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ON THE MODIFIED MERCALLI INTENSITIES AND MAGNITUDES OF THE 1811/1812 NEW MADRID, CENTRAL UNITED STATES, EARTHQUAKES

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1 Abstract

Few debates in seismology have been as persistently vexing as that concerning the magnitudes of the principal earthquakes of the great New Madrid sequence of 1811-12. While many lines of indirect evidence suggest moment magnitudes of ≈ 7 for the three largest events, *Johnston* (1996) obtained values of ≈ 8 by comparing the isoseismal areas determined by *Nuttli* (1973) with those from other large stable continental region earthquakes worldwide. In this study, we reexamine the original felt reports analyzed by *Nuttli* (1973) and *Street* (1984) to determine revised isoseismal maps for the largest three events. In many cases we interpret lower values than those assigned by the earlier studies. In some cases the revisions result from an interpretation of original felt reports with a modern appreciation for site response issues. More generally, the earlier studies had assigned MMI values of V-VII to a substantial number of reports that we conclude do not describe damage (and other effects) commeasurate with intensities this high. Isoseismal contours are rather poorly constrained by the revised MMI values, for the second and third mainshocks especially. For the first event (2:15 a.m. local time, 12/16/1811) we use three methods to draw contours: one subjective, one based on a least-squares optimization approach, and one based on a Boolean regression scheme. All three approaches yield areas that, given the area-moment regressions of *Johnston* (1996), imply M_ω in the range of 7.1-7.6 for the December event. We conclude that, given the likely site response biases, the data are most consistent with M_ω7.2-7.3. Data are considerably more sparse for the second and third large events, which occurred at approximately 8:00 a.m. on 1/23/1812 and approximately 3:45 a.m. on 2/7/1812. We do not consider the data sufficient to determine isoseismal areas as well as is possible for the first event. However, the relative sizes of the events can be established directly from the accounts. Consistently, the second and third mainshocks are reported as having been slightly smaller and somewhat larger, respectively, than the first. Based on the available information for the February event, we conclude that M_ω of approximately 7.4-7.5 is most consistent with both the felt reports and the established geometry of the Reelfoot fault (which all evidence suggests to have been the causative structure). We note that, in many cases, the inference of lower magnitudes for the New Madrid events implies that site response may play a significant role in controlling seismic hazard along river valleys in the central United States and coastal areas in the east.

2 Introduction

The earthquake sequence that struck the New Madrid region of the Mississippi Valley in 1811-1812 had, without question, remarkably far-reaching effects [*Mitchill*, 1815; *Bradbury*, 1819, *Fuller*, 1912; *Nuttli*, 1973; *Penick*, 1981; *Street*, 1984; *Johnston*, 1996]. Contemporary accounts document three principal events: approximately 2:15 a.m. local time on 12/16/1811; around 8:00 a.m. on 1/23/1812, and approximately 3:45 a.m. on 2/7/1812 (henceforth NM1, NM2, and NM3, respectively). All three events were felt throughout much the central and eastern United States. Additionally, a large aftershock to NM1 occurred near dawn on 12/16/1811. Substantial aftershock activity following all events was also documented, with felt events persisting throughout the 1810's [*Fuller*, 1912; *Penick*, 1981].

Because paleoseismic investigations have suggested a repeat time on the order of 400-500 years for the New Madrid events [e.g., *Tuttle and Schweig*, 1996; *Tuttle et al.*, 1999], the magnitude of the earthquakes becomes a critical issue for an understanding of intraplate earthquake processes. That is, the low strain rate inferred by geodetic studies [e.g. *Newman et al.*, 1999] and general geomorphic considerations imply that if the New Madrid earthquakes were extremely large ($M_\omega \approx 8$) and the repeat time estimates are correct, the seismicity rate must be highly non-stationary.

The New Madrid earthquakes are of considerable societal as well as scientific importance. A repeat of the 1811-1812 sequence would clearly have a tremendous impact on the present-day mid-continent region. The New Madrid Seismic Zone contributes a non-trival component of seismic hazard for relatively far-flung midwestern cities such as Saint Louis, Missouri, and Cincinnati, Ohio [*Frankel et al.*, 1996]. Yet the 1811-1812 sequence has remained vexingly enigmatic because of several factors: 1) The lack of instrumental data; 2) Our generally limited knowledge of intraplate earthquakes, and 3) The geology of the New Madrid/Mississippi Embayment region, which effectively obscures most surface expression of faulting.

Because an evaluation of the magnitudes of the 1811-1812 events is so critical to a determination of long-term seismic hazard in the region [e.g. *Frankel et al.*, 1996] tremendous effort and ingenuity has been invested in gleaning quantitative information from the limited available data. Available data include: 1) Paleoliquefaction features preserved by the sediments within the Mississippi embayment [e.g. Tuttle and Schweig, 1996]; 2) The present-day distribution of seismicity in the New Madrid Seismic Zone, which is assumed to illuminate the principal fault zones [e.g., *Gomberg*, 1993; *Johnston*, 1996], 3) Modern estimates of the long-term deformation/strain accumulation in the region [*Weber et al.*, 1998; *Newman et al.*, 1999] and 4) Contemporary 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 on the felt reports and their interpretation for MMI intensities, which provide arguably the only direct constraint on magnitude. *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) 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 M7.0 for the 08:15 (local time) aftershock of December 16, 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. The new macroseismic data determined by *Street* (1984) have not previously been interpreted with isoseismal contours.

Johnston (1996) carried out a comparison between intensity distribution and moment magnitude, M_ω 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 available intensity contours; those determined by *Nuttli* (1973). Thus the current widely accepted magnitude determinations for the New Madrid mainshocks were derived from one set of isoseismal contours drawn subjectively based on less than half of the available data.

Both interpretation of felt reports and contouring of MMI data