Cataloging the 1811–1812 New Madrid, Central U.S., Earthquake Sequence

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ABSTRACT

The three principal New Madrid, central U.S., mainshocks of 1811–1812 were followed by extensive aftershock sequences that included numerous felt events. Although no instrumental data are available for the sequence, historical accounts provide information that can be used to estimate magnitudes and locations for the large aftershocks as well as the mainshocks. Several detailed eyewitness accounts of the sequence provide sufficient information to identify times and rough magnitude estimates for a number of aftershocks that have not been analyzed previously. I also use three extended compilations of felt events to explore the overall sequence productivity. Although one generally cannot estimate magnitudes or locations for individual events, the intensity distributions of recent, instrumentally recorded earthquakes in the region provide a basis for estimation of the magnitude distribution of 1811–1812 aftershocks. The distribution is consistent with a *b*-value distribution. I estimate *Mw* 6–6.3 for the three largest identifiable aftershocks, apart from the so-called dawn aftershock on 16 December 1811.

INTRODUCTION

The 1811–1812 New Madrid earthquake sequence included three well-documented mainshocks that have been described and analyzed in considerable detail (*e.g.*, Mitchill 1815; Fuller 1912; Nuttli 1973; Penick 1981; Street 1982, 1984; Johnston 1996b; Hough *et al.* 2000; Bakun and Hopper 2004a). The three principal mainshocks occurred at approximately 02:15 local time (LT) on 16 December 1811; around 07:15 LT on 23 January 1812, and approximately 03:00 LT on 7 February 1812 (henceforth NM1, NM2, and NM3, respectively). The so-called dawn aftershock on 16 December 1811 was also widely felt (*e.g.*, Johnston 1996b; Hough *et al.* 2000). The magnitude estimates of the four principal events—*i.e.*, the three mainshocks and the dawn aftershock—have been the subject of considerable debate, with published *Mw* estimates ranging from ~7 to >8 (*e.g.*, Nuttli 1973; Johnston 1996b; Hough *et al.* 2000, Bakun and Hopper 2004a).

Each of the three mainshocks was followed by an energetic aftershock sequence. The aftershocks are not included in the National Center for Earthquake Engineering Research (NCEER) catalog of historical central/eastern U.S. earthquakes (Armbruster and Seeber 1992). Nor are aftershocks included in a more recent study (Bakun and Hopper 2004b), which presents locations and magnitudes for moderate historical earthquakes in the eastern/central U.S. but does not include any events prior to 1827.

A number of eyewitness accounts from the New Madrid region document the unrest without providing much if any detail about individual events. Two eyewitnesses, Daniel Drake in Cincinnati, Ohio, and Jared Brooks in Louisville, Kentucky, kept detailed records of felt events, in both cases ranked by perceived relative severity of shaking. Drake's accounts were included as an appendix to a book published in 1815 (Drake 1815); Brooks's accounts were published posthumously (McMurtrie 1819). An additional account from the settlement of New Bourbon (approximately 155 km north of New Madrid and 80 km south of St. Louis; see Figure 1), published in the *Otsego Herald* on 28 March 1812, provides a detailed list of events between 16 December 1811 and 24 December 1812. With these accounts and other archival sources, previous researchers have estimated magnitudes and locations for a number of large aftershocks and triggered earthquakes (Table 1). These events include a large aftershock on 17 December 1811, which Hough and Martin (2002) conclude was probably south of the New Madrid seismic zone (NMSZ), and triggered earthquakes in the Louisville, Kentucky, region, on 27 January 1812 and the night of 7 February 1812 (Hough 2001; Table 1.)

Street (1982) identifies a total of 12 aftershocks that were widely felt and for which multiple archival accounts are available. These events include most of the events in Table 1. One immediate complication, in particular for analyzing events for which only a few accounts are available, is that one cannot assume that all of the events occurred in the New Madrid region. That is, Hough (2001) and Hough *et al.* (2003) conclude that the 1811–1812 sequence included remotely triggered earthquakes, including at least three moderate events in the Louisville, Kentucky, region. More recently, several studies have concluded that remote triggering occurs pervasively in diverse tectonic settings (Hough 2005; Hough 2007; Velasco *et al.* 2008). Thus, for example, event A8 in Table 1, which was felt in Charleston, South Carolina, and Cincinnati, Ohio, could

