`). A tension factor of 0 yields the minimum curvature solution, which can produce minima and maxima away from constrained values. With a value of 1, the solution is harmonic and no minima or maxima occur away from control points. We use a T value of 0.25. Different choices smear the signal from controlled points to a greater or lesser degree, although the overall character of the results is not very sensitive to the value used. Our experience is that a T value of 0.25 yields a qualitatively reasonable degree of smoothing of the data, particularly of isolated high MMI values that are inferred to reflect site response (see Hough *et al.*, 2000). Low MMI values are introduced artificially around the periphery of the map so that the low-intensity field tapers off at the edges. We then plot the results following the coloring convention developed to generate ShakeMap representations of intensities (Wald *et al.*, 1999). Conventional ShakeMaps use instrumental data to estimate shaking severity; here we generate intensity maps directly from MMI values. Figure 2 presents a map of documented shaking distribution for NM2.

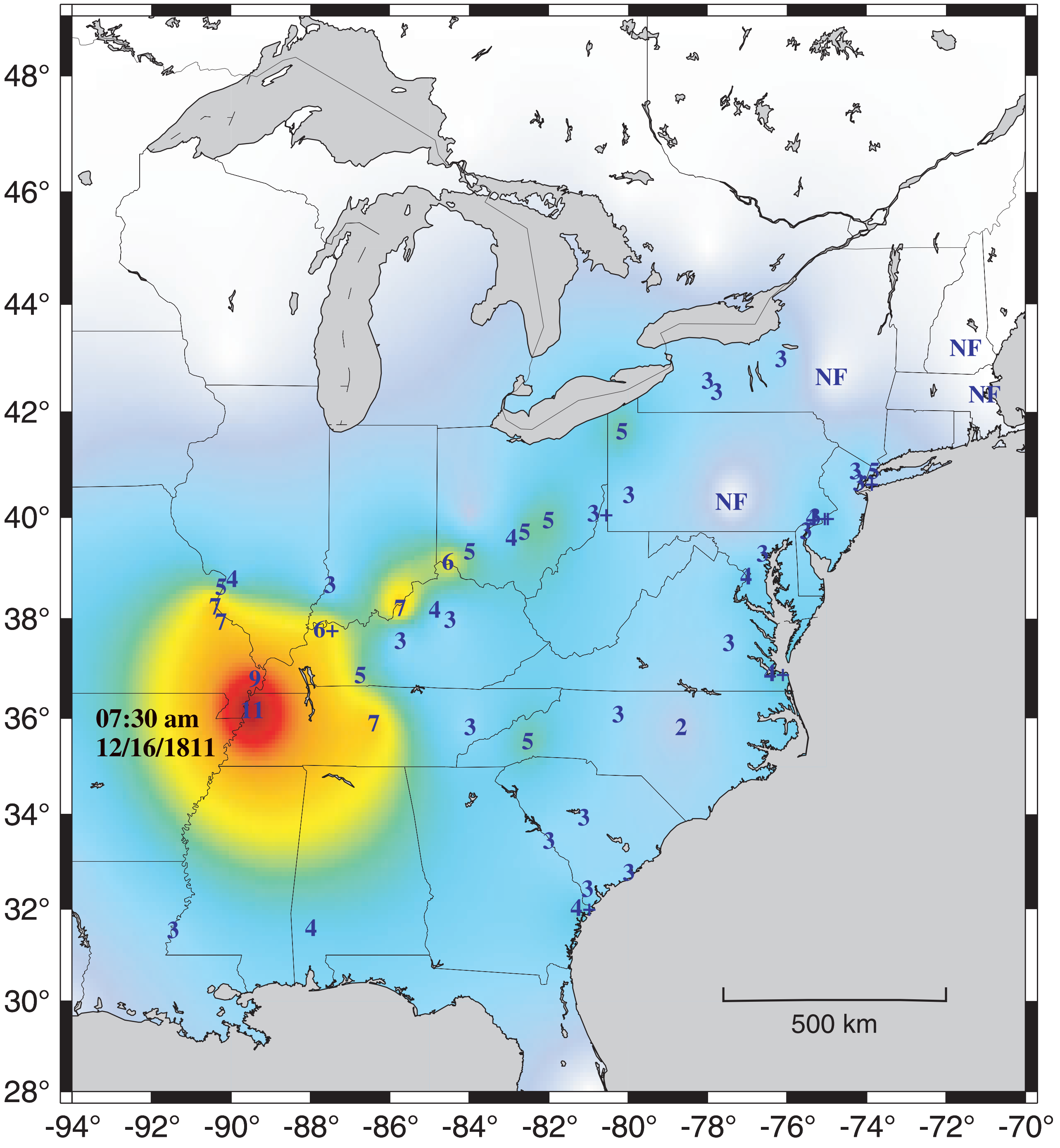
There are now several methods to determine magnitude from MMI data. Hough *et al.* (2000) used the isoseismal area-M_w regressions developed by Johnston (1996a) to determine magnitudes for the three principal mainshocks. More recently, Bakun and Wentworth (1997) presented a method to determine magnitude from the distance decay of MMI values. This method estimates an optimal magnitude and location using observed MMI values as a function of distance and calibrations established from instrumentally recorded earthquakes in a given area. We will use this method, for which Bakun *et al.* (2003) developed calibrations from central/eastern North American earthquakes, to investigate the location of NM2. A key question in such analysis is whether sufficient data exist to constrain the calibration relationships for large earthquakes. In any analysis of New Madrid events, one must also consider the preferential-site condition sampling discussed by Hough *et al.* (2000). That is, because of early American settlement patterns, accounts from the Midwest are preferentially from sites at which sediment-induced amplification is expected. In this study, however, our primary concern is the location of NM2, not its magnitude.

