Scientific overview and historical context of the 1811-1812 New Madrid earthquake sequence

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Abstract
The central and eastern United States has experienced only 5 historic earthquakes with M_w 7.0, four during the New Madrid sequence of 1811-1812: three principal mainshocks and the so-called «dawn aftershock» following the first mainshock. Much of the historic earthquake research done in the United States has focused on the New Madrid Seismic Zone (NMSZ), because the largest New Madrid earthquakes may represent the archetype for the most damaging earthquakes to be expected in intraplate regions. Published magnitude values ranging from 7.0 to 8.75 have generally been based on macroseismic effects, which provide the most direct constraint on source size for the events. Critical to the interpretation of these accounts is an understanding of their historic context. Early settlments clustered along waterways, where substantial amplification of seismic waves is expected. Analyzing the New Madrid intensity values with a consideration of these effects yields preferred values of M_w 7.2-7.3, 7.0, and 7.4-7.5 for the December, January, and February mainshocks, respectively, and of 7.0 for the «dawn aftershock». These values are consistent with other lines of evidence, including scaling relationships. Finally, I show that accounts from the New Madrid sequence reveal evidence for remotely triggered earthquakes well outside the NMSZ. Remotely triggered earthquakes represent a potentially important new wrinkle in historic earthquake research, as their ground motions can sometimes be confused with mainshock ground motions.

Key words *New Madrid earthquakes – intraplate – historic*

1. Introduction

The earthquake sequence that struck the New Madrid region of the North American mid-continent in 1811-1812 had remarkably far-reaching effects. By some accounts, they are among the largest – if not the largest – to have ever occurred in a so-called Stable Continental Region (SCR) (Johnston, 1996). Ground motions from the three principal events were felt in places as far away as Canada, New England, and at a number of locations along the Atlantic coast (Mitchill, 1815; Bradbury, 1819; Fuller, 1912; Nuttli, 1973; Penick, 1981; Street, 1984; Johnston, 1996). Contemporary accounts document three principal events: 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). All three events were felt throughout much of the central and eastern United States. Additionally, a large aftershock to NM1 (NM1-A) occurred near dawn on 16 December 1811. Substantial aftershock activity following all events was also documented (Fuller, 1912; Penick, 1981).

Paleoseismic investigations suggest a repeat time of the order of 400-500 years for the New

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Madrid events; they also suggest that the New Madrid seismic zone tends to produce prolonged sequences with multiple, distinct mainshocks, the magnitudes of which are comparable to those of the 1811-1812 events (*e.g.*, Tuttle and Schweig, 1996; Tuttle *et al.*, 2002). Thus, the magnitudes of the earthquakes become a critical issue for the quantification of regional hazard in central North America. A repeat of the 1811-1812 sequence would clearly have a tremendous impact. The New Madrid Seismic Zone (NMSZ) contributes a nontrival component of seismic hazard in relatively distant midwestern US cities such as St. Louis, Missouri (Frankel *et al.*, 1996).

A second impetus to investigate the 1811-1812 sequence stems from their implications for general issues related to intraplate earthquake processes. The NMSZ is among the best-understood intraplate source zones in the world, largely because it has been so active throughout the historic and recent prehistoric past. This relative abundance of data affords the opportunity to explore critical unanswered scientific questions regarding large SCR earthquakes, most notably the questions of why such events occur in certain regions but (apparently) not in others.

Because an evaluation of the magnitudes of the 1811-1812 events is so critical for several reasons, tremendous effort has been invested in gleaning quantitative information from the limited available data. Available data include i) paleoliquefaction features preserved by the sediments within the Mississippi embayment (*e.g.*, Tuttle and Schweig, 1996); ii) the present-day distribution of seismicity in the NMSZ, which is assumed to illuminate the principal fault zones (*e.g.*, Gomberg, 1993; Johnston, 1996); iii) first-hand reports («felt reports») of the shaking and/or damage caused by the events over the central/eastern United States (*e.g.*, Nuttli, 1973; Street, 1984).

Determination of magnitudes for the 1811-1812 mainshocks hinges exclusively on the felt reports and their interpretation for Modified Mercalli Intensity (MMI) values. Nuttli (1973) drew isoseismal contours based on his compilation of approximately 40 felt reports. He determined $m_b = 7.2$, 7.1, and 7.4 for NM1, NM2, and NM3, respectively, based on a relationship between ground motion and intensities from smaller and more recent instrumentally recorded earthquakes in the central United States. With an exhaustive archival search, Street (1984) greatly expanded the number of reports (to approximately 100 for NM1) and assigned them intensity values. Street (1982, 1984) used these new data and the same method used by Nuttli (1973) to obtain $m_b = 7.1$ and 7.3 for NM2 and NM3 and m_b 7.0 for the 07:15 LT aftershock of 16 December 1811. Street (1982) determined these values by assuming the m_b value for NM1 determined by Nuttli (1973) and comparing the relative isoseismal areas of the other events.

Johnston (1996) carried out a comparison between intensity distribution and moment magnitude M_w for large earthquakes in stable continental regions worldwide. He compared areas within isoseismals of discrete intensities with instrumentally measured moment magnitudes. On the basis of this calibration, he assigned 8.1 ± 0.31, 7.8 ± 0.33, and 8.0 ± 0.33 for NM1, NM2, and NM3, respectively. In this calculation, Johnston (1996) used the only published intensity contours; those determined by Nuttli (1973).

Hough *et al.* (2000) revisited the magnitude determination for the New Madrid mainshocks in two ways. First they reconsidered intensity assignments for the reports compiled by Nuttli (1973) and Street (1984). This reinterpretation focused on effects that were considered relatively objective, such as descriptions of damage to structures.