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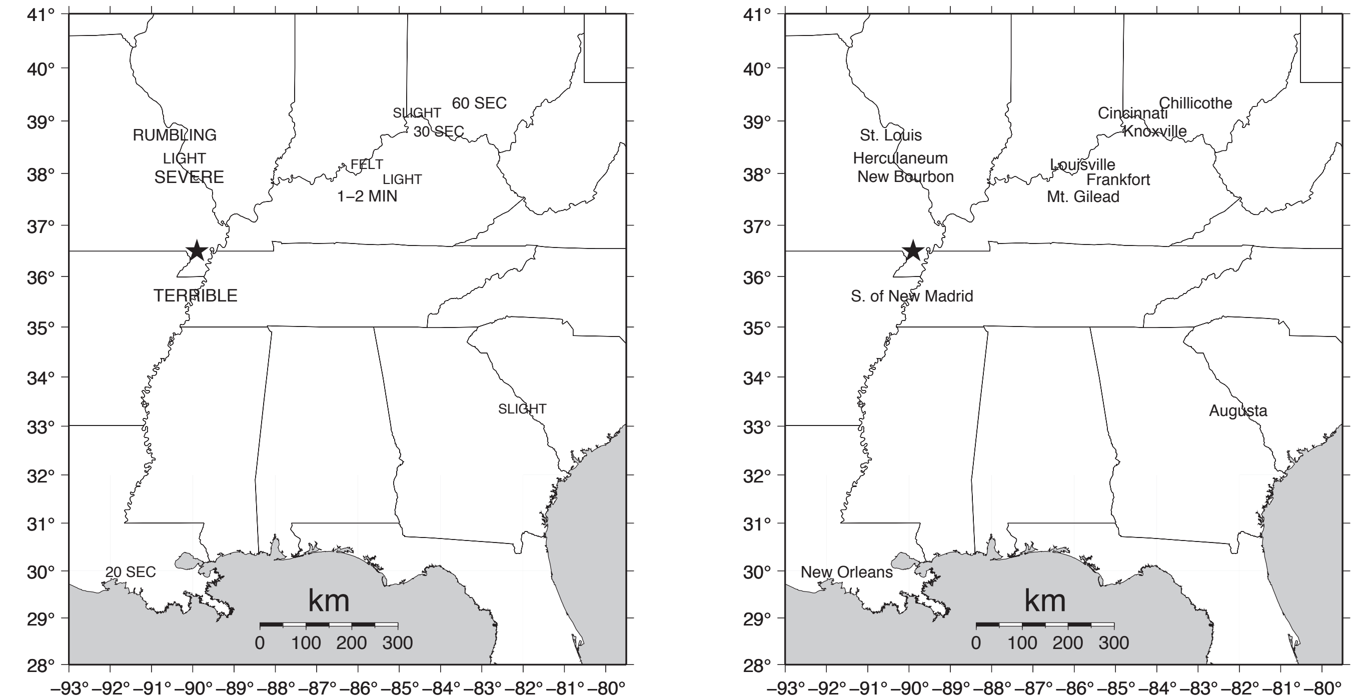
have been either a large New Madrid event or a more moderate earthquake close to the inferred location of other triggered events (*e.g.*, near Louisville, Kentucky). In fact, if one accepts the likelihood that the sequence triggered earthquakes at regional distances, there is no *a priori* basis for assuming a location for any given aftershock. Several of the "widely felt," presumably large aftershocks identified by Street (1982) were documented only in Cincinnati and Louisville, and are not included in Table 1. To analyze individual events one must consider the overall distribution of documented intensities, as well as the accounts themselves, to provide some indication of location.

A further complication arises with the timing of events. In many cases the reported time of any given earthquake is imprecise, for example, a report of shaking "after daylight" or "around 2 in the morning." In other accounts times are given precisely but are clearly only as accurate as local time-keeping, which was not standardized. The time of the initial mainshock is widely reported as having been "around 2 in the morning" or at 2:15 AM. In some locations, however, the reported time is as late as 3 AM. As discussed by Burke (2007), local times of earthquakes in the early 19th century were often established from observations of local noon on a sundial. Thus reported times tend to



▲ **Figure 1.** A) Descriptive accounts of event at approximately 3:00 AM (LT) on 16 December 1811. Accounts are centered on locations of reports. B) Locations corresponding to accounts shown in 1A.

TABLE 1
Aftershocks and triggered earthquakes analyzed in previously published studies. The three mainshocks (16 December 1811; 23 January 1812; 7 February 1812) are not included, although event A2 is the "dawn aftershock."