Allowing the location of NM2 to be unconstrained, we find an optimal location to be at –88.41°W, 36.96°N (western Kentucky; Figure 2), with a preferred M_w value of 6.8. That



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

▲ **Figure 2.** MMI values inferred from felt reports of event NM2 at approximately 08:45 AM (LT) on 23 January 1812. Symbols are centered on locations of towns. Map shows optimal location using method of Bakun and Wentworth (1997) (small star), location of documented liquefaction in White County (large circle), other sites of documented liquefaction in 1811–1812 (small circles), and our preferred location (large star).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
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INSTRUMENTAL INTENSITY	**I**	**II-III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X+**

▲ **Figure 3.** Shaking intensity map for event NM1-A.

the optimal location is east of the NMSZ is not surprising: locations are never well constrained when earthquakes are located at the edges of one-sided intensity distributions. Comparing the intensity distribution with that of NM1-A, however, which was apparently similar in size to NM2, one finds a systematic shift in the intensity pattern (Figure 3). Focusing on the MMI V–VII values in Figure 2 compared to Figure 3, we see a shift not only to the north but also to the east.

All of the accounts used to estimate the MMI values are available in Street (1984) and discussed by Street (1982). In the following section we discuss just a few of the salient observations.

At New Madrid, Eliza Bryan (one of the few faithful correspondents in the New Madrid region) described NM2 as being as severe as any of the previous shocks. The event was also described as being more severe, and causing more damage, than the previous shocks at Cape Girardeau and St. Louis, to the north of New Madrid. These accounts are consistent with a location toward the northern end of the NMSZ. NM2 was also particularly severe at a number of locations well east of the NMSZ, however. In Louisville, Kentucky, the event was described as more severe than NM1, breaking off several chimneys. In Chillicothe, Ohio, NM2 was described as "much more terrible" than NM1. (All accounts are included in the compilation of Street, 1984.)

It is possible that NM2 was simply larger than NM1 and NM1-A, but the overall intensity distributions provide evidence to the contrary. It is also possible that radiation pattern differences contributed to differences in the distribution of shaking effects. We conclude that Figures 2 and 3 suggest a north-northeast shift of source zone for NM2 relative to the earlier events.

Considering the distances between New Madrid and locations such as Louisville (a distance of 380 km), it seems unlikely that the relative intensities of NM1 and NM2 can be explained by a location of the latter being only tens of kilometers to the north of the former.

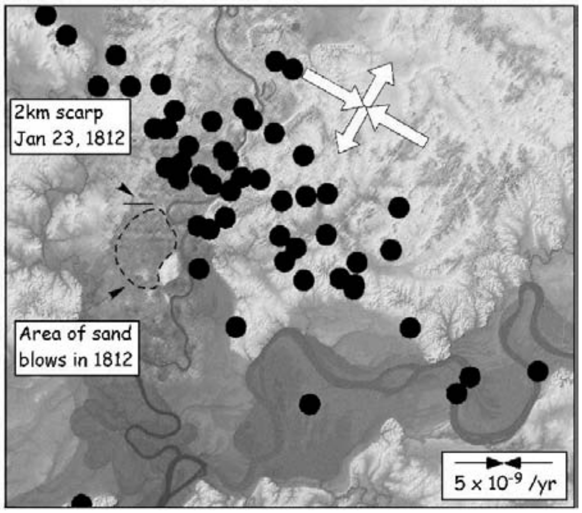
Earlier studies (*e.g.*, Johnston and Schweig, 1996) locate NM2 at the northern end of the NMSZ in part because of the Bryan account, which suggests that, in the village of New Madrid, NM2 was comparable in severity to NM1 and NM1-A. Bryan's account of NM1 and NM1-A do not describe any actual damage in New Madrid from either of these events, however. Instead her letter describes disruptions of the river current as well as falling trees. Considering other accounts of NM1, trees appear to have toppled only along the riverbank, apparently a consequence of slumping and/or the disruption of river currents. Comparable effects could have been generated by the long-period energy from a large event at somewhat greater distances. A separate account, by Robert McCoy, states that the early shocks (NM1 and NM1-A) destroyed the village of Little Prairie, Missouri, "but the one that did material injury to the village of New Madrid was not until the 7th of February, following." Bryan lived in the village of New Madrid, which is 30–40 km north of the inferred northern terminus of NM1, and approximately 30 km north of the southern end of the Reelfoot Fault. On the other hand, New Madrid is located directly on the northern limb of the NMSZ. Had an earthquake similar in magnitude to NM1 and NM1-A ruptured this limb, one would expect the shaking to have been very much stronger than that from NM1 or NM1-A. When the NM3 mainshock ruptured on the nearby Reelfoot Fault, Bryan did in fact distinguish this to be the "hard shock." Other accounts from the Mississippi Valley also describe NM3 as the most severe shock. We consider it implausible that an earlier M ~7 earthquake occurred in nearly the same location, causing so little damage and meriting so little attention.