The reinterpreted MMI values can be used to define new isoseismal contours using subjective as well as systematic approaches, and the isoseismal contours can then be used to obtain M_w estimates following the procedure and calibration established by Johnston (1996). The results can then be interpreted with a consideration of their historic context, most notably early American settlement patterns. The population of the United States was $\approx 7\,000\,000$ in 1811, with sizable numbers in the states of Tennessee, Kentucky, and the region including the present-day states of Missouri and Louisiana. The 1810 Census gives the population for several districts for which felt reports are considered, including the Dis-

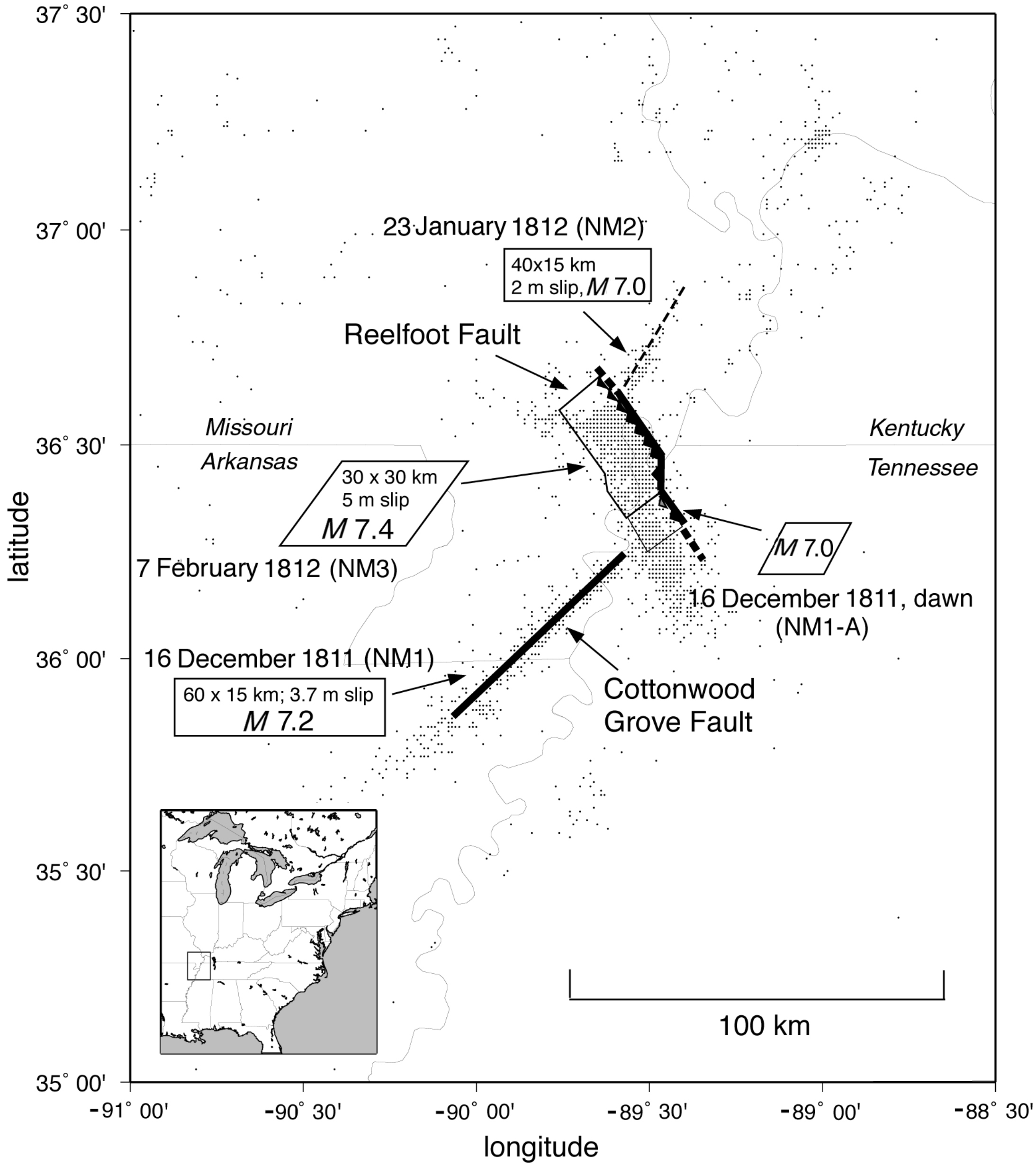


Fig. 1. Map showing location of the New Madrid seismic zone as illuminated by microseismicity between 1974 and 1996. Locations are from the New Madrid catalog (see Taylor *et al.*, 1991), which are reported only to two significant figures in decimal degrees. Epicenters of the three principal 1811-1812 mainshocks are shown with large open circles (after Johnston and Schweig, 1996). Solid line shows inferred location of Reelfoot Fault (after Odum *et al.*, 1998). Rupture scenarios for NM1, NM1-A, and NM3 are also indicated. Scenario for NM2, indicated with dashed line, is considered relatively uncertain.

trict of St. Louis (population 5667), Cincinnati (2540), New Orleans (24 552), Louisville (1357), and New Madrid (2103).

Although present-day Missouri was relatively sparsely populated in 1811, available contemporary accounts (*e.g.*, Brackenridge, 1817, Bradbury, 1819) provide a fairly thorough documentation of demographic and related information. These sources reveal that some towns were more than simple villages by 1811, with solidly constructed houses appearing by the turn of the century. The oldest brick building west of the Mississippi was built in the town of Sainte Genevieve in 1804; this town is along the Mississippi River valley north of New Madrid. This house and ≈ 50 others that predate the New Madrid sequence, are still standing today.

This paper summarizes and expands on the results published by Hough *et al.* (2000). The reader is referred to this publication for many of the details regarding the results summarized here. Additionally, I summarize evidence that the 1811-1812 sequence included a number of significant, potentially damaging earthquakes, that occurred well outside of the NMSZ.