Ev.	Day	Mo	Yr	Time	Mw	Long.	Lat.	Comment
A1	16	12	1811	3:00 AM	6.3	89.9	36.5	New Madrid aftershock
A2	16	12	1811	7:15 AM	7.0	89.5	36.2	Dawn aftershock
A3	16	12	1811	8:00 AM	5.0?			Triggered earthquake?
A4	16	12	1811	10:00 AM				Insufficient information
A5	16	12	1811	noon	6.3	89.9	36.5	New Madrid aftershock
A6	17	12	1811	noon	6.0	89.2	34.6	South of New Madrid?
A7	27	1	1812	8:45 AM	4.2	85.0	39.6	Triggered earthquake near Louisville
A8	4	2	1812	5:00 PM	5–5.5			Location uncertain
A9	7	2	1812	8:30 PM	4.4	84.1	39.4	Triggered earthquake near Louisville
A10	7	2	1812	10:40 PM	5.2	84.1	38.7	Triggered earthquake near Louisville
A11	10	2	1812	4:00 PM	5–5.5			Location uncertain
A12	11	2	1812	6:00 AM	5–5.5			Location uncertain

follow de facto time zones, although standardized time and time zones were not adopted in the United States until the late 19th century. A further complication arises with observations made by individuals on river boats, since one does not know where their clocks were set. In any case, the preponderance of reported times on or near the hour and half hour (see Table 2) suggests that times were simply not noted precisely, as indeed one might expect for events at this time of night.

Unreliable timing complicates efforts to distinguish individual events in an aftershock sequence; it is often important to consider the relative times of multiple events documented by any one eyewitness. It is also important to consider how accounts compare to each other. For example, the New Bourbon account is notably precise, providing times to the nearest minute, but the times of events are consistently about 10 minutes earlier than times reported at other locations.

THE NEW MADRID SEQUENCE: DAY ONE

Although the time of the mainshock cannot be determined precisely, accounts suggest that the initial mainshock on 16 December 1811 occurred around 2:15 AM LT. Close examination of modern instrumental recordings sometimes reveals early large aftershocks buried in the codas of mainshocks (*e.g.*, Peng *et al*. 2007). Macroseismic accounts not uncommonly include description of multiple episodes of shaking, but presumably in many cases are noting the arrival of later arriving mainshock phases. Very early aftershocks are thus plausible but virtually impossible to discern based on macroseismic data.

Looking beyond the time of the mainshock, the first identifiable distinct event occurred approximately 45 minutes after the mainshock. Some accounts of shaking around 3:00 AM (LT) on 16 December 1811 clearly correspond to the mainshock, but 12 accounts clearly describe both the mainshock and a second felt event. Accounts of the separation range from 30 to 60 minutes (Table 2.)

This event (A1) is reported as felt at a number of locations in Ohio and Kentucky, as well as in New Orleans. The event is described as "severe" at New Bourbon and was described by boatman John Bradbury, who was moored to a small island south of New Madrid, as "terrible, but not equal to the first" (Figure 1). Available accounts suggest this was a significant aftershock in the New Madrid region—the first identifiable large aftershock of the sequence.

Street (1982) assigns a time of 8:15 AM (LT) to the so-called dawn aftershock (A2, Table 1), the large event that is sometimes regarded as the fourth principal earthquake of the 1811–1812 sequence. Street (1982) also identifies a large, widely felt aftershock around 7:15 AM local time on 16 December 1811. It is clear that a large aftershock did occur in the New Madrid region around dawn: as discussed by Hough and Martin (2002), a detailed account by John Hardeman Walker (see Cummings 1847) provides a compelling account of severe, presumably near-field ground motions at a location that was very close to the inferred surface projection of the Reelfoot fault. Many accounts from the Midwest and East Coast describe strong shaking around 8:15 AM LT, but, considering carefully the accounts from the morning of 16 December 1811, I conclude that the most reliable accounts from locations in proximity to the NMSZ describe the most severe shaking to have occurred between 7:00 and 7:20 AM The account from New Bourbon, for example, states that the most severe shaking felt on 16 December 1811 occurred at 7:12 AM I therefore conclude that the large "dawn aftershock" (Table 1, A2)—the event described in detail by Walker—occurred at approximately 7:15 AM local time.

Several accounts describe multiple felt events between 7:00 AM and 8:00 AM on 16 December 1811. In New Bourbon, for example, light shaking was reported at 7:50 AM. In contrast, an account from Chillicothe, Ohio, describes "tolerable hard" shaking at 8:05 AM, and Jared Brooks describes a series of shocks in Louisville, Kentucky, culminating in "tremendous" shaking around 7:50 AM. Given fragmentary accounts and

TABLE 2
Locations where accounts describe event A1 as well as the initial mainshock (M/S). Times given are reported local times (AM).

