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Magnitude Estimates of Two Large Aftershocks of the 16 December 1811 New Madrid Earthquake

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Abstract The three principal New Madrid mainshocks of 1811–1812 were followed by extensive aftershock sequences that included numerous felt events. Although no instrumental data are available for either the mainshocks or the aftershocks, available historical accounts do provide information that can be used to estimate magnitudes and locations for the large events. In this article we investigate two of the largest aftershocks: one near dawn following the first mainshock on 16 December 1811, and one near midday on 17 December 1811. We reinterpret original felt reports to obtain a set of 48 and 20 modified Mercalli intensity values of the two aftershocks, respectively. For the dawn aftershock, we infer a M_W of approximately 7.0 based on a comparison of its intensities with those of the smallest New Madrid mainshock. Based on a detailed account that appears to describe near-field ground motions, we further propose a new fault rupture scenario for the dawn aftershock. We suggest that the aftershock had a thrust mechanism and occurred on a southeastern limb of the Reelfoot fault. For the 17 December 1811 aftershock, we infer a M_W of approximately 6.1 $\pm$ 0.2. This value is determined using the method of Bakun *et al.* (2002), which is based on a new calibration of intensity versus distance for earthquakes in central and eastern North America. The location of this event is not well constrained, but the available accounts suggest an epicenter beyond the southern end of the New Madrid Seismic Zone.

Introduction

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). The three principal mainshocks occurred at approximately 02:15 local time (LT) on 16 December 1811; around 08:00 LT on 23 January 1812, and approximately 03:45 LT on 7 February 1812 (henceforth NM1, NM2, and NM3, respectively; see Fig. 1). 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 for these events, respectively. In the Hough *et al.* (2000) reinterpretation, modified Mercalli intensity (MMI) assignments were based on accounts that were considered relatively objective: the extent to which people were reportedly awakened by events NM1 and NM3 and descriptions of damage to structures.

The Hough *et al.* (2000) study did not attempt to analyze the dawn aftershock, which occurred near dawn on 16 December 1811 (hereinafter referred to as NM1-A). Earlier studies estimated the magnitude of this aftershock to be only slightly smaller than NM2 (e.g., Johnston, 1996b).

Although the magnitude of the 1811–1812 mainshocks is of paramount importance for hazard assessment, the largest aftershocks are extremely important earthquakes as well. Regardless of their precise magnitudes, some of the large aftershocks were clearly among the largest handful of earthquakes to have occurred in the central United States in historic times. As better methods are developed to exploit intensity observations, it is worthwhile to revisit the accounts of these events. In this article, we estimate intensity values for the dawn aftershock and use them to estimate its magnitude. We also consider two detailed, near-field accounts of this aftershock that lead us to propose a new fault rupture scenario for the event.

We additionally determine MMI values for an aftershock that occurred near noon on 17 December 1811 (henceforth NM1-B). Street and Nuttli (1990) identified this event as a large aftershock that was felt as far east as the Atlantic Seaboard. To our knowledge, accounts of this event have not previously been used to estimate its magnitude.

The Dawn Aftershock

Our estimated MMI values for NM1-A are given in Table 1. To map out the shaking distribution we employ a simple mathematical approach whereby the data are contoured us-

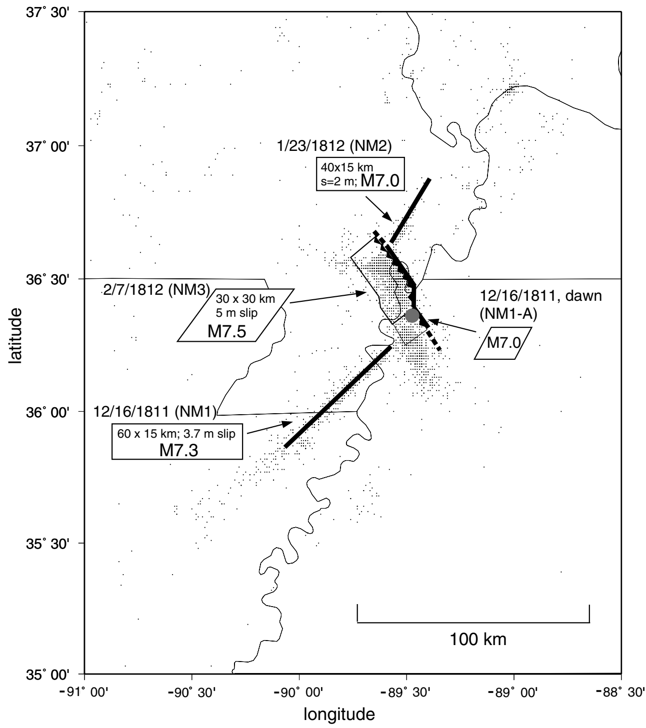


Figure 1. Map showing location of the New Madrid Seismic Zone as illuminated by microseismicity between 1974 and 1996. Locations are from the New Madrid Catalog (Taylor *et al.*, 1991), which are reported only to the nearest hundredth degree. Proposed fault ruptures for the three principal 1811–1812 mainshocks are shown (schematically) (after Johnston and Schweig [1996] as modified by Hough *et al.* [2000] and modified further as discussed in the text). The rupture scenario proposed in this study for the NM1-A aftershock is also shown. Solid gray circle indicates location of John Hardeman Walker at the time of this aftershock. Solid line with dashed ends shows inferred location of Reelfoot fault (after Odum *et al.* [1998]).

ing a continuous curvature gridding algorithm. A uniform grid of estimated intensity values, $I(x, y)$, are determined by solving the equation

$$(1 - T) \cdot L(L(I)) + T \cdot L(I) = 0, \qquad (1)$$

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 on-line Generic Mapping Tools [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 isolated high MMI values that are inferred to reflect site response (see Hough *et al.*, 2000). Low MMI values are introduced around the periphery of the map so that the low-intensity field decays at the edges. We then plot the results following the convention developed to generate ShakeMaps (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 historical ShakeMap for NM1-A.