2. Intensity reports

2.1. *Original sources: general considerations*

Hough *et al.* (2000) concluded that many of the original MMI assignments by Nuttli (1973) were too high for two basic reasons: a general bias in the interpretation of reports whose drama is belied by low levels of actual damage reported, and, to a lesser extent, a failure to take site response issues into account. Many of the original accounts describe the effects of long-period shaking; this kind of shaking can be dramatic for large (M_w 7 and larger) events at regional distances even when the overall effects of the shaking is low.

Overall, many of the accounts do not appear to support values as high as those originally assigned. In St. Louis, Missouri, Fuller (1912) describes reports (from the *Louisiana Gazette*, 21 December 1811) of people having been wakened by NM1 and furniture and windows having been rattled. He notes that «several chimneys were thrown down», and a few houses «split». To understand such accounts one must be familar with the vernacular of the time; in this case, the word «split» seems to have been used in a number of accounts to mean «cracked» rather than destroyed. Consistently, as in the above example, the phrase «thrown down» is used to describe catastrophic damage to chimneys, walls, or houses. The *Louisiana Gazette* account goes on to note that «no lives have been lost, nor has the houses sustained much injury». This observation also suggests that the word «split» does not imply substantial damage. On the basis of these reports, a MMI of VI-VII appears to be more appropriate than the value of VII-VIII that Nuttli (1973) assigns for NM1.

At many locations at regional distances (roughly 500-1000 km) event NM1 is generally reported as having been «distinctly» (often the word «sensibly» is used) felt but with no reports of damage. Instead, reports describe the rattling of washing stand pitchers, glass, china, and furniture. Reports from these locations also generally indicate that «many» were awakened by the event. Such descriptions are consistent with an MMI value of IV-V, whereas higher values were assigned in the earlier study. In two instances (Arkport, in Western New York, and Lexington, Kentucky) it appears that Nuttli (1973) was simply mistaken in either his reading of the original sources, or the MMI assignments.

The reinterpretation of Hough *et al.* (2000) thus represents both a revision and a substantial expansion of the original intensity work by Nuttli (1973).

2.2. *Site response*

In addition to the reassignments discussed above, Hough *et al.* (2000) also assigned – and interpreted – MMI values with a consideration of site response. Arguably, the key to understanding the effects of the New Madrid earthquakes lies with an appreciation for their historic context. As a first-order observation, the intensity data are very sparse and concentrated along major river valleys and other bodies of water. The latter observation reflects the distribution of the overall population in the more sparsely populated parts of the central and southeastern United States in the early 1800s. Because the New Madrid sequence predates the construction of railroad lines into the midcontinent, settlements tended to remain clustered in proximity to waterways. Westward expansion followed the major rivers, and virtually all early 1800s settlements in Missouri (the extent of the western frontier at that time) were within a few miles of the Mississippi River. In addition to the influx of settlers from the east, settlers of French descent also arrived in the area from Quebec to the north, primarily along the Wabash River.

By the early 1820s, early settlers had begun to recognize the pitfalls associated with life on the immediate river banks, which included poor drainage, floods, and disease (Missouri Historical Review, 1911). However, the very earliest settlements of the late 1700s and very early 1800s often were on fluvial sites, immediately adjacent to rivers. New Madrid was built so close to the river bank that even before the earthquakes, parts of the town regularly gave way under the continued assault of river currents (Penick, 1981). One of the other sizable Missouri settlements of the time, Sainte Genevieve, had been moved to higher ground approximately a mile from the river after a flood in the late 1700s resulted in substantial erosion of the river bank upon which the town had originally been built (Brackenridge, 1817). This town, which is 160 km north of the town of New Madrid and 75 km south of St. Louis, provides a unique hard-rock sample point, as I will discuss later.

Notwithstanding a handful of exceptions, at the time of the 1811-1812 sequence, the population of the US was clustered in proximity to waterways, especially throughout the sparsely populated mid-continent. Intensity data from river bank and other coastal regions will almost certainly reflect a significant site response resulting from the amplification of seismic waves in unconsolidated (and often water-saturated) sediments. The importance of site response in controlling earthquake ground motion has been understood for over a century (Milne, 1898), and even correctly inferred by one astute witness to the New Madrid sequence (Drake, 1815). However, the potential magnitude of site amplifications at regional distances has perhaps not been fully appreciated until it was so dramatically demonstrated in a number of destructive earthquakes in recent years (*e.g.*, Singh *et al.*, 1988). Recent dramatic examples of site response have tended to involve lake beds, valleys or basins, and coastal regions such as the San Francisco Bay area, but significant site amplifications along river valleys have also been documented (*e.g.*, Stover and Von Hake, 1982).

A close reading of original sources reveals that the role of site response in controlling ground motions from the New Madrid events is documented in several contemporary accounts of the events. For example, Fuller (1912) quotes an account by Daniel Drake of Cincinnati, Ohio: «(Event NM1) was so violent as to agitate the loose furniture of our rooms, open partition doors that were fastened with falling latches, and throw off the tops of a few chimneys in the vicinity of the town». It was this account that apparently prompted Nuttli (1973) to assign a MMI value of VI-VII for Cincinnati for NM1, yet Drake goes on to say that, on the «elevated ridges» in Kentucky, less than 20 miles from the river, many people were not awakened by the event. This account (in particular the fact that many people away from the river slept through the event) suggests a MMI value of perhaps IV, certainly not as high as V. Considering reported effects from the river valley and those from higher ground, one obtains a MMI range of IV-VI for Cincinnati, or an average of V. Equivalently, this approach corresponds to separate assignments for river valley and hill sites at Cincinnati. Of the felt reports from the New Madrid sequence, site response is explicitly documented at six different locations.