Location	Time	Account of A1 (duration if noted)	M/S
New Bourbon, MO	3:00	extremely severe	2:05
S. of New Madrid	2:30	terrible but not equal to first	2:00
St. Louis, MO	2:47	rumbling, less violent than first	2:15
Cincinnati, OH	3:00	slight	2:24
Chillicothe, OH	3:04	~1 minute, less violent than first	2:15
Herculaneum, MO	3:00	light, short duration	~2
Mt. Gilead, KY	2:30	less severe than first, 1–2 min	~2
Louisville, KY	3:15	felt	2:15
New Orleans, LA	2:30	~20 seconds	~2
Augusta, GA	3:15	slighter than first	2:30
Frankfort, KY	>3:00	"a little after three," light	~2
Knoxville, TN	2:30	~20 seconds	~2

inconsistent time-keeping, these accounts cannot be unraveled to identify events with confidence. They do, however, provide an intriguing suggestion that a moderate triggered earthquake might have occurred in the Kentucky/Ohio region around 8:00 AM LT (Table 1, A3).

Another apparently significant earthquake occurred around 10:00 AM on 16 December 1811 (Table 1, A4). The account from New Bourbon describes "light" shaking that continued for two minutes. Additional accounts are available from Chilliocothe, Ohio ("slight," 10:08 AM) and Cincinnati, Ohio ("not generally observed," between 10–11a.m). Other accounts describe events around 10:00 AM as well, but considering the reported time of the initial mainshock at these locations, these may not correspond to the same event. A significant event at 10:00 AM is moreover missing from several fairly detailed accounts, including that from St. Louis. The location and magnitude of this aftershock thus remain extremely uncertain.

Accounts of an event around noon on 16 December 1811 (not included in the compilation of Street [1982] but given in Table 1 as A5) are more straightforward: shaking is described as "violent" and "hard" at two sites along the Mississippi River valley, as "smart" in St. Louis, and "slight" at several locations in the Midwest and New Orleans. The felt extent and effects are roughly comparable to those of event A1, although the intensity distribution is not as well constrained.

THE REST OF THE SEQUENCE

The detailed account from New Bourbon is critical for the interpretation of events through 24 December 1811 because it provides an indication of the severity of shaking along the Mississippi River Valley. In general, progressively fewer accounts are available for locations in proximity to the NMSZ for events in January and February, presumably due in part to a cold spell in January and early February during which the Ohio River froze and in part to an exodus of settlers from the New Madrid region. Reporting limitations notwithstanding, both Drake's and Brooks's accounts suggest that the aftershock sequence following the 23 January 1812 mainshock was relatively sparse. This could reflect the magnitude as well as the location of the mainshock. If this mainshock occurred well north of the NMSZ (Mueller *et al.* 2004; Hough *et al.* 2005), the estimated magnitude could have been as low as 6.8.

Of the later events for which multiple accounts are available, several (A8, A11, and A12 in Table 1) were felt in Cincinnati, Louisville, and either Columbia or Charleston, South Carolina (Street 1982.) In the absence of reports from other regions, available accounts suggest the events were probably moderate earthquakes in the Louisville region, and the felt extent suggests magnitudes on the order of 5.0–5.5. However, in the absence of *a priori* constraint on likely location, accounts are insufficient to infer even tentative locations or magnitudes.

For most of the events in Table 1 one can analyze the distribution of documented intensities. Several methods have been developed to determine magnitude from modified Mercalli intensity (MMI) data. Hough *et al.* (2000) use the isoseismal area-*Mw* 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. Bakun and Hopper (2004a) present a revised attenuation model for central-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.

Preliminary results indicate that the results of the Bakun and Hopper (2004a) method are not consistent with those of Johnston (1996a) for *Mw* 7 and above 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. In any case, one expects the method of Bakun and Hopper (2004a) to be more reliable for moderate events than for earthquakes as large as the New Madrid mainshocks, since the results are not as dependent on extrapolation beyond the magnitude range of the calibration events.

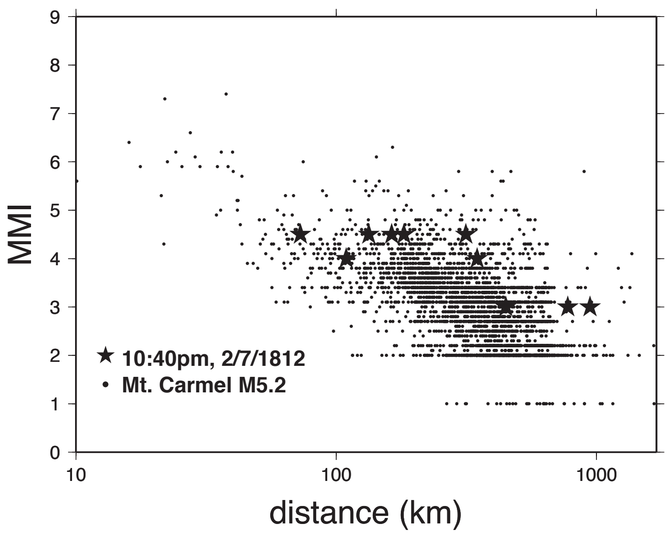
Applying the method and attenuation relation of Bakun and Hopper (2004a) to event A1, and assuming a location of -89.9W, 36.5N, the inferred magnitude is *Mw* 6.3. Using a grid search approach, the optimal location is -90.0W, 37.0N, and the magnitude is *Mw* 6.2. *Mw* 6.2–6.3 is a reasonable estimate for the magnitude of A5 (Table 1), for which the intensity distribution is less well constrained but roughly comparable to that of A1 (Table 1).