As Bakun and Hopper (2004) noted, the available intensity results cannot constrain a location of NM2 with any precision. Considering the absence of documented damage in the village of New Madrid during NM2, however, the overall intensity distribution suggests a location somewhere to the north-northeast of the NMSZ.

WAGON LOADS OF SAND BLOWS

In addition to the accounts discussed above, a number of accounts in the compilation of Street (1984) describe liquefaction in both Kentucky and Illinois, well north of the NMSZ. These accounts include only general observations consistent with liquefaction, however; they do not specify exactly when the effects occurred. Such accounts have not been analyzed in previous investigations because they cannot be used to assign MMI values for particular earthquakes. We will discuss them here because they provide evidence that liquefaction occurred well north of the NMSZ at some point during the 1811–1812 sequence.

In Kaskaskia, Illinois (–89.92°N, 37.92°W), "the soil cracked so deeply in the very streets that they could not sound the bottom of the crevice, and the water drawn from it exhaled a most disagreeable odor." Near Paducah, Kentucky, "a large circular basin was formed, more than one hundred feet in diameter, by the sinking of the earth." In Cahokia, Illinois (–90.18°W, 38.57°W), "the earth opened in many places, especially about three miles from our monastery. Only sand and water came from the opening." This account goes on to note that, "Fortunately our poor cabins of wood and sand can withstand a great deal of shaking without much danger." The most intriguing account of liquefaction well north of the NMSZ is available from White County, Illinois (–88.09°N, 38.09°W). The account was by Mr. Yearby Land, who lived in White County as a boy and relayed his account some years later to a second party (quoted in its entirety by Berry, 1908; see also Heigold and Larson, 1994). In spite of its retrospective nature the account is quite detailed, providing detailed information about the nature and location of the effects described. In 1812, the locale of Land's family farm was known as Big Prairie, near the present town of Epworth, Illinois, just west of the Big Wabash River. (Unlike the similarly named Little Prairie, Big Prairie was not in the New Madrid region.)



▲ **Figure 4.** Location in White County, Illinois where Land account documents liquefaction and the formation of a two-mile-long "crack." The original homestead was at the western edge of the inferred scarp location (shown); the swamp land shown in Figure 6 is at the eastern end of the scarp. Dashed line indicates region where sand blows were described and can still be seen today. Circles indicate recent microseismicity as located by Pavlis *et al.* (2002); their temporary deployment recorded background seismicity at a significantly lower detection threshold than the regional network. Direction of regional strain field is indicated by arrows.

▲ **Figure 5.** Photograph of marker indicating location of original Fikeland homestead.

The account (Berry, 1908) reads,

> In the prairie, about two miles east of his father's house, a big crack was made in the ground, and you could not see to the bottom of it. The ground on the south of the crack sunk down about two feet. "This crack" was on the land owned afterwards by Mr. Jacob Parker on the N.W. Qr. Of Sec. 35, T. 5, S.R. 10E. 3d p.m. It was well defined when I first saw the place in 1858. Across a field that sloped slightly upward to the north, was a well marked line of uplift and downfall. The lower side to the south. This line extended east and west. It started on some high ground, west of the field, extended eastward through the woodland and was lost in some swamp land further on. It could be traced about two miles. The field was in cultivation for wheat when I first saw it, and the slope of the uplift, or northern side, was about six feet long, as it had been worked down in cultivation. South and eastward from this farm was a wide extent of low flat, untimbered land, extending to the Marshall Hills, on the Big Wabash, eastward, and nearly to the Little Wabash southward. In those days this land was not outflowed by the Big Wabash. It was covered by a verdurous growth of grasses and was a splendid summer and winter range, or pasture for horses, cattle and swine. There were many square miles of level plain, and over it, in the earthquake times, piles and piles of pure, snow white sand were heaved up. In the words of Uncle Yearby Land, as we called him, those piles "were from the size of a bee-gum to three or four wagon loads."