The town of Sainte Genevieve, which had been moved onto a hard-rock site, provides a key example. No account of the earthquakes from this town was included in the compilation of Street (1982). A brief account was discovered by the author following a focused archival search. The account states that the earthquakes were felt in Sainte Genevieve but caused no damage (Rozier, 1890). The pristine, original appearance of brick and other masonry homes in the town also testifies to the absence of damage. This illustrates an important general point about poorly sampled intensity data from historic earthquakes: people are more likely to document their observations (by writing letters, etc) if their experiences were dramatic, than if a felt earthquake had little real impact. It also provides *prima facie* evidence that the hard-rock ground motions from the New Madrid earthquakes were not damaging (even to vulnerable structures) at a distance of ≈ 160 km.

For those cases where shaking and/or damage is reported to have been worse within a valley or along a riverbank than on adjacent higher ground, one can assign distinct MMI values for riverbank/valley sites and «hard rock» sites away from the waterways. Where the reports do not explicitly document relatively higher shaking along shorelines, Hough *et al.* (2000) do not attempt to correct the MMI values for site response. However, in some cases, it appears that high intensity values were assigned based solely on riverbank effects which may have been the result of agitation of the river itself; some of these values were downgraded. Clearly, differentiating between the effects of river disturbances along the Mississippi and ground shaking is difficult, if not impossible.

In the final analysis, some level of bias will inevitably remain in any set of interpreted MMI values. However, in some cases the available data are sufficient to assign a more representative regional MMI level based not on the maximum effects reported at soft-sediment sites but on a full consideration of all available reports.

Overall, Hough *et al.* (2000) assigned significantly more MMI IV-V values and significantly fewer VI-VII ones compared to the earlier studies, although in a few instances their MMI assessments for a given location were higher than those of Street (1982). Clearly, however, the reinterpreted values were lower in general than those assigned in the earlier studies, which implies that the differences are due to systematic differences in interpretation rather than random differences in interpretation of ambiguous accounts. A final map of reinterpreted MMI values for event NM1 is shown in fig. 2. These results include MMI values based on data from the following sources: Mitchill (1815), Fuller (1912), Nuttli (1973), and Street (1984), as well as a small number of additional sources, including a single point west of the Mississippi River, at the location of Fort Osage.

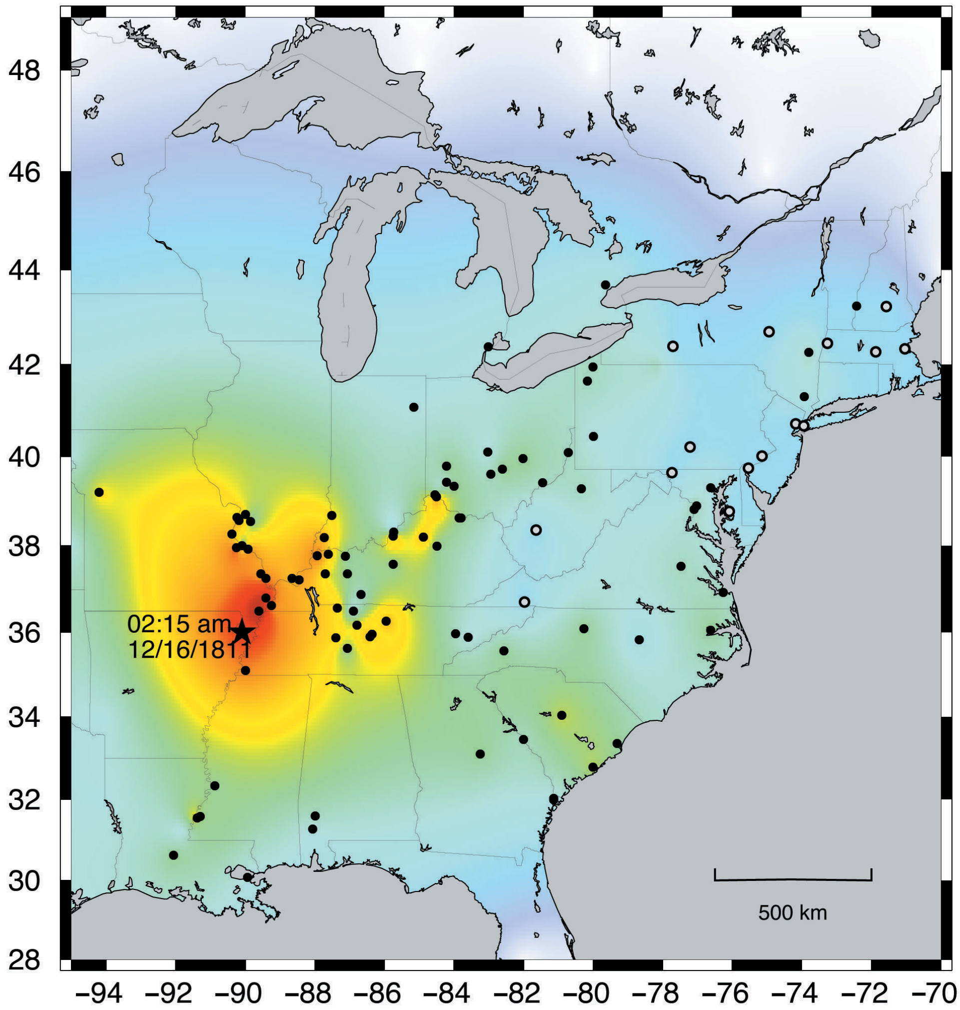
3. Isoseismal areas

Considering the data shown in fig. 2, it is clear that isoseismal contours are not well-constrained. To obtain magnitude estimates using the equations derived by Johnston (1996), however, one must estimate isoseismal areas. Hough *et al.* (2000) employed three different approaches to contour the data from NM1: one subjective, one based on the least-squares minimization schemes presented by Seeber and Armbruster (1987) (see also Armbruster and Seeber, 1987), and one in which the MMI values are treated as Boolean data. If a data point falls within the appropriate isoseismal area (*e.g.*, a value of IV that falls between the MMI IV and V contours) the residual is zero. If a data point is outside the appropriate contour, the residual is equal to the (whole number) difference between the observed and calculated values. This approach was designed to reproduce the usual conventions applied when intensity data are contoured subjectively. That is, isoseismals are generally drawn to outline areas of equal intensity.