Hough (2001) presents rough magnitudes for the three inferred remotely triggered earthquakes, A7, A9, and A10 in Table 1. Using the method and attenuation relation of Bakun and Hopper (2004a) yields slightly lower magnitude values, including an estimate of 5.2 for the largest inferred triggered event (A10). The intensity distribution of A10 can be compared to the Community Internet Intensity Map intensities for the 2008 Mt. Carmel, Illinois, earthquake, for which *Mw* 5.2 has been determined from waveform modeling of regional data (Herrmann *et al.* 2008). The comparison reveals a good correspondence between MMI as a function of distance for the two events (Figure 2).

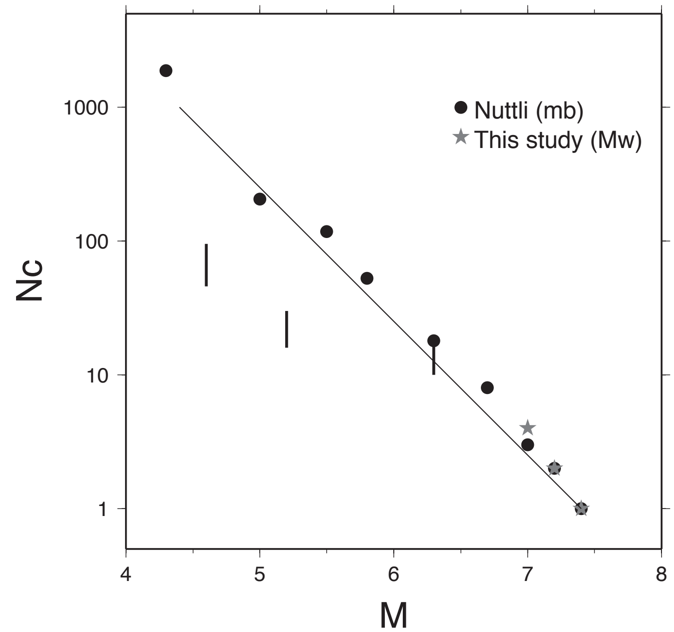
SEQUENCE STATISTICS

Jared Brooks's chronicle of the New Madrid sequence, which continued until 5 May 1812, included not only information on individual felt events but also a tally of the number of earthquakes of each level of severity (McMurtrie 1819). His intensity scale included six levels ranging from "1st rate" to "6th rate" (hereinafter JBI-1–JBI-6; Table 3). According to Brooks's classification, JBI-6 shocks were not felt, but caused disturbances

TABLE 3				
Intensity classifications of Jared Brooks, magnitude estimates from Nuttli (1973).				
JBI	**Effects**	**MMI**	**#**	***mb* (N)**
1st	Damage to chimneys, gables	VII	3	7.1–7.4
			5	6.7
2nd	Less violent but very severe	V–VI	10	6.3
3rd	Moderate but generally alarming	IV–V	35	5.8
4th	Perceptible to those standing still	III	65	5.5
5th	(not defined)	II	89	5.0
6th	Pendulums swung, not felt	I	1667	4.3



▲ **Figure 2.** Community Internet Intensity Map intensities for the 18 April 2008 *Mw* 5.2 Mt. Carmel, Illinois earthquake (black circles) and intensities estimated by Hough (2001) for event A10 in Table 1 (black stars).



▲ **Figure 3.** Tally of New Madrid sequence estimated by Nuttli (1973) (dark circles) and by this study (gray stars and bars). Line indicates *b*-value of 1.

of rudimentary instruments that he constructed to respond to subtle horizontal and vertical shaking: pendulums with lengths ranging from one to six inches, and a mass hung on a spring.

The distribution of events tallied by Brooks appears to be grossly consistent with a *b*-value distribution of magnitudes (Gutenberg and Richter 1944). As discussed by Nuttli (1973), one can establish an equivalence between Brooks's scale and a traditional MMI scale (Table 3). Thus, if one can establish a correspondence between intensity levels at Louisville and magnitude, Brooks's tally can thus be used to constrain the overall productivity of the 1811–1812 sequence. By Nuttli's calculations, $mb = 4.3$ is a conservative estimate for events large enough to cause Brooks's pendulums to swing (JBI-6). Of the eight JBI-1 shocks, Nuttli interpreted these events as including the three (*mb* 7.1–7.4) mainshocks and five ~*mb* 6.7 aftershocks. Carrying this calculation through to lower JBI values, Nuttli determined the values shown in Table 3 and Figure 3. According to this interpretation, the sequence included 50 aftershocks with *mb* 5.8–6.7.