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 *et al.* (2003) presented a method to determine magnitude from the distance decay of MMI values for earthquakes in eastern North America. 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 central/eastern North America.

For NM1-A, however, there are limitations associated with both of the aforementioned methods. The MMI values for NM1-A are considered too sparse to allow for a reliable determination of isoseismal area for any MMI level, as required by the Johnston (1996a) approach. Also, preliminary results indicate that the results of the Bakun *et al.* (2003) method are not consistent with those of Johnston (1996a) for large ($M \geq 7$) earthquakes, with the former yielding magnitudes that are smaller by typically 0.2–0.3 units. The latter study was constrained by more large earthquakes from stable continental regions worldwide. The former included fewer large earthquakes but was restricted to events from central and eastern North America. This eliminates the possibility that the results will be biased by data from regions with different attenuation characteristics but raises the possibility that the results are not well constrained by data for the largest events. A reconciliation of this discrepancy is beyond the scope of this study, so we estimate a M_W for NM1-A by comparing its MMI values as a function of distance from the presumed epicenter (see below) with those of the 23 January 1812 mainshock (Fig. 3). We find the two sets of values to be very similar. To further compare the data sets further we fit both with the equation

$$I(r) = A - Br - C\log(r), \qquad (2)$$

where r is the distance to the assumed epicenter and A, B, and C are constants. For NM1-A the values of the parameters are found to be sensitive to the one high intensity value, discussed below, near the town of Little Prairie (for which an r of 5 km is assumed). This sensitivity reflects the oversimplification in the form of equation (2), in particular at near-field distances. Nonetheless, the results of these regressions, also shown in Figure 3, support the conclusion that

Table 1
NMI-A Accounts

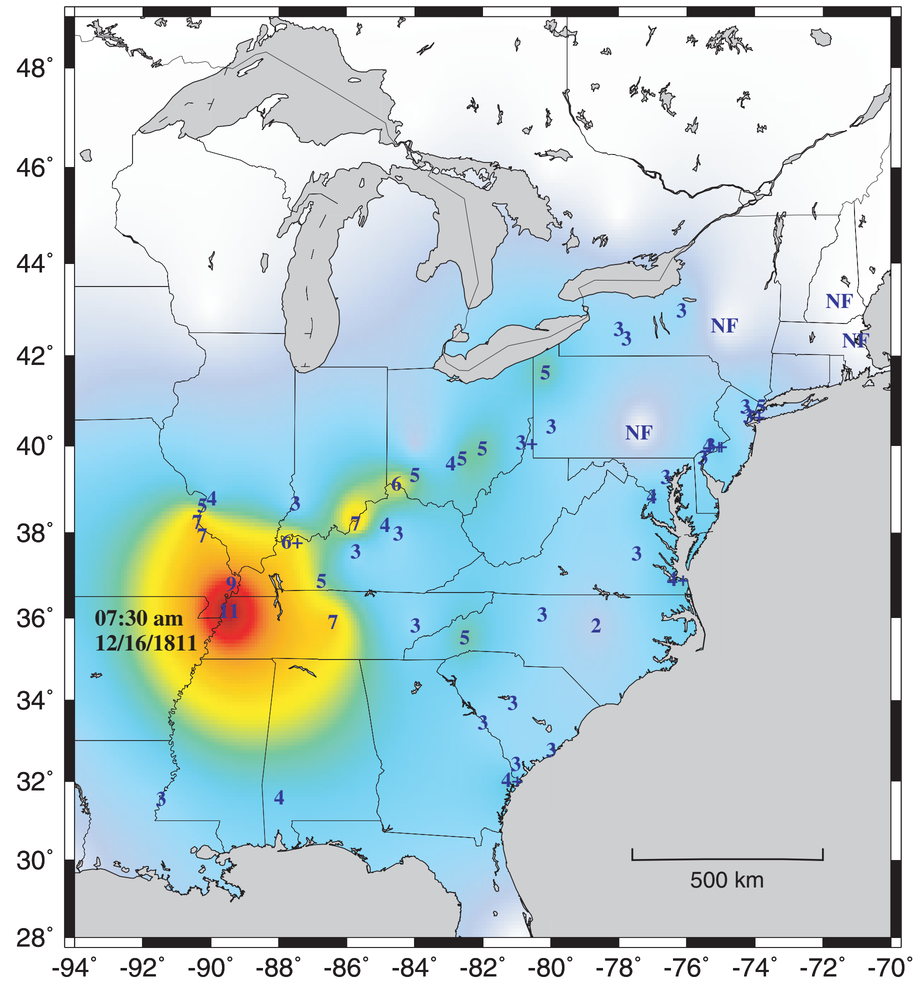
Location	Longitude	Latitude	MMI	Report
Alexandria, Virginia	−77.03	38.85	4	sensibly felt
Arkport, New York	−78.00	42.60	3	lightly felt
Asheville, North Carolina	−82.53	35.53	5	trees swayed
Augusta, Georgia	−81.97	33.37	3	felt
Baltimore, Maryland	−76.67	39.18	3	felt
Boston, Massachusetts	−71.03	42.37	NF	not felt
Carlisle, Pennsylvania	−77.40	40.30	NF	not felt
Charleston, South Carolina	−79.97	32.90	3	felt
Chillicothe, Ohio	−83.00	39.35	5	water in streets sloshed
Cincinnati, Ohio	−84.52	39.16	6	slightly less strong than mainshock
Circleville, Ohio	−82.94	39.61	4	"houses agitated"
Columbia, SC	−81.12	33.95	3	felt
Concord, NH	−71.50	43.20	NF	not felt
Cooperstown, NY	−74.88	42.67	NF	not felt
Coosawhatchie, SC	−81.02	32.44	3	felt
Fort St. Stephens, AL	−87.98	31.60	4	house shaken
Frankfort, Kentucky	−84.87	38.19	4	less severe than mainshock
Goshen, Illinois	−89.97	38.80	4	"house quivered"
Hackensack, NJ	−74.05	40.89	3.5	those standing experienced dizziness
Henderson, Kentucky	−87.60	37.80	6.5	a few chimneys damaged
Herculaneum, Missouri	−90.55	38.30	7	damaged chimneys
Hodgenville, Kentucky	−85.74	37.57	3	felt
Knoxville, Tennessee	−83.98	35.82	3	felt
Lancaster, Ohio	−82.60	39.72	5	trees swayed
Lexington, Kentucky	−84.50	38.33	3	felt
Little Prairie, Missouri	−89.46	36.17	11	trees broken
Louisville, Kentucky	−85.73	38.18	7	house gable broken
Meadville, Pennsylvania	−80.12	41.63	5	trees swayed
Natchez, Mississippi	−91.38	31.55	3	felt
New Bourbon, Missouri	−90.05	37.98	7	chimneys damaged
New Madrid, Missouri	−89.40	36.80	9	difficult to "keep seats"
New York, New York	−73.94	40.67	2	not felt
Norfolk, Virginia	−76.20	36.90	4.5	"very violent"
Onondaga Valley, NY	−76.15	43.00	3	felt
Philadelphia, Pennsylvania	−75.13	40.01	3.5	sensibly felt
Pittsburgh, Pennsylvania	−80.22	40.50	3	felt
Raleigh, North Carolina	−78.78	35.87	2	felt by few
Red Banks, Tennessee	−86.40	35.90	7	many chimneys damaged
Richmond, Virginia	−77.33	37.50	3	felt
Saint Louis, Missouri	−90.38	38.75	5	almost as violent as mainshock
Salem, North Carolina	−80.25	36.08	3	felt
Savannah, Georgia	−81.20	32.13	4.5	no damage
South Union, Kentucky	−86.66	36.88	5	trees and buildings shaken
Saint Louis, Missouri	−90.24	38.64	5	almost as violent as mainshock
Vincennes, Indian	−87.51	38.68	3	felt
Wheeling, West Virginia	−80.70	40.08	3.5	not as violent as mainshock
Wilmington, Delaware	−75.53	39.74	3	felt
Zanesville, Ohio	−82.01	39.95	5	buildings shaken, clocks stopped