In both regressions, the starting model for the falloff of intensity with distance is derived from the empirical equations of Johnston (1996). The inversion schemes then allow for iteration away from this model based on the distance decay of the data.

Using the regression approaches, the treatment of the «not felt» (NF) reports becomes a critical issue. Following Street (1984), Hough *et al.* (2000) assign a NF value to those locations where a local newspaper is known to have not mentioned an earthquake as having been felt in that location. Because NM1 and NM3 occurred at times when people can be assumed to have been asleep, a NF report is taken to indicate a bound of MMI < IV (the shaking level at which «some» people are awakened (Stover and Coffman, 1993). For NM2, which occurred around 08:00 a.m. LT, a NF report is taken to imply a bound of MMI < III.

Hough *et al.* (2000) do not attempt a subjective contouring of the data for events NM2 and



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+

Fig. 2. MMI values based on a reinterpretation of original felt reports from towns as documented by Nuttli (1973) and Street (1984). Interpolations are done using a standard mathematical algorithm (for details see: Hough and Martin, 2002); black circles indicate locations where MMI values are available, while outlined gray circles indicate locations where Hough *et al.* (2000) assigned a «not felt» value.

NM3. Given the sparsity of the data for these events, both the ellipticity and the shape of the distance decay are fixed to match that determined for NM1. The decision to fix ellipticity is a pragmatic one; allowing another free parameter with the sparse data results in unstable solutions.

Once the isoseismal contours are determined, M_w values can be estimated from each individual isoseismal contour using the equations derived by Johnston (1996). Johnston (1996) derives western correction factors for extrapolation of isoseismals from the New Madrid sequence to the west, using the 1843 Marked Tree, Arkansas earthquake to derive correction factors for NM1 and the 1895 Charleston, Missouri, earthquake to derive a different set of factors for NM2 and NM3. Hough *et al.* (2000) used the same factors.

The method of Johnston (1996) yields independent estimates of M_w from each isoseismal area (MMI 4-8) from each event. To obtain an average M_w for each event, one can estimate seismic moment, M_o using the standard formula, $\log(M_o) = 1.5\, M_w + 16.05$, and compute an average M_o value that we then translate it to M_w.

To investigate the uncertainties associated with each regression, we apply a bootstrap analysis in which isoseismals are fit using 50 randomly resampled sets of data points. For each intensity, the five most extreme results are discarded and bounds are estimated from the remaining 45 sets. The uncertainty ranges resulting from the bootstrap analysis are approximately ± 0.1-0.2 units for NM1 and ± 0.2-0.4 for NM2 and NM3. The reader is referred to Hough *et al.* (2000) for a more thorough discussion of these results.

4. Interpretation

For NM1 the range from both regressions is 0.3 units. For NM2 and NM3, ranges of 0.35-0.7 are inferred. However, considering the range of results from both the Boolean and least squares approaches for each event, one obtains uncertainties of approximately a full magnitude unit for all three events. Hough *et al.* (2000) concluded, however, that the magnitudes of each event are constrained to better than ± 0.5 magnitude units. They concluded that while the Boolean approach would be preferred given a sufficiently complete set of felt reports, it is yielding overestimates of isoseismal areas for the New Madrid events because of the biased sampling of site conditions. The least squares regressions, on the other hand, result in contours that are closer to what one would draw subjectively based on an assessment of site response.

The least squares results for events NM2 and NM3 yield the preferred magnitude estimates. For event NM1 the preferred estimate is the one resulting from the subjective contouring. Although it is not possible to quantify the uncertainties precisely, the bootstrap results do provide a good general indication of the appropriate error bars. The final, preferred estimates for the three events are M_w 7.2, $M_w \approx 7.0$, and M_w 7.4, respectively, with uncertainties of ≈ 0.3 units in each case. Hough and Martin (2002) estimate M_w 7.0 for the dawn aftershock, and conclude that this event most likely occurred on a southeastern segment of the Reelfoot thrust fault.

5. Remotely triggered earthquakes

In his compilation of accounts of the New Madrid sequence, Street (1982) compiled a list of all events for which there are multiple accounts, identifying a number of «large aftershocks» that were widely felt. At the time of this earlier study the seismological community did not yet generally appreciate the fact that large earthquakes are capable of triggering events at distances far greater than those associated with classic aftershocks. Since the 28 June 1992, Landers, California, mainshock, however, numerous studies have documented the reality of so-called «remotely triggered earthquakes» (*e.g.*, Hill *et al.*, 1992). Triggering appears to be associated with dynamic strain associated with the surface wave (Gomberg and Davis, 1996). Although the physical mechanism where by strains cause distant earthquakes remains unclear, remotely triggered earthquakes are generally assumed to be earthquakes that would have happened at some point, but that were «nudged along» by the triggering event. It is possible, however, that remotely triggered earthquakes represent events that would not have occurred otherwise.

Hough (2001) reexamined three of the large «aftershocks» of the New Madrid sequence, events occurring at approximately 08:45 a.m. (LT) on 27 January 1812; 08:30 p.m. (LT) on 7 February 1812; and 10:40 p.m. (LT) on 7 February 1812 (hereinafter, NM2-A, NM3-A, and NM3-B, respectively; table I). The first of these events followed NM2 by approximately four days; the second and third events occurred the night following the NM3 mainshock (which occurred at approximately 03:45 a.m., LT).