The distribution of magnitude values inferred by Nuttli (1973) is consistent with an overall Gutenberg-Richter distribution (Gutenberg and Richer 1944) with a *b*-value of 1 (Figure 3). I suggest, however, that this result is problematic for several reasons. First, the level of completeness is unrealistic. One cannot expect Brooks's tally of JBI-6 events to be complete, since the tally was based on a visual assessment of pendulum motions. The sensitivity of Brooks's pendulums is also difficult to gauge. Nor would one expect his tally of JBI-5 events to be complete; *i.e.*, Brooks did not describe the effects associated with this level of shaking, but clearly it was less severe than JBI-4: perceptible to those standing still.

I revisit the calculations of Nuttli (1973), first considering the strong evidence that the sequence included remotely triggered earthquakes in the Louisville region and, second, considering recent results from the USGS Community Internet Intensity Map Web page (http://earthquake.usgs.gov/eqcenter/dyfi), which provide constraint on the intensity distribution of moderate earthquakes in the region.

TABLE 4
Intensity Classifications of Daniel Drake

DDI	Effects in Cincinnati	MMI	#	Notes	JBI
1	Damage to chimneys	VI	3	Three principal mainshocks	1
2	Moderate shaking	V	3	A2, A7, A10	1
3	Generally felt	IV	13+		2
4	Felt by those at rest	III	13+		3
5	Not generally felt	II			4

If the sequence included events closer to Louisville than to the NMSZ, and extant accounts are clustered in the Louisville region, assuming a NMSZ location for all events will clearly lead to an unknowable overestimate of magnitudes. In addition to the relatively large remotely triggered earthquakes that can be identified individually, a moderate triggered event will be followed by its own aftershock sequence (Richter 1955; Hough and Kanamori 2002).

Reconsidering the eight JBI-1 shocks documented by Brooks's detailed chronology, four of these events clearly correspond to the three mainshocks and the dawn aftershock. Considering Brooks's detailed chronology, three JBI-1 shocks occurred the week that ended 9 February 1812: the 7 February mainshock and events that occurred at 8:30 PM and 10:40 PM on the night of 7 February. The latter two events correspond to A9 and A10 in Table 1, events that Hough (2001) concludes were moderate triggered earthquakes in the Louisville region. Of the three JBI-1 shocks that occurred the week ending 22 December 1811, from Brooks's detailed account it is clear that one was the 16 December mainshock and one was the event around 8:00 AM that morning (Table 1, A3). The timing of the third event is not clear, but it probably was the dawn aftershock at 7:20 AM LT. As discussed earlier, available accounts of A3 suggest that this was also a moderate triggered event in the Louisville region. Thus, of the four JB-1 events in addition to the three mainshocks and dawn aftershock, at least two and possibly three were likely to have been moderate triggered earthquakes in the Louisville, Kentucky region, rather than large aftershocks in the New Madrid region.

Brooks's tally further includes a total of 10 JBI-2 shocks: four, one, and five following NM1, NM2, and NM3, respectively. It is more difficult to identify each of these individual events in the daily chronology. However, one can reasonably assume that events A1 and A6 in Table 1, respectively, were two of the JBI-2 shocks during the week ending 22 December 1811. As discussed earlier and in Hough and Martin (2002), using the method of Bakun and Hopper (2004a) one estimates *Mw* 6.1–6.3 for these two events, as well as event A5 in Table 1.

Brooks's account can also be considered together with the detailed account by Drake (1815), which provides a chronicle of events at Cincinnati, Ohio, a location ~140 km farther from the NMSZ, and includes significantly fewer events than those tallied by Brooks. For example, between January 3 and 22, 1812, Drake reports no vibrations "strong enough attract general notice," whereas between January 6 and 19, 1812, Brooks reports one JBI-2 event, four JBI-4 events, six JBI-5 events, and 205 JBI-6 events. For the period 10 February 1812 to 15 March 1812, Drake reports a total of 14 events; in this same span of time Brooks reports a total of 78 events strong enough to be at least weakly felt (12 JBI-3 events, 28 JBI-4 events, 38 JBI-5 events) as well as 708 JBI-6 events. These comparisons reveal that JBI-4 events were not generally felt in Cincinnati.