The account goes on to explain that a bee-gum is a hollowed-out gum log about 20 inches long and 14–18 inches in diameter.

This account provides enough information to determine the location of the "crack" and sand blows with a reasonable measure of certainty. For example, "Sec. 35, T.5, S.R. 10E." indicates state section 35, Township 5, Range 10E, which can be found on modern maps. (Federal land surveys in southern Illinois began in 1806.) Heigold and Larson (1994) conducted a resistivity profile in the northwest corner of Section 35, Hawthorne Township, based on this account and were able to determine the dimensions of a surficial sand body that they considered likely to be a sand blow. We were able to verify additional details of the Land account with our own field reconnaissance and to pinpoint the probable location of the "crack" (Figure 4). Although no vertical offset remains visible, the site of the original Land ("Fikeland") homestead is marked (38°02.827′N, –88°06.415′W; Figure 5), and two miles due east of this location one finds swampy land (38°02.954′N, –88°03.646′W; Figure 6). To the south of the presumed crack location one finds a field in which evidence of sand blows can still be seen (38°02.959′N, –88°05.292′W; Figure 7). This field extends to the Big Wabash River to the east and to hills to the south, again consistent with the account.

▲ **Figure 6.** Photograph of swampy ground approximately two miles due east of the Fikeland homestead. The historic account describes a two-mile-long, east-west crack that ended in swampy ground.

▲ **Figure 7.** Photograph of sand blow still evident in field described in Land account (see Figure 4 for location). We did not measure the dimensions of the sandy patch, which we assume to have been significantly altered by cultivation; it was approximately 4–5 m in diameter.

A precise east-west orientation of the "crack" cannot be constrained from the historic account or field observation. An orientation within perhaps 30° of due east-west would be consistent with the details in the historic account. Given the geographic landmarks and the Township/Range information in the historic account, we do consider the location and general orientation of the "crack" to be well constrained.

Although historic accounts are anecdotal and sometimes misleading, it is important to note that, in 1812, witnesses would have had few preconceived ideas about the expected effects of large earthquakes. Where accounts are consistent with modern scientific understanding and are exceptionally clear in detail, they can establish their own veracity. In this case, Land describes effects that appear to indicate either surface rupture on an east-west-trending fault or, at a minimum, ground slumping that extended for about two miles. The fact that this feature cut in an east-west direction starting in hills and running across woodland and swamp land does not appear to be consistent with large-scale ground failure. The reported south-side-down motion across the crack is essentially at right angles to the course of the river in this location. Unlike other accounts of ground failure during the New Madrid sequence, this is clearly not a description of slumping along the edge of a river valley. There is, moreover, no obvious reason why lateral spreading should have occurred in this area: that is, no apparent geologic or topographic features that provide an obvious explanation for the location and orientation of the crack. The description of "pure, snow white sand (being) heaved up" is consistent with sand blows, which apparently covered several square miles of land just west of the Big Wabash River.

Berry (1908) noted that there was no damage to structures in the Big Prairie region beyond chimney damage, but, echoing the account from Cahokia, goes on to observe that the buildings were all extremely flexible, "built like a basket." This account had not previously been analyzed in detail to our knowledge, probably because the accounts do not link the effects to a specific date or earthquake, and thus cannot be used in standard intensity analysis.

At a minimum, as Heigold and Larson (1994) noted, the White County account indicates that ground motion severe enough to cause substantial liquefaction occurred in the area at some point during the 1811–1812 sequence. It is possible for relatively small earthquakes to cause liquefaction: Armbruster *et al.* (1998) discussed accounts of sand blows generated by a M 5.1 NMSZ event on 2 July 1851. "Three or four wagon loads" suggests a fairly substantial liquefaction event, however. Considering older liquefaction features along riverbanks in the Wabash Valley, Obermeier *et al.* (1992) concluded that a large, distant New Madrid mainshock would not likely cause substantial liquefaction in the area.

The liquefaction susceptibility at the Land site is unknown. No obvious, sharply defined abandoned channels or cut-offs are apparent in the local topography, suggesting that the late Holocene sedimentation is dominated by fine-grained overbank sedimentation, which presumably overlies late Pleistocene/early Holocene glaciofluvial deposits (Obermeier *et al.*, 1992). A recent CPT result revealed only modest susceptibility at a single location near the inferred eastern end of the "crack"; the test was not conducted near a visible sand blow, however (Holzer, personal communication, 2004).