Longitude and latitude (decimal degrees) estimated from U.S. Census database for modern cities where available; estimated MMI value from this study; brief summary of effects from accounts of Street (1984) and Fuller (1912).

the magnitude of NM1-A was close to that estimated by Hough *et al.* (2000) for the January mainshock: M_W 7.0.

If we apply the method of Bakun *et al.* (2003) to event NM1-A, with the constraint that the epicenter of the event be within 20 km of the location of the account that seems to describe extreme, near-field, ground motions (see below), we obtain a magnitude of 6.7. This is consistent with earlier findings that the Bakun *et al.* (2003) method generally gives somewhat smaller magnitudes for larger events than does the method of Johnston (1996a).

The MMI distribution for NM1-A includes two high values very near to the presumed location of the event. In the town of New Madrid, one observer described shaking so severe that "before it receded we rebounded up and down,



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. ShakeMap representation of ground motions from aftershock NM1-A as constrained by available accounts. The MMI value of 11 corresponds to the account by Walker, which describes trees being broken (Cummings, 1847). The contouring is generated using an interpolation scheme described in the text. Figure is determined from MMI values directly. The scale bar shows relationships between ground motion parameters and MMI values determined from earthquakes in California (Wald *et al.*, 1999). These relationships may not be appropriate for earthquakes in other regions.

and it was with difficulty we kept our seats." The most intriguing account of this event, however, was that by John Hardeman Walker, who in 1811 was 15 years old and a resident of Little Prairie (Cummings, 1847). Walker and a companion, Jean Baptiste Zebon, had traveled to a lake that is described as being in Tennessee about 10 miles east of the Mississipi River at Little Prairie (now Caruthersville, Missouri). The lake is described as having been "of considerable magnitude," crescent-shaped, and "something like three miles long." It is difficult to assign a precise uncertainty to the location, but we consider it unlikely that the author was grossly wrong about either the walking distance or direction of the lake relative to Little Prairie. Walker and his companion describe being awakened by the mainshock, which occurred at approximately 2:15 am (LT) (Cummings, 1847, p. 139):

. . . we were awakened by a noise like distant thunder,

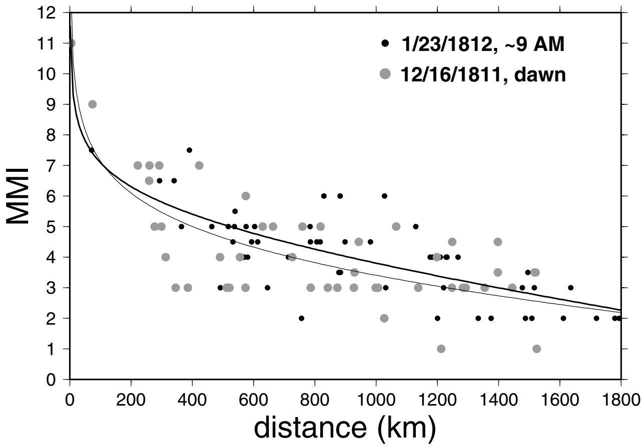


Figure 3. Estimated MMI values for NM1-A (gray dots) compared to values from Hough *et al.* (2000) for NM2 (black dots). Regression results (equation 2) are also shown for both events (light and dark lines, respectively).