Many of the accounts describe the shaking from NM3-B as «severe» or «violent». The NM3-A event is generally described as less severe than NM3-B, but still strong. Two individuals experienced the New Madrid sequence and endeavored to not only document every event they felt, but also to rank the events by severity of shaking: Daniel Drake of Cincinnati, Ohio, and Jared Brooks, of Louisville, Kentucky (see, McMurtrie, 1819; Fuller, 1912). Brooks describes NM3-A as having been, «violent in the first degree, but of too short duration to do much injury». (He presumably means short in relation to the shaking from the New Madrid mainshocks, which are typically described as lasting for 2-4 min. in the Ohio-Kentucky region). Brooks describes the shaking from NM3-B as «violent in the second degree», quickly strengthening to «tremendous», which is the descriptor Brooks reserved for the most severe levels of shaking (McMurtrie, 1819). According to Brooks, the strongest shaking from NM3-B lasted only a few seconds, suggestive of an event in the midwest rather than the New Madrid region. Daniel Drake also described the ground motions from NM3-A and NM3-B as having been qualitatively different from those caused by other events. Evaluating the distribution of intensities with the Johnston (1996) regressions, one obtains magnitudes of ≈ 4.5 and 5.0-5.5 for NM3-A and NM3-B, respectively, and locations well outside the NMSZ (fig. 3).

Event NM2-A, which followed NM2 by 4 days, was apparently smaller than NM3-A and NM3-B; Hough (2001) does not determine a magnitude for this event. Additionally, a handful of accounts describe the NM2 mainshock as having comprised multiple episodes of shaking within a few minutes. While not definitive, this suggests that remote earthquakes of substantial size could have been triggered in the immediate wake of the S/surface wave arrivals generated by NM2. Such immediate triggering is often observed following modern earthquakes (*e.g.*, Hough and Kanamori, 2002).

In addition to the inferred remotely triggered earthquakes discussed above, Hough and Martin (2002) analyzed accounts from a large

Table I. New Madrid sequence: mainshocks, principal aftershock, and triggered events.

Event	Year	Month	Day	hr:min	Long.	Lat.	M_w
NM1	1811	12	16	02:15	–90.0	36.0	7.2
NM1-A	1811	12	16	07:15	–89.5	36.3	7.0
NM1-B	1811	12	17	noon	–89.2	34.6	6.0
NM2	1812	1	23	08:45	–89.7	36.6	7.0
NM2-A	1812	1	27	09:00	–84.0	38.9	NE
NM3	1812	2	7	03:45	–89.6	36.4	7.4
NM3-A	1812	2	7	20:30	–84.0	38.9	≈ 4.5
NM3-B	1812	2	7	22:40	–84.0	38.9	5.0-5.5

Event; year, month, day; local time; crudely estimated longitude and latitude in decimal-degrees north and west; preferred moment magnitude estimate, NE: no estimate.

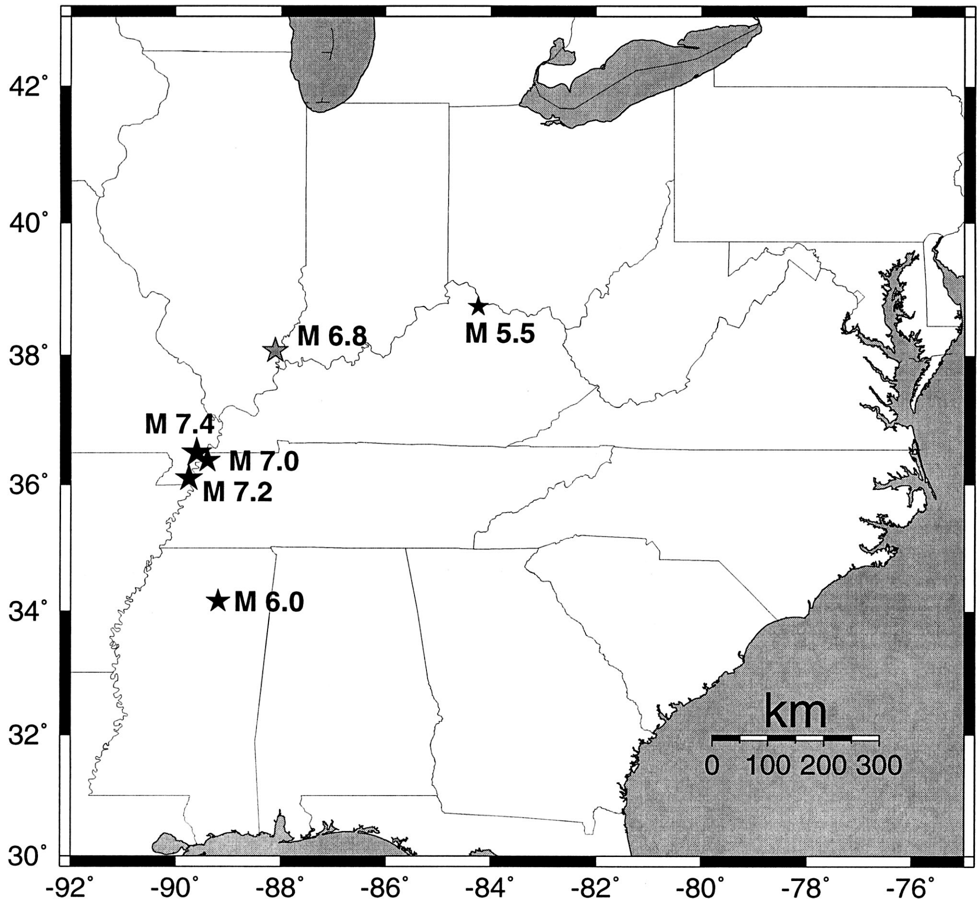


Fig. 3. Map showing inferred locations of principal and remotely triggered earthquakes that occurred during the 1811-1812 «New Madrid» sequence. Black stars indicate locations given in table I; gray star indicates possible source zone for event NM2 as proposed recently by Mueller *et al.* (2004).

event that occurred near noon (LT) on 17 December 1811. They obtain a preferred magnitude estimate of 6.0 and a location well south of the NMSZ (table I; fig. 3).