We conclude that the description of the two-mile-long "crack", and its vertical offset, are more suggestive of faulting than ground failure. Intriguingly, there are rapids along the Big Wabash River near the town of Maunie, just south of an eastward extrapolation of the line shown in Figure 4. Although these rapids could be caused by a change in lithology, a tectonic origin is also plausible given their location relative to the "crack." Topography along the river bottom would presumably be very young to persist in such an active fluvial environment. In any case, if the "crack" were in fact tectonic offset, it could represent either a primary or a secondary rupture. Considering the intensity distribution of NM2, this event represents by far the most plausible candidate to have generated these features. We consider it highly unlikely that another aftershock or remotely triggered earthquake could have generated effects of this magnitude in White County. Such an event would have been widely felt throughout the midcontinent, and the other large events in the sequence are all accounted for, in the sense of having sources constrained to be located elsewhere.

The broad, relatively flat intensity distribution of NM2 (Figure 2) is consistent with a deep source. Given the very sparse population in southern Illinois, we cannot rule out the possibility that no high intensities were documented simply because there were so few structures in the epicentral region that might have been damaged in the event. The available data are also not sufficient to definitively rule out a rupture on the northern limb of the NMSZ. We prefer a White County source for NM2 for the following reasons: (1) The distribution of intensities provides *prima facie* evidence that the event was centered well to the north and east of the other mainshocks; (2) the distribution of seismicity along the northernmost limb of the NMSZ falls within a predicted side lobe of increased stress from a rupture on the Reelfoot Fault, suggesting that, as with the other two minor limbs, this apparent fault limb does not correspond to zones of primary mainshock rupture (Mueller *et al.*, 2004); (3) a location in southeastern Illinois would explain the absence of a high-intensity "bull's-eye" in the intensity pattern of NM2, as this region was very sparsely populated in 1812; (4) a location to the northeast of the NMSZ would explain why remotely triggered earthquakes occurred in northern Kentucky after NM2 (Hough, 2001), while no evidence for remotely triggered earthquakes in this region following NM1 has been found in spite of its larger size; and (5) the location explains the observed liquefaction that occurred elsewhere in southern Illinois. Leaving open the possibility that the liquefaction in White County was caused by another, smaller, triggered earthquake, the above lines of evidence still point to a NM2 source zone outside of the traditionally defined 1811–1812 NMSZ source zone. (Interestingly, Cincinnati resident Daniel Drake observed that, while the original 1811–1812 disturbance was focused between New Madrid and Little Prairie—a remarkably astute observation—the seat of the disturbance seemed to migrate to the north-northeast over the following few years [Drake, 1815.])

In summary, we conclude that disparate lines of evidence point to a NM2 source zone to the north-northeast of the NMSZ as traditionally defined. Much of this evidence would be consistent with a source zone somewhere other than White County, for example in western Kentucky. We consider the White County region to be the most promising target for further investigation because of the clearly documented (and verified) effects in this area in 1811–1812. Further geologic investigations, for example trenching across the "crack", should help determine whether it was a lateral spread or a tectonic feature.

GEOLOGIC SETTING

Although the Wabash Valley is one of the most active regions in the central United States apart from the NMSZ, little is known about active faults in this area. The Wabash Valley seismic zone (WVSZ) extends some 100 km north-northeast from the Rough Creek graben, which, like the Reelfoot Rift, is interpreted as having developed as a reactivated Precambrian rift (Soderberg and Keller, 1981; Braile *et al.*, 1982; Pratt *et al.*, 1989, 1990; Kolata and Nelson, 1997). To the south of the WVSZ, the east-west-trending Rough Creek graben appears to be relatively aseismic. The WVSZ is a series of north-northeast-trending normal faults. In the vicinity of White County, these faults form a zone ~20 km in width, bounded to the east by the Wabash River (Wheeler *et al.*, 1997). Two of these faults, the Meadow Bank and Phillipstown Faults, cut through the site of the former Land farm (Heigold and Larson, 1994). Closer to the river, the Maunie fault zone has been mapped over a distance of about 25 km (Heigold and Larson, 1994).

Seismic-refraction profiles acquired across the Phillipstown and Meadow Bank Faults reveal offsets in Paleozoic rocks but do not image offsets in Quaternary strata (*e.g.*, Heigold and Larson, 1994). As far as we know, the inferred location of the east-west "crack" has not previously been the target of focused seismic or geophysical investigations.