> and a trembling of the earth, which brought us both to our feet. The dash of the water against the bank of the lake, and rattling of the limbs in the tree-tops—now and then the falling of a dry branch in the water, or near the ground—all these were things first led me to believe there was a storm approaching . . .

Although Walker and Zebon describe being frightened by the mainshock, the above account pales in comparison to that of Walker's description of NM1-A (p. 140):

> It was awful! Like the other—first, a noise in the west, like heavy thunder, then the earth came rolling towards us, like a wave on the ocean, in long seas, not less than fifteen feet high. The tops of the largest sycamores bending as if they were coming to the ground-again, one rises as if it were to re-instate, and bending the other way, it breaks in twain, and comes to the ground with a tremendous crash. Now the scene became awful in the extreme. Trees were falling in every direction—some torn up by their roots, others breaking off above the ground . . . and the earth opening, as it were, to receive us, in gaps sometimes fifteen feet wide-then it would close with the wave.

This account is consistent with others from in and near Little Prairie and New Madrid in that it describes significantly stronger ground motions during the aftershock than the mainshock. Johnston and Schweig (1996) pointed out that the accounts imply that NM1-A was farther north (i.e., closer to Little Prairie and New Madrid) than the mainshock. The account of ground waves "fifteen feet high" is not considered credible, but such accounts are common in both older and modern first-hand accounts of strong shaking. It is possible that these accounts result from an illusion related to human visual perceptions (T. Heaton, personal comm., 2000). Walker goes on to say: "The water of our little lake was fast emptying itself in these openings, and as soon as they would close, it would spout high in the air—and soon, as far as I could see, with the alternate wave of the earth and water of the lake, there was a crashing of timber, and spouting of water."

When the motions finally stopped, Walker describes the scene as follows: "The whole forest seemed as if an awful hurricane had completely destroyed it. The soft alluvial earth was opened in many rents of great depth, in which our little lake had completely lost itself." (p. 140).

A footnote to Walker's account, included in Cummings (1847, p. 142), notes that, "The lake, which evidently was once the bed of the main river, is now as high and dry a piece of ground as there is anywhere in the vicinity, and is now a beautiful prairie." A location "ten miles east of Little Prairie" is near the modern small towns of Calvary and Broadmoor, Tennessee. The closest modern lake, Running Reelfoot Bayou, is 6–8 km to the north of this location.

According to the scenario proposed by Johnston and Schweig (1996), Walker and his companion would have been near the northern terminus of a strike-slip rupture on the southern limb of the New Madrid Seismic Zone (Fig. 1). However, we conclude that Walker's account suggests that the aftershock may have been associated with permanent vertical deformation. Further considering the location of these observations, we suggest that the NM1-A was a magnitude M_w 7.0 earthquake on a southern segment of the Reelfoot thrust fault as illustrated in Figure 1.

The scenario illustrated in Figure 1 is patterned after that proposed by Hough *et al.* (2000) for the three New Madrid mainshocks. However, it differs from the earlier mainshock scenario is one respect. Hough *et al.* (2000) assumed a 40-km length for NM3 based on both the extent of the Reelfoot fault as illuminated by background seismicity and on standard scaling relationships between fault area and magnitude. If we now assert that the NM1-A aftershock ruptured a distinct southern segment of the Reelfoot fault and assume that this segment did not rerupture during the NM3 event, then one cannot fit a 40-km rupture within the fault zone as defined by current seismicity. It is possible that the NM3 rupture extended beyond the zone of modern seismicity. But it is also possible that the rupture area of this earthquake was smaller than that predicted from standard scaling relationships. This possibility derives a measure of indirect support from consideration of the 26 January 2001, Bhuj, India earthquake, another large blind thrust rupture that occurred away from an active plate boundary (e.g., Bendick *et al.*, 2001). Preliminary results reveal this to have been a high stress drop event, with a markedly small rupture area for its magnitude (e.g., Antolik and Dreger, 2001).

If NM1-A and NM3 are assumed to have ruptured distinct fault segments, and if their combined rupture was confined to the zone between the two strike-slip faults, a 30-km rupture length for NM3 implies that NM1-A had a rupture length of perhaps 12 km. This is again somewhat shorter than expected for a M_w 7.0 earthquake; for comparison, the M_w 6.7 1994 Northridge earthquake had estimated rupture dimensions of 15 km (length) by 20 km (down-dip width) (Wald *et al.*, 1996). However, a dimension of 12 km is not considered implausible considering (1) the possibility that NM1-A was also a high-stress-drop event, and (2) the possibility that, as suggested by the method of Bakun *et al.* (2003); NM1-A was somewhat smaller than M_w 7.0.

Our rupture scenario for NM1-A is based on three observations: (1) a formerly low-lying region ended up "high and dry," (2) the draining of the lake during the event itself, and (3) the location of the account, which, although somewhat imprecise, appears to be immediately atop the edge of the hanging wall of the southeastern limb of the Reelfoot fault. Clearly this interpretation is speculative although arguably supported by more precise observations than the earlier proposed scenario, which was based only on the relative location of NM1-A and the mainshock.

Previous studies have concluded that the Reelfoot fault is indeed segmented. Liu (1997) inferred four segments based on the distribution of seismicity and source parameters. Mueller and Pujol (2001) infer fewer distinct segments, but their analysis does confirm the existence of a southeast segment whose strike and dip are distinct from that of the northwest segment.