6. Discussion and conclusions

The magnitude of the principal New Madrid mainshocks has been the matter of some debate in recent years. As is often the case with historic earthquakes, macroseismic data provide the most direct constraint on magnitude. As summarized in this paper, the key to interpreting such data in this case is twofold:

1) to assign intensity values based on objective observations such as damage to structures rather than on the apparent drama of anecdotal accounts, and 2) to consider the earthquakes' effects in light of their historic context. The preferred estimates for the moment magnitudes of the three principal events are M_w 7.2, ≈ 7, and 7.4-7.5, respectively, and 7.0 for the dawn aftershock. These values are more consistent with

other lines of evidence, such as geomorphology, that provide indirect constraint on event size.

The geometry and extent of the Cottonwood Grove Fault, which is assumed to have generated NM1, is established primarily from recent microseismicity (*e.g.*, Gomberg, 1993; Johnston and Schweig, 1996). Event NM2 is difficult to analyze in any detail because the inferred causative fault, the northern strike-slip limb of the NMSZ (Johnston, 1996), is the least well-understood part of the zone. Also, although the hour of the event provided a better characterization of the low-intensity (MMI III-IV) field, reporting of the event was likely hampered by a cold spell that had frozen the river and halted boat traffic along the Ohio River and Mississippi River until 22 January 1812. Very recently, Mueller *et al.* (2004) have reexamined this event and questioned whether it occurred within the NMSZ at all. At a minimum, this event remains the least well-understood of the three principal mainshocks.

However, recent investigations have provided significant constraint of the Reelfoot Fault, the thrust fault in between the two strike-slip limbs of the NMSZ that is inferred to have produced NM3 (*e.g.*, Russ, 1982; Kelson *et al.*, 1992; Johnston, 1996). Structure of the Reelfoot fault has been elucidated in recent years with seismic reflection profiling. Odum *et al.* (1998) infer an overall fault length of at least 30 km and constrain the dip to be ≈ 31°. More recently, Champion *et al.* (2001) concluded that the Reelfoot fault does not exhibit clear geomorphic expression to the southeast of the northern terminus of the Cottonwood Grove fault. Given their inferred spatial extent of the actively deforming Reelfoot fault, they conclude the fault could host plausibly a low- to mid-M_w 7 earthquake. Gomberg (1993) reached similar conclusions based on the fault area estimated from current microseismicity.

Although no direct measurements of fault scarp height are available for NM3, contemporary accounts from boats on the Mississippi describe waterfalls forming on the river. As discussed by Odum *et al.* (1998), these observations correspond to points where the inferred fault rupture crossed the river. The height of these waterfalls is not well constrained, although some information can perhaps be gleaned from available reports. In light of these accounts and the established geometry of the Reelfoot Fault, one obtains an average slip of 4-5 m.

One can account for a M_w of 7.5 on the Reelfoot fault with plausible rupture parameters: a length L of 40 km, a width W of 30 km (consistent with the maximum depth of microseismicity, see Gomberg, 1993), and an average slip D of 5.0 m. These rupture parameters are consistent with established scaling relationships derived from worldwide events (Wells and Coppersmith, 1994). Given a rupture length of 40 km and an average slip of 5 m, one obtains M_w 6.9 and M_w 7.5 from the scaling relationships for rupture length versus magnitude and slip *versus* magnitude, respectively.

The faulting parameters illustrated in fig. 1 are thus consistent with the lateral and depth extent of the NMSZ faults as inferred from microseismicity. The static stress drop values are also consistent with those inferred from finite fault inversions of more recent large earthquakes (*e.g.*, Hough, 1996). Clearly one cannot prove that the New Madrid earthquakes did not have exceptionally high static stress drop values. However, Hanks and Johnston (1992) showed that high-frequency shaking, and thus isoseismal areas, will depend on stress drop. Thus if the New Madrid events had higher stress drop values than the average of those used to obtain the regression results of Johnston (1996), the magnitudes of the New Madrid earthquakes would be lower than the estimates derived from these results.

Because the regression results of Johnston (1996) were calibrated with similarly subjective data, one critical question is the extent to which the Hough *et al.* (2000) assignments are consistent with those on which the regressions were based. To answer this question, one must consider both our general approach to the MMI assignments as well as our treatment of site response issues. In general, there is some precedent for keying an MMI assessment on the most dramatic effects described. However, considering the MMI assignments made for the 1968 m_b 5.3 southcentral Illinois earthquake (Gordon *et al.*, 1970) as an example, it is clear that an MMI of VI is typically assigned when there are multiple instances of the damage usually associated with this level of intensity: broken windows, cracked plaster, damage to brick chimneys, etc. At some locations the specific report suggesting a high MMI value in the New Madrid sequence is one that suggests relatively long-period shaking effects. There is ample precedent for not assigning an MMI value based on such a report when the effects related to higher-frequency shaking (*i.e.* toppling of small objects and furniture) indicate a much lower value (*e.g.*, Armbruster and Seeber, 1987).