Overall, no evidence for shallow Holocene faulting has been found in the Wabash Valley region (see McBride *et al.*, 2002), although available oil industry and other data would not have been able to image an east-west-trending feature in the region shown in Figure 4. Reflection surveys have identified possible blind thrust faults at 20–25 km depth that are oriented roughly north-south (Bear *et al.*, 1997; McBride *et al.*, 2002). The m_b 5.5 southern Illinois earthquake (Langer and Bollinger, 1991), which had a focal depth of 22–25 km, is interpreted by McBride *et al.* (2002) to have occurred on this type of fault. If this source did generate a M_w 6.6–6.8 earthquake in southern Illinois (*i.e.*, NM2), then the observed east-west crack would represent shaking-induced ground disruption or secondary faulting—for example, a tear fault similar to that observed following the 2001 Bhuj, India earthquake (Wesnousky *et al.*, 2001). Alternatively, a displacement of two feet is consistent with expectations for a M 6.8 earthquake. If the surface feature did represent a primary fault rupture, a normal mechanism is suggested. An east-west-trending normal fault would not be consistent with the overall east-west-trending maximum compressive stress axis (*e.g.*, Zoback and Zoback, 1980); it is consistent, however, with the oblique orientation of the regional stress field as inferred recently from GPS data by Hamburger *et al.* (2002).

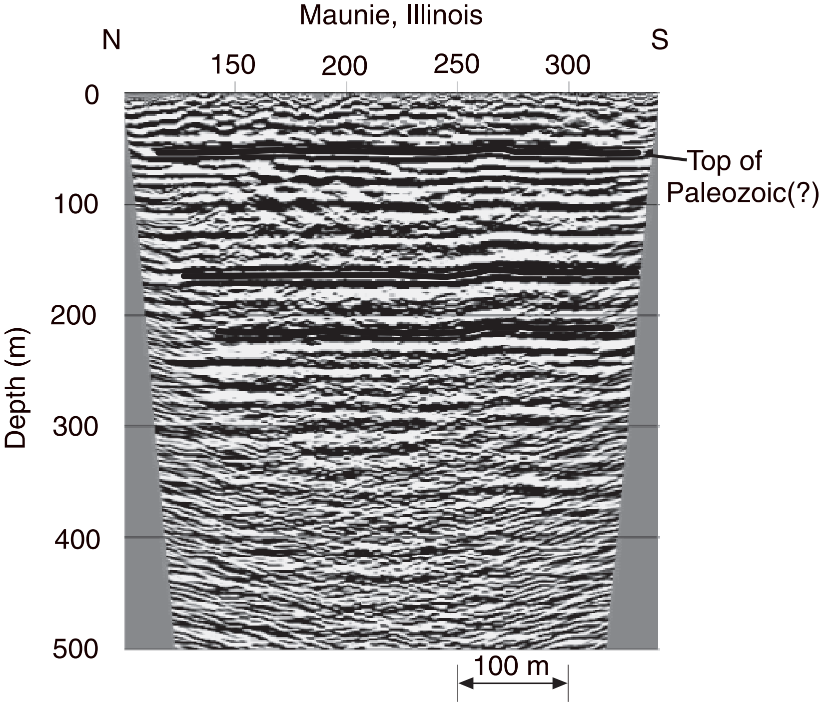
There is some evidence for an east-west structure coincident with the location of the surface feature shown in Figure 4. Although speculative, the structural model presented by Marshak and Paulsen (1997) includes an "accommodation zone" through this region, presumably a strike-slip structure between normal fault segments. A recent deployment of temporary seismometers also revealed a zone of microseismicity as shown in Figure 4 (Pavlis *et al.*, 2002). Pavlis *et al.* (2002) speculated that this seismicity might be mining-induced, but the trend illustrated in Figure 4 extends for a considerable distance.

Previous studies have also found evidence for east-west faulting elsewhere in the WVSZ. Perhaps 40–45 km south of the Land farm, the east-west-trending Cottage Grove Fault is inferred to be a zone of weakness that was reactivated during late Paleozoic times (Heigold and Kolata, 1993). Recently, Kim (2003) analyzed waveforms from the M_w 4.6 Caborn, Indiana earthquake of 18 June 2002 and obtained a strike-slip mechanism with nodal planes striking 28° and 297°. Kim (2003) preferred the north-northeast-striking nodal plane, which is consistent with the orientation of the nearby Caborn Fault. The second nodal plane is consistent with the orientation of the east-west feature shown in Figure 4.

SLEDGEHAMMERS AMONG THE SOYBEANS

To explore the former Land farm further, we conducted a high-resolution seismic-reflection experiment along a dirt road that passes alongside the swampy ground shown in Figure 6. This experiment involved a sledgehammer source and approximately 250 shot points. Approximately 480 m of data were acquired using a 2-m source and receiver station spacing. The source was a 4.5-kg sledgehammer, with records for two hammer impacts stacked at each receiver. The 30-fold common midpoint (CMP) data were recorded on Geometrics RX-60 instruments. We applied conventional processing techniques that included a dip move-out (DMO) correction and poststack finite-difference depth migration.