If NM1-A was caused by rupture on the Reelfoot fault (Fig. 1), Walker and his colleague would have been immediately above the edge of the hanging wall. Even if the rupture did not reach the surface, ground motions approaching (or exceeding) 1*g* have been recorded in such circumstances. The high implied ground motions do not require a thrust mechanism, of course, but they are consistent with one. And shaking of this severity is consistent with Walker's account of trees being broken. Following the 1906 San Francisco earthquake, now generally thought to have had a magnitude of M_w 7.7–7.9, trees in the vicinity of Loma Prieta were reported uprooted and/or broken over a swath ~200 ft in width (Hansen, 1989).

The 17 December 1811 Aftershock

Street and Nuttli (1990) identified a large aftershock that was felt across the central and eastern United States around noon on 17 December 1811. Our MMI assignments for this aftershock are given in Table 2.

The most dramatic accounts of the NM1-B aftershock are from a handful of individuals who were on boats on the Mississippi River at the time of the event. For example, the aftershock was described by John Bradbury (Bradbury, 1819, p. 205) by the following: "We did not experience any more shock(s) until the morning of the 17th, when two occurred; one about five and the other about seven o'clock. We continued our voyage, and about twelve this day, had a severe shock, of long duration."

Other observers on the Mississippi River also described a strong event at the same time. William Pierce (see Street, 1984) wrote of a "long and dreadful shock, that appeared threatening" at "5 after 12 meridian." However, land accounts from New Madrid and Little Prairie do not include reports of a damaging event at this time.

Figure 4 shows the overall MMI distribution for the NM1-B aftershock. Although no accounts describe damage caused by this aftershock, it was widely felt. To estimate a magnitude for this event we use the method of Bakun and Wentworth (1997), as modified for eastern North America events by Bakun *et al.* (2003). Although, as mentioned earlier, this yields lower magnitudes for large events than the isoseismal area approach of Johnston (1996a), Bakun *et al.* (2002) concludes that the two methods do yield consistent results for earthquakes whose magnitudes do not exceed 6. For NM1-B, which by all indications has a magnitude well below 7, the approach of Bakun *et al.* (2002) is considered preferable because it obviates the need to determine isoseismal contours from extremely sparse data.

Applying this method to event NM1-B with the MMI values listed in Table 2, we find an optimal location in north-central Mississippi, at 34.6N, 89.2W. This location, over 200 km southeast of the New Madrid Seismic Zone, is considered somewhat implausible given the absence of felt reports from central Tennessee. However, as illustrated by Figure 4, the location is not well constrained; epicenters along and west of the Mississippi River yield residuals not much higher than the optimal value. In any case, the estimated intensities appear to be inconsistent with a location close to New Madrid because the intensities in that region are relatively low. Also, relatively strong shaking was experienced at a number of locations to the south and southeast. At Natchez, Mississippi, for example, some clocks were reportedly stopped and "a cow bell was heard to tinkle." (31 December 1811, *Louisiana Gazette*; see the compilation of Street [1984]). At Chickasaw Bluffs, near the present-day city of Memphis, the event is described as among the three most violent felt over 16–17 December 1811 (see also Street, [1984]).

Considering the overall distribution of shaking effects, we conclude that a location at least as far south as Chickasaw Bluffs (35.1N, 90.0W) is suggested. Chiu *et al.* (1997) identified a band of seismicity extending southwest from just south of the New Madrid Seismic Zone past the city of Memphis and into Arkansas. A location within the southwestern one-third to one-half of this band would be consistent with our results.

A location south of the New Madrid Seismic Zone would explain a number of observations: (1) The relatively high MMI values to the south/southeast of New Madrid, (2) the relatively low ones to the north/northeast, and (3) a lack of damage ascribed to the event. The population density along the Mississippi River Valley south of New Madrid was extremely sparse at that time (e.g., Anderson, 1937), so there would have been few structures in this region to be damaged.

In spite of the uncertainty in location, the magnitude of NM1-B is found to be fairly robust. For virtually any plausible location of the aftershock, both south or southeast of

Table 2
NM1-B Accounts

Location	Longitude	Latitude	MMI	Report
Charleston, South Carolina	−79.97	32.90	3	"sensibly felt" by those at rest
Chickasaw Bluffs, Tennessee	−90.00	35.10	7.0	one of 3 strongest shocks felt
Chillicothe, Ohio	−83.00	39.35	3	slight
Cincinnati, Ohio	−84.52	39.16	4	"strong," "fourth class"
Columbia, South Carolina	−79.97	32.90	4	"smart shock"
Fort Massac, Illinois	−88.65	36.25	2	lightly felt
Fort St. Stephens, AL	−87.98	31.60	4	house shaken
Georgetown, South Carolina	−78.78	33.38	4.5	"severe," no damage
Louisville, Kentucky	−85.73	38.18	4.5	"strong to intense"
Marietta, Ohio	−81.45	39.42	3	lighter than mainshock
Meadville, Pennsylvania	−80.12	41.63	3	lighter than mainshock
Mississippi (Pierce)	−89.70	36.25	5	"long and dreadful"
Mississippi	−89.68	36.00	4.5	"heavy," trees shaken
Mississippi (Bradbury)	−89.63	35.93	5	"severe," long duration
Natchez, Mississippi	−91.38	31.55	4.5	some clocks stopped
Natchitoches, Louisianna	−93.10	31.75	3.5	felt, less severe than mainshock
New Bourbon, Missouri	−90.05	37.98	4.5	"severe," no damage described
Richmond, Virginia	−77.33	37.50	4.5	"violent," no damage described
Saint Louis, Missouri	−90.38	38.75	4	"smart shock"
Savannah, Georgia	−81.13	32.03	3	felt
Strasburgh, Virginia	−81.13	32.03	4	"severe," no damage
Wheeling, West Virginia	−80.70	40.08	2	"faint"
Zanesville, Ohio	−82.01	39.95	4.5	church steeple agitated

Longitude and latitude (decimal degrees) estimated from U.S. Census database for modern cities where available; estimated MMI value from this study; brief summary of effects from accounts compiled by Street (1984). MMI value for Natchitoches, Louisianna, is based on an account in the 29 February, 1812 Philadelphia Aurora, which is not included in the Street (1984) compilation; values for Chickasaw Bluffs and Charleston are from accounts in the *Richmond Enquirer*.

the New Madrid region, a M_w value of approximately 5.8–6.2 is inferred. This value is largely controlled by the overall felt extent of the aftershock and so is insensitive to the precise location. The optimal solution shown in Figure 4 yields a magnitude of 6.1.