Considering Drake's overall tally of events, he distinguishes five classes of events, as shown in Table 4. He identifies the three mainshocks as having been "first class" and further identifies A2, A7, and A10 (the dawn aftershock and two remotely triggered earthquakes; see Table 1) as having been "second class." Of the remainder, he notes that about half were "fourth class," felt only by "persons *not* in action" and half were "third class," what he describes as intermediate severity. He further identifies remaining "numerous tremors & ebullitions," events that were not generally felt, as "fifth class." The total number of third and fourth class events is not entirely clear. In addition to the six identified first- and second-class events (hereinafter DDI-1 and DDI-2, respectively), Drake's tally includes 26 distinct events between 16 December 1811 and 5 May 1812 as well as descriptions of days when frequent tremors reportedly occurred but are not listed separately (Table 4). Comparing Drake's tally with that of Brooks, one can establish a rough correspondence, as shown in Table 4. The inferred correspondence again suggests that most of the shocks classified by Brooks as JBI-3 were large enough to be generally felt at a distance of 560 km, but JBI-4 events were generally not felt at 560 km.

Intensity distributions collected by the online Community Internet Intensity Map (CIIM, or "Did You Feel It?") Web page offer guidance in interpreting Brooks's and Drake's observations. One approach is to consider the distance ranges over which people fill out CIIM questionnaires (Figure 3 of Atkinson and Wald 2007), assuming that the maximum distance provides an indication of the maximum felt extent of an earthquake. (Although people do submit "not felt" reports via CIIM, such responses typically account for a small percentage of the total.) From Figure 3 in Atkinson and Wald (2007) one infers a minimum *Mw* of 4.4–5.0 and 4.8–5.2 for events that are weakly felt at a distances of 420 km and 560 km, respectively. As examples, the *Mw* 5.2 2008 Mt. Carmel, Illinois, earthquake generated MMI 2.5–4 shaking at many locations at 500–600 km epicentral distance, while the **M** 4.6 2003 Fort Payne, Alabama, earthquake generated MMI 2–4 shaking at 420 km.

These considerations lead to the inferred aftershock magnitude estimates of *Mw* 5.2 for JBI-3 (DDI-4) and 4.6 for JBI-4 (DDI-5), assuming locations in the NMSZ. Based on the

TABLE 5
Interpretation of events chronicled by Drake (1815). Magnitude values marked by asterisk correspond to rough estimates of events assuming NMSZ locations.

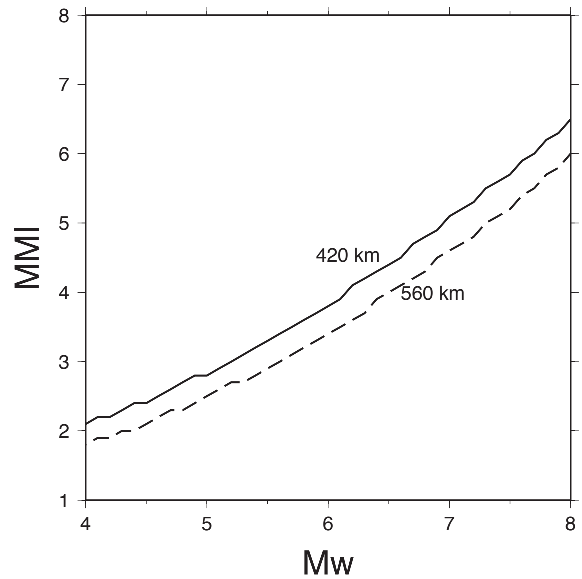
DDI	Number	Magnitudes	Notes
1	3	7.1, 7.0, 7.4	Three principal mainshocks
2	3	7.0, 4.4, 5.2	Dawn aftershock, two remotely triggered earthquakes
3	6–13	6.3*	Large NMSZ aftershocks, moderate triggered earthquakes
4	6–13	5.2*	Moderate NMSZ aftershocks, small triggered earthquakes
5	30–65	4.6*	Moderate NMSZ aftershocks, small triggered earthquakes

inferred magnitude estimates for the large aftershocks that in a few cases can be investigated in detail, I estimate *Mw* 6.3 for JBI-2 (DDI-3). The results shown in Table 5 for DDI-3, DDI-4, and DDI-5 levels are estimated assuming a NMSZ location. The detailed consideration of strong events reported by both Drake and Brooks suggests that as many as half of these events might have been smaller local events. The number of DDI-5 events is even more problematic, since Drake does not provide a tally of this shaking level. Assuming these events correspond to JB-4 shaking in Louisville, one infers a very rough estimate of 65, again presumably an unknown mixture of NMSZ events and remotely triggered earthquakes.

The final inferred magnitude distribution for the sequence is shown in Figure 3. The result is again roughly consistent with the expected Gutenberg-Richter distribution, but the inferred distribution is considerably more ragged than that inferred by Nuttli (1973). I suggest, however, that the results from this study are much more realistic. That is, since the number of $Mw < 5.5$ events is constrained primarily from accounts 400–550 km away from the NMSZ, the catalog is expected to be grossly incomplete.