The resulting seismic image (Figure 8) did not reveal any structure above the (inferred) location of the Paleozoic, which appears as a characteristically strong reflector at approximately 50-m depth. (In the absence of well control we rely on massive data redundancy to estimate velocities and infer depths. The precise depth of the Paleozoic strata is, however, relatively unimportant in our interpretation.) Intriguingly, near shot point 270 we observed a small offset in the otherwise flat layers. This offset has a south-side-up sense of dis-



▲ **Figure 8.** Results from seismic reflection survey across inferred end of "crack" described in historic account and shown in Figure 4. No structure is resolved above the inferred top of the Paleozoic (indicated); a small, south-side-up deflection is noted in deeper layers near shot point 270.

placement, opposite to the south-side-down motion described in the Land account. We note, however, that the location of this offset coincides extremely well with the location of the crack, assuming we have located the right patch of swampy ground. If an active fault does exist in this location, our preliminary results lead to the hypothesis that the feature might be a reactivated reverse fault that is accommodating normal motion in the current stress regime (Hamburger *et al.*, 2002). The "bump" in Paleozoic structure does appear to have a steep dip, which might not be consistent with reverse (or normal) faulting. It is difficult to resolve the geometry of this feature given the limited preliminary field survey.

We note that similar evidence for fault activation was described by Sexton (1992), who concluded that a deeper structure beneath Sikeston Ridge in the NMSZ is a mirror image of offsets seen at the surface.

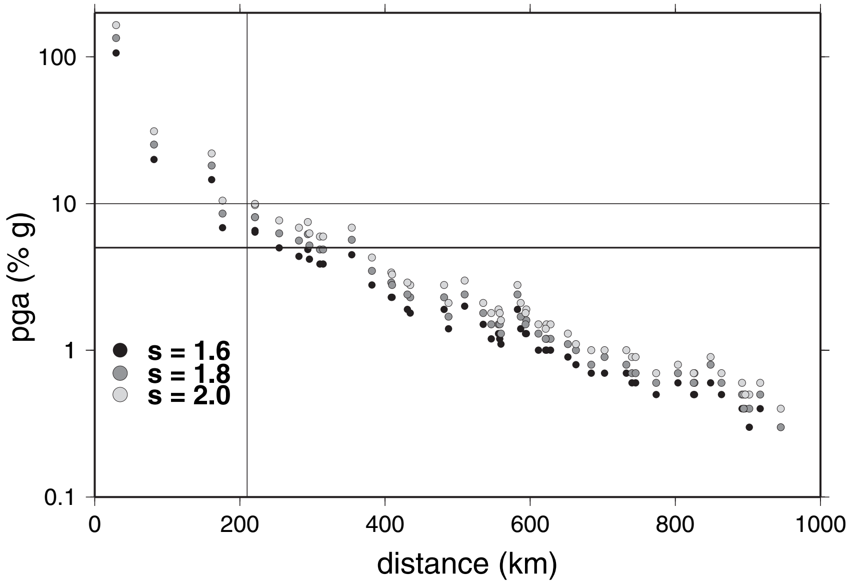
WABASH VALLEY LIQUEFACTION FROM NEW MADRID MAINSHOCKS?

Although our preferred interpretation of the Land account is that it documents the occurrence of a large earthquake in White County, we also consider the alternate possibility, that one or more large NMSZ mainshocks caused liquefaction in this location. As an exploration of this possibility, we use the method of Beresnev and Atkinson (1997) (hereinafter BA97) to generate predicted ground motions from a NMSZ mainshock. A similar analysis was published by Atkinson and Beresnev (2002). That study assumed a New Madrid mainshock of M 7.5–8.0, however, whereas we will use M 7.4, our preferred estimate for the largest New Madrid mainshock (Hough *et al.*, 2000; Mueller and Pujol, 2001; Guccione *et al.*, 2002). In the BA97 method, a rupture is simulated using fault-plane subelements, each of which is treated as a point source with a spectral shape constrained to have an ω^2 shape. The method is attractive for this application because of its computational ease and because few model parameters must be assigned. We note, however, that a high degree of uncertainty will attend any estimate of regional 1811–1812 ground motions.