Discussion and Conclusions

Interpretation of intensity data is always fraught with a certain level of uncertainty, especially with older accounts such as those from the New Madrid sequence. However, recently developed methods (e.g., Bakun and Wentworth, 1997) do allow for more thorough quantitative interpretations than have previously been possible.

Our result for the NM1-A is consistent with earlier studies (e.g., Johnston and Schweig, 1997) in that we estimate a magnitude close to that of the smallest New Madrid mainshock, NM2. Our estimate of M_w 7.0 is lower than that obtained (for both events) by Johnston (1996b), for reasons discussed at length by Hough *et al.* (2000).

Our alternate rupture scenario for NM1-A is admittedly speculative, supported by an account that appears to describe significant vertical deformation associated with the event and by subsequent documentation of apparent elevation of a formerly low-lying region. However, as illustrated on Figure 1, the Reelfoot fault is large enough to have generated both a M_w 7.0 aftershock and a M_w 7.5 event (the February mainshock). In fact, the full extent of the Reelfoot Fault, as highlighted by background seismicity, extends at least 20 km east of the postulated aftershock rupture zone shown in Figure 1 (Kelson *et al.* 1992; Liu, 1997; Odum *et al.*, 1998, Mueller and Pujol, 2001). However, basic Coulomb stress transfer theory (e.g., King *et al.*, 1994) predicts that strike-slip rupture on a southern New Madrid fault would have reduced the compressional stress on a thrust fault to the southeast of the juncture between the strike-slip and thrust faults, discouraging rather than encouraging a subsequent thrust event to the southeast. It therefore appears more likely that a strike-slip rupture on the southern limb would have triggered a thrust event to the north-northwest of the juncture. For this reason, our proposed scenario confines the rupture of NM1-A to a relatively small segment of the Reelfoot fault to the northwest of this juncture.

Considerable uncertainties remain regarding the effect of Coulomb stress changes on complex fault systems, so a rupture extending farther southeast than that shown in Figure 1 clearly cannot be ruled out. However, it is not necessary to violate basic stress transfer theories to construct a plausible rupture scenario.

The general issue of stress triggering during the New Madrid sequence is clearly a complex one and beyond the scope of this article to explore in detail. We have invoked