Established empirical relations suggest that an average aftershock sequence will follow a *b*-value distribution with the largest aftershock approximately one unit smaller than the mainshock. Thus, if the largest New Madrid aftershock was **M** 7.4, one would expect the overall sequence distribution to include a *b*-value distribution for **M** 6.4 and smaller events, not a continuous *b*-value distribution below **M** 7.4. However, clearly the New Madrid sequence, with three principal mainshocks as well as the exceptionally large early aftershock, did not conform to guidelines for an average mainshock-aftershock sequence.

The above calculations are based on general conclusions drawn from CIIM results. Alternatively one can use the intensity attenuation relations determined by Atkinson and Wald (2007) to predict MMI values for a range of magnitudes at distances of 420 and 560 km (Figure 4). These predictions correspond to the mean of the observed CIIM values; the observed residuals vary between ± 1 intensity unit, with a small number of larger values. Because the early settlements of Cincinnati and Louisville were immediately adjacent to the Ohio River, it is likely that 1811–1812 intensities were amplified relative to average CIIM values. Drake explicitly noted that "the convulsion was greater along the Mississippi, as well as along the Ohio, than in the uplands." He went on to observe that "the strata in both vallies are loose. The more tenacious layers of clay and loam spread over the adjoining hills, many of which are composed of horizontal limestone, suffered but little derangement" (McMurtrie 1819). It seems unlikely that an amplification of less than a full intensity unit would have left this impression. If one assumes an amplification of just 0.5 intensity units, the results predict that an *Mw* 5.0 event will generate MMI 3 shaking at 560 km, and an *Mw* 5.8 event will generate nearly MMI 4 at this distance. This confirms the conclusion that it is unlikely that Brooks's "4th rate" events, which were not generally felt in Cincinnati, were as large as **M** 5.5.



▲ **Figure 4.** MMI level predicted using the relations of Atkinson and Wald (2007) for distances of 420 and 560 km, assuming no site amplification.

It is difficult to estimate magnitude values for JB-5 and JB-6 events, knowing only that they were very weakly felt and not generally felt at a single location. The numbers of these events are moreover in doubt because they presumably include many small events in the Louisville region.

DISCUSSION AND CONCLUSIONS

Although magnitude estimates and sequence statistics remain uncertain, careful consideration of available accounts provides the basis for an exploration of the 1811–1812 New Madrid earthquake sequence. As demonstrated by Nuttli (1973), available accounts reveal a Gutenberg-Richter distribution of aftershocks. However, the magnitudes and numbers of large events estimated in this study are lower than those estimated in Nuttli's study. This is a result of 1) the recognition that the sequence included remotely triggered earthquakes as well as NMSZ aftershocks, 2) application of the method and attenuation relation developed by Bakun and Hopper (2004a), which yields lower *Mw* estimates for identifiable large aftershocks than those derived from the *mb* values inferred by Nuttli (1973), and 3) newly available CIIM results, which provide reliable indication of the intensity distributions of moderate central/eastern U.S. events. The revised inferred overall sequence statistics are still consistent with a Gutenberg-Richter distribution.

Furthermore, I estimate the magnitudes of the largest inferred NMSZ aftershocks (A1, A5, and A6 in Table 1) using the method and attenuation relation of Bakun and Hopper (2004a) and intensity distributions inferred from archival accounts. Low *Mw* 6 values are estimated for all three events. Thus, in contrast to the ~50 *mb* 5.8–6.7 aftershocks inferred by Nuttli (1973), I conclude that, in addition to the four principal events, the sequence included no more than a few aftershocks as large as low-*Mw* 6. I further note that the intensity distribution of the 2008 Mt. Carmel earthquake perhaps provides a general note of caution regarding the interpretation of sparse intensity distributions for historical central/eastern U.S. earthquakes: this moderate *Mw* 5.2 event was not only generally felt at distances of 500–600 km, but it also generated estimated MMI III–IV shaking at distances upwards of 1,000 km (Figure 2).

The last New Madrid event identified in this study occurred on 11 February 1812. Brooks's tally of felt events continues until 5 May 1812. Drake's record of events extends until 12 December 1813. One can find some correspondence between the two records. For example, both describe "slight" shaking around 11:00 AM on 4 May 1812. In the absence of archival accounts from other locations, it is impossible to interpret such observations. Neither account, however, suggests that any significant aftershocks occurred between mid-February and early May. Drake describes a "moderate vibration" around dawn on 15 September 1812. Further archival research might yield additional accounts of this event as well as other aftershocks and regional events between 1812 and 1827.

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