The most important free parameter in the BA97 method is the "strength parameter", S_f, which is related to the maximum slip velocity, v_m, according to

$$v_m = \frac{0.618\,y\left(\Delta\sigma\right)S_f}{\rho\beta}\,, \tag{2}$$

where β is the shear wave velocity, y is the rupture propagation velocity as a fraction of β, $\Delta\sigma$ is the subevent stress drop, and ρ is density (Beresnev and Atkinson, 2001). Although rupture velocity can vary along strike, the formulation of Beresnev and Atkinson (2001) includes only a single value of S_f for each rupture model. As discussed by Beresnev and Atkinson (2001), the amplitude of high-frequency radiation depends strongly on S_f. S_f was found to vary between 1.0 and 2.4 for a wide range of earthquakes in eastern and western North America. In our application, the depth of faulting is another unknown, but Hough *et al.* (2002) concluded that predicted ground motions depend much more strongly on S_f than on depth. We there-



▲ **Figure 9.** Predicted hard-rock peak acceleration values for M 7.4 rupture on the Reelfoot Fault using method of Beresnev and Atkinson (1997) and three different values of the strength factor. Vertical line indicates distance between the Land farm and the Reelfoot Fault; horizontal lines indicate range of shaking at which liquefaction begins to occur.

fore calculate peak ground acceleration (PGA) for a M 7.4 Reelfoot Fault rupture with a range of strength parameters.

Figure 9 shows the predicted hard-rock ground motions as a function of distance for models in which strength factor is varied between 1.6 and 2.0. At a distance of 210 km, the predicted PGA value is 5–10% g. Assuming that hard-rock shaking is amplified by the factor of 2–4 that intensity observations suggest is typical for soft-sediment sites (*e.g.*, Hough *et al.*, 2000), this analysis yields shaking levels of 10–40% g. Although the shaking threshold for liquefaction depends on a number of variables (*e.g.*, Todorovska and Trifunac, 1999), the upper half of this range is probably high enough to cause liquefaction in highly susceptible materials (*e.g.*, Youd and Idriss, 2001). The results of Kochkin and Crandell (2004), which are based on established attenuation relationships, indicate that observed chimney damage in St. Louis (at a distance of approximately 250 km from New Madrid) is most consistent with peak hard-rock ground motions of about 0.03 g. Considering this as well as our modeling results, we conclude that shaking at sediment sites at 210 km would have likely been no higher than 0.1 g.

During the M_w 7.6 2001 Bhuj, India earthquake, the most distant liquefaction occurred near Porbunder, about 250 km south of the epicenter (Rajendran and Rajendran, 2002). Tuttle *et al.* (2002) inferred a similar estimate, 240 km, for the most distant extent of liquefaction.

The results of these preliminary calculations are vexingly inconclusive. We cannot rule out the possibility that liquefaction in White County, Illinois was caused by a large earthquake in the NMSZ. We do not favor this interpretation for two reasons. First, the extent of liquefaction (piles of sand as big as "three or four wagon loads") does not appear to be consistent with expectations for a location at the farthest extent of the liquefaction region. Second, this explanation cannot account for a two-mile-long "crack" with vertical displacement and none of the usual characteristics of ground slumping or lateral spreading.

CONCLUSIONS

Although our proposed rupture scenario for the 23 January 1812 earthquake remains somewhat speculative, it is supported by better evidence—and by more lines of evidence—than that used to assign the earthquake to the northern limb of the NMSZ.

At a minimum, the Land account (Berry, 1908) describes dramatic shaking effects in southern Illinois, at a distance of approximately 210 km from the NMSZ, and field reconnaissance verifies many of the details in this account. The hypotheses presented in this paper can be tested. Field investigations should be able to document further the extent of liquefaction, and the size of liquefaction features, in the White County region bounded by the Wabash River to the east and the Dogtown Hills to the south. Further analysis based on trench excavations and by shallow seismic and other geophysical techniques should moreover be able to find, or demonstrate the absence of, an east-west-trending fault corresponding to the location shown in Figure 4. It may also be able to glean further evidence to constrain the shaking effects of NM2 by revisiting the historic record.

Assuming our interpretation is correct, it is interesting to consider the result in light of previous recent studies of the 1811–1812 New Madrid sequence. Hough (2001) and Hough *et al.* (2003) presented evidence for a number of remotely triggered earthquakes in the northern Kentucky/southern Ohio region. The largest of these, at approximately

10:40 PM on 7 February 1812, was felt as far east as the Atlantic seaboard and is estimated to have had a magnitude of about 5.5. Hough and Martin (2002) presented evidence that another magnitude ~6 event occurred well south of the NMSZ near noon on 17 December 1811. Although there is compelling evidence that the three largest earthquakes in the sequence (NM1, NM1-A, and NM3) were in the NMSZ, there is also compelling evidence that potentially damaging events occurred to the south, northeast, and east of the NMSZ at distances ranging from 200 to 500 km. The observational evidence suggests that hazard associated with known midcontinent source zones may be more spatially distributed than previously recognized.

ACKNOWLEDGMENTS

We thank Rus Wheeler, Jim Dewey, Martin Chapman, and two anonymous reviewers for comments and constructive criticisms.

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