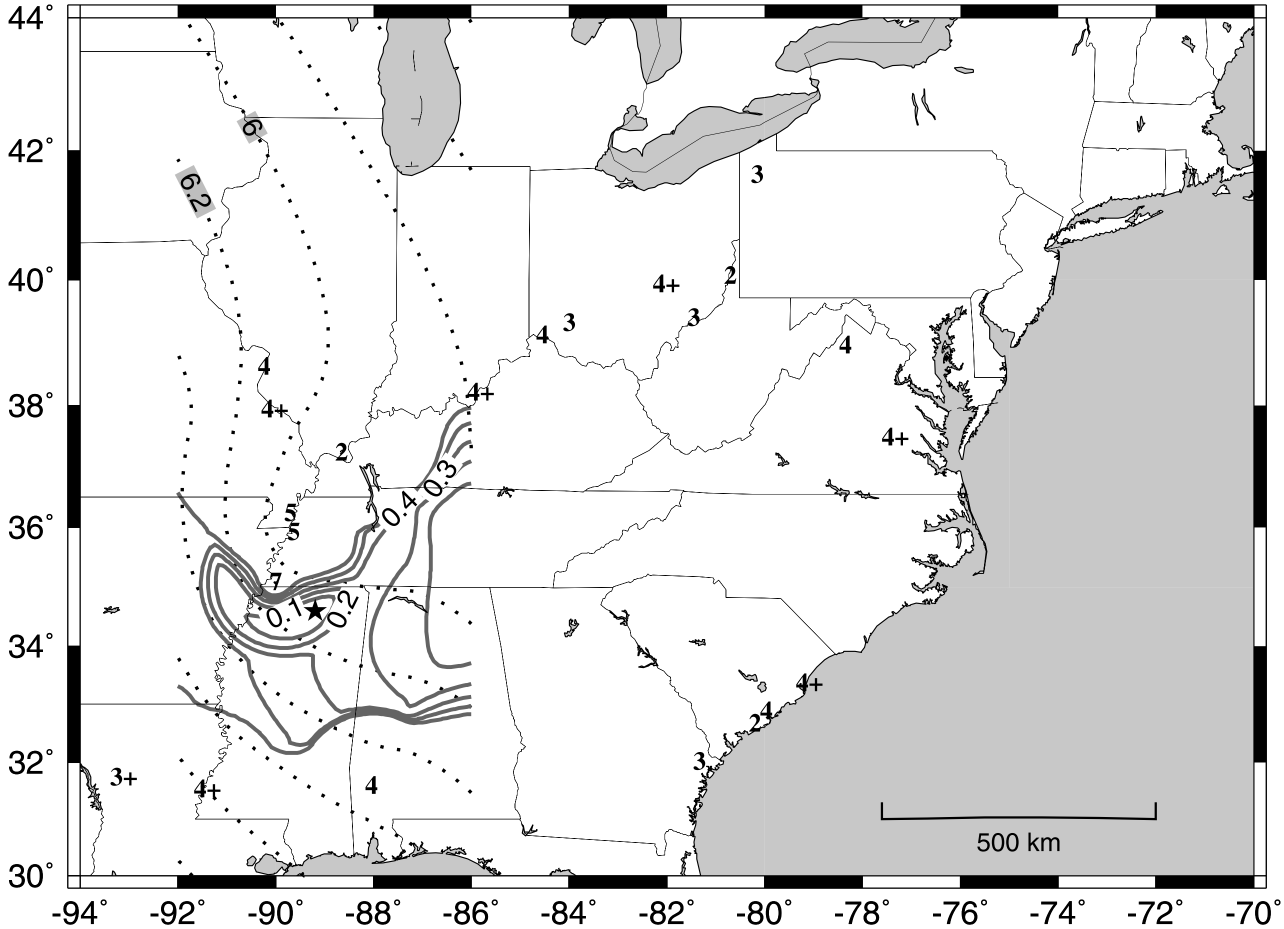


Figure 4. Estimated MMI values for aftershock NM1-B. Values immediately along the Atlantic coast line are shifted west by 0.2 degrees for clarity; one of three MMI values in the bootheel region of Missouri is not shown. Assuming the location to be within 300 km of 35N, −90 W, we obtain a magnitude and misfit for each trial location using the method of Bakun and Wentworth (1997). Solid and dotted lines indicate misfit and magnitude (respectively) for the array of trial locations. The optimal solution for this aftershock (star) is found to be to the south of the New Madrid Seismic Zone.

only basic, first-order tenets of stress triggering theory to develop our rupture scenario for NM1-A given our conclusion that it was a thrust event. Previously, Gomberg and Ellis (1994) used boundary element modeling to explore proposed rupture scenarios for the three mainshocks and NM1-A in more detail. However, the rupture parameters and scenario proposed by Hough *et al.* (2000) are significantly different than those tested by Gomberg and Ellis (1994); the Gomberg and Ellis (1994) modeling approach also did not allow for the consideration of thrust faulting. Other studies published since the early 1990s have also illuminated the details of fault structure within the New Madrid Seismic Zone (e.g., Mueller and Pujol, 2001). We suggest that a detailed revisitation of stress triggering during the New Madrid sequence would therefore likely be fruitful.

The magnitudes and rupture lengths presented in this study and by Hough *et al.* (2000) appear to be consistent with other lines of evidence. One must note, however, that the true values will very likely never be known with precision. Even the magnitude estimates remain uncertain by an amount that is difficult to quantify. Improved estimates may be obtained by better calibrations between intensity and magnitude for events in central/eastern North America, but there are other sources of uncertainty as well. As discussed by Hough *et al.* (2000), accounts of shaking from the New Madrid sequence are likely to be biased because early nineteenth-century settlement was heavily concentrated along river valleys and coasts. Sediment-induced amplification is therefore much more likely to affect reports from the early part of the nineteenth century than those from the twentieth century (or even the mid-nineteenth century). Similar sampling biases are likely to be present for the aftershocks analyzed in this study, although they are difficult to investigate in detail because of the sparsity of the data. However, we consider it unlikely that our estimate of the magnitude of NM1-A is badly biased. We estimate the magnitude of this aftershock only from a comparison with NM2, and site response issues were considered by Hough *et al.* (2000) in the estimation of the magnitude of NM2.

For the 17 December 1811 aftershock, however, we estimate magnitude using the method of Bakun and Wentworth (1997), constrained by regressions from instrumentally recorded events in eastern North America (Bakun *et al.*, 2003). Because of possible biases associated with a preferential sampling from soft-sediment sites, it is possible that our estimate for this event (6.1) is somewhat high. However, a magnitude close to or upward of 6 is not unreasonable for an earthquake that was felt over a radius of over 1000 km.

Available accounts of the 17 December 1811 aftershock do not allow for a precise determination of location, much less a fault rupture scenario. However, by virtue of the relatively high intensities to the south and the relatively low values to the north and northeast, we consider the optimal location for this event to be at least as far south as 35.1N. The location is also consistent with the lack of damage described during this event, because the Mississippi River Valley was very sparsely populated to the south of New Madrid at that time. This puts the aftershock well south of the inferred location of the 16 December 1811 mainshock and possibly close to the modern city of Memphis, Tennessee.

Considering the aftershock and remotely triggered earthquake sequences generated by other large earthquakes (e.g., Bodin and Gomberg, 1994; Hough, 2001; Meltzner and Wald, 2001), a large New Madrid aftershock at this distance from its mainshock would be quite plausible. Whether our preferred location for NM1-B is correct, results from recent large earthquakes serve as a reminder that damaging aftershocks can occur well away from the mainshock rupture. The hazard associated with future large New Madrid mainshocks therefore include a significant additional component associated with large aftershocks that occur outside the New Madrid Seismic Zone as commonly defined.

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References

Anderson, H. M. (1937). Missouri, 1804–1828: peopling a frontier state, *Mo. Hist. Rev.* **31,** 150–180.

Antolik, M., and D. S. Dreger (2001). Source rupture process of the 26 January, 2001 Bhuj, India earthquake (M 7.6), (abstract), *EOS* **82,** 941.

Bakun, W. H., and C. M. Wentworth (1997). Estimating earthquake location and magnitude from seismic intensity data, *Bull. Seism. Soc. Am.* **87,** 1502–1521.

Bakun, W. H., A. C. Johnston, and M. G. Hopper (2003). Estimating locations and magnitudes of earthquakes in eastern North America from modified Mercalli intensities, *Bull. Seism. Soc. Am.* (in press).