In general, there is a fundamental distinction between the 1811-1812 New Madrid events and those used by Johnston (1996) to derive the isoseismal area-moment magnitude regressions: the latter events are those for which instrumental magnitudes are available, which means they are from the 1900s (1925 onward). The New Madrid sequence is upward of 100 years less recent, and so its collection of felt reports is considerably more sparse than the others. Systematic differences in sampling of site conditions can clearly introduce substantial biases. In 1811-1812, logistical constraints induced most of the population to live along river banks (or coasts), which are often characterized by alluvial near-surface geological conditions. Later in the nineteenth century, the introduction of round transportation allowed settlement to shift to higher ground, away from potential flooding hazard. 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). Although this probably results in a systematic bias in the 1811-1812 intensity data, I do not correct for it systematically in our assignment of MMI values. It would, indeed, not be appropriate to «correct» MMI values for site response and then apply the Johnston (1996) regressions because the MMI data used to derive the regressions were not similarly corrected.

I have, however, addressed the issue of site response in two ways: i) by revising the MMI assignments where contemporary accounts do document significant site response, which we view as consistent with the usual practice of assigning site-specific MMI values based on site-specific information, and ii) by using judgement in choosing preferred isoseismal contours.

The subjective contouring approach is considered to be the most reasonable proxy for the ideal procedure, which one is unable to do in this case: to allow the MMI values to define the shape of the contours, with clear definition of high-intensity lobes. We conclude that it would clearly be inappropriate to allow the contours to «balloon» out, as was done by Nuttli (1973), based on values that surely represent «spokes» of anomalously high ground motions.

A systematic site response correction could be done via a careful consideration of intensity distributions from more recent events. Hopper *et al.* (1983) present a map of isoseismals expected from a repeat of a New Madrid mainshock in which site response is included implicitly. I note, however, that site corrections for the 1811-1812 data would require a very detailed analysis because settlement patterns changed so drastically in the decades following the New Madrid sequence.

Hough *et al.* (2000) focused on the moderate intensity contours because their isoseismal areas are the critical inputs to the area-based magnitude determination method of Johnston (1996). Isoseismal contours for MMI levels IV-VII can be constrained by relatively objective reports of damage to structures and the perceptions of individuals who (it can generally be assumed) were asleep at the time of events NM1 and NM3. The felt reports closer to the New Madrid seismic zone are relatively incontrovertible in documenting the extent of damage and ground failure. However, interpretation of these reports is greatly complicated by the vast extent of poorly consolidated and largely water-saturated sediments within the Mississippi embayment. Once again, the natural settlement patterns would have resulted in a strong correlation between population density and proximity to the Mississippi River.

According to the results of Hough *et al.* (2000), NM1 was also similar in magnitude to the 1886 Charleston, South Carolina, earthquake, which Johnston (1996) estimates to have been M_w 7.3. Although perhaps at odds with «conventional wisdom» regarding the relative sizes of the two events, we note a striking degree of reciprocity between our results and the isoseismal contours from the Charleston event determined by Bollinger (1977). Both events generated values of MMI ≈ V for areas midway between New Madrid and Charleston, and Charleston generated a small swatch of MMI ≈ VI values in the immediate vicinity of New Madrid.

Clearly, magnitude estimates for the New Madrid mainshocks will always be plagued by a certain level of uncertainty; a level that is, moreover, difficult to even quantify. We argue that the central issue is not one of precisely determined mathematical uncertainties but rather overall consistency and credibility. Magnitudes of 7.2-7.3, 7.0, and 7.4-7.5 for the three principal mainshocks, NM1, NM2, and NM3, respectively, are consistent with both known and plausibly inferred faulting parameters and the shaking distribution as inferred from our reinterpreted MMI values. Magnitude values significantly lower than these estimates strain credulity for two reasons: i) comparisons with more recent, better-constrained events, such as the 1886 Charleston, South Carolina, and 1926 Grand Banks earthquakes (Bent, 1995), and ii) the evidence, discussed above, that NM3 was associated with significant surface faulting.

On the other hand, significantly larger magnitude values are problematic for reasons that have been addressed at length in other studies; primarily, the lack of sufficient fault area and slip to generate three separate events with M_w close to 8.0. (Although one could plausibly argue for a greater depth extent of large earthquake ruptures in the NMSZ, even a factor of 2 increase in fault width would increase M_w estimates by only 0.3 units).

One interesting consequence of our reinterpretation concerns the relative magnitudes of the three principal mainshocks. In the interpretation of Johnston (1996), NM1 is larger than NM3, and NM2 is of appreciable size. In contrast, our results reveal NM3 to be substantially larger than the other two. This implies that rather than being a mostly strike-slip system with thrust faulting associated with a compressional stepover, thrust faulting may have been the dominant mechanism associated with the 1811-1812 New Madrid sequence. At least, this would be the case if the mechanism of NM3 was predominantly thrust, as has generally been inferred. A predominant thrust mechanism is consistent with the hypothesis that post-glacial rebound provides the driving force for large late Holocene earthquakes in the NMSZ (*e.g.*, Wu and Johnston, 2000).

Although the results of Hough *et al.* (2000) represent a «down-grading» of the magnitudes of the principal New Madrid mainshocks, several lines of evidence argue for substantial distributed hazard throughout the North American mid-continent. First, the hazard is a function of the expected ground motions, which, in the case of the New Madrid sequence, appear to have been significantly elevated in many cases by site response. An evaluation of site response may therefore be critical for seismic hazard assessment at many locations in the central/eastern United States, particularly those immediately adjacent to major rivers and the Atlantic seaboard. Secondly, remotely triggered earthquakes potentially represent an additional source of distributed hazard. Finally, the recent earthquake history of western India reveals that large earthquakes can occur close together in time, not on the same fault but on neighboring faults (*e.g.*, Hough and Bilham, 2003). Although the 1811-1812 New Madrid sequence provides a unique and critically important data set, a more thorough investigation of potential neighboring and regional source zones in the midcontinent appears to be warranted.

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