Bendick, R., R. Bilham, E. Fielding, V. Gaur, S. E. Hough, G. Kier, M. N. Kulkarni, S. Martin, K. Mueller, and M. Mukul (2001). The January 26, 2001 Bhuj, India earthquake, *Seism. Res. Lett.* **72,** 328–335.

Bodin, P., and J. Gomberg (1994). Triggered seismicity and deformation between the Landers, California, and Little-Skull-Mountain, Nevada, earthquakes, *Bull. Seism. Soc. Am.* **84,** 835–843.

Bradbury, J. (1819). *Travels in the Interior of America in the Years 1809, 1810, and 1811*, Sherwood, Neely, and Jones, London.

Chiu, S. C., J-M. Chiu, and A. C. Johnston (1997). Seismicity of the southeastern margin of Reelfoot Rift, Central United States, *Seism. Res. Lett.* **68,** 785–796.

Cummings, S. (1847). *The Western Pilot*, George Conclin, Cincinnati, Ohio, 1847.

Fuller, M. (1912). The New Madrid Earthquake, *U.S. Geol. Surv. Bull.* **494.**

Gomberg, J., and M. Ellis (1994). Topography and tectonics of the central New Madrid seismic zone-results of numerical experiments using a 3-dimensional boundary-element program, *J. Geophys. Res.* **99,** 20,299–20,310.

Hansen, G., E. Condon, and D. Fowler (1989). *Denial of Disaster: The Untold Story and Photographs of the San Francisco Earthquake and Fire of 1906*, Cameron and Co., San Francisco.

Hough, S. E. (2001). Triggered earthquakes and the 1811–1812 New Madrid, central U.S. earthquake sequence, *Bull. Seism. Soc. Am.* **91,** 1574–1581.

Hough, S. E., J. G. Armbruster, L. Seeber, and J. F. Hough (2000). On the modified Mercalli intensities and magnitudes of the 1811–1812 New Madrid, central U.S. earthquakes, *J. Geophys. Res.* **100,** 23,839–23,864.

Johnston, A. C. (1996a). Seismic moment assessment of earthquakes in stable continental regions. I. Instrumental seismicity, *Geophys. J. Int.* **124,** 381–414.

Johnston, A. C. (1996b). Seismic moment assessment of earthquakes in stable continental regions. III. New Madrid 1811–1812, Charleston 1886, and Lisbon 1755, *Geophys. J. Int.* **126,** 314–344.

Johnston, A. C., and E. S. Schweig (1996). The enigma of the New Madrid earthquakes of 1811–1812, *Annu. Rev. Earth Planet. Sci. Lett.* **24,** 339–384.

Kelson, K. I., G. D. Simpson, R. B. VanArsdale, C. C. Haraden, and W. R. Lettis (1992). Multiple Holocene earthquakes along the Reelfoot fault, central New Madrid seismic zone, *J. Geophys. Res.* **101,** 6151–6170.

King, G. C. P., R. S. Stein, and J. Lin (1994). Static stress changes and the triggering of earthquakes, *Bull. Seism. Soc. Am.* **84,** 935–953.

Liu, Z. (1997). Earthquake modeling and active faulting in the New Madrid Seismic Zone, *Ph.D. Thesis*, St. Louis University, St. Louis, Missouri, 164 pp.

Meltzner, A. J., and D. J. Wald (2001). Aftershocks and triggered events of the great 1906 San Francisco earthquake, based on intensity observations (abstract), *Seism. Res. Lett.* **72,** 227.

Mueller, K., and J. Pujol (2001). Three-dimensional geometry of the Reelfoot blind thrust: implications for moment release and earthquake magnitude in the New Madrid seismic zone, *Bull. Seism. Soc. Am.* **91,** 1563–1573.

Nuttli, O. W. (1973). The Mississippi Valley earthquakes of 1811 and 1812: intensities, ground motion, and magnitudes, *Bull. Seism. Soc. Am.* **63,** 227–248.

Odum, J. K., W. J. Stephenson, and K. M. Shedlock (1998). Near-surface structural model for deformation associated with the February 7, 1812 New Madrid, Missouri, earthquake, *Geol. Soc. Am. Bull.* **110,** 149–162.

Penick, J. L., Jr. (1981) *The New Madrid Earthquakes*, Revised Ed., University of Missouri Press, Columbia.

Street, R. W. (1982). A contribution to the documentation of the 1811–1812 Mississippi Valley earthquake sequence, *Earthquake Notes* **53,** 39–52.

Street, R. W. (1984). *The Historical Seismicity of the Central United States: 1811–1928*, Final Report, Contract 14-08-0001-21251, U.S. Geological Survey, Washington, D.C., Appendix A, 316 pp.

Street, R. W., and O. W. Nuttli (1990). The great central Mississippi Valley earthquakes of 1811–1812, Kentucky Geological Survey Special Publ. 14, Series XI.

Taylor, K., W. Stauder, and R. Herrmann (1991). A comprehensive unified data set for the New Madrid, seismic array, *Seism. Res. Lett.* **62,** 187.

Wald, D. J., T. H. Heaton, and K. W. Hudnut (1996). The slip history of the 1994 Northridge, California, earthquake determined from strong-motion, teleseismic, GPS, and leveling data, *Bull. Seism. Soc. Am.* **86,** S49–S70.

Wald, D. J., V. Quitoriano, T. H. Heaton, H. Kanamori, C. W. Scrivner, and C. B. Worden (1999). TriNet "ShakeMaps": rapid generation of instrumental ground motion and intensity maps for earthquakes in southern California, *Earthquake Spectra* **15,** 537–556.

Wessel, P., and W. H. F. Smith (1991). Free software helps map and display data, *EOS* **72,** 441, 445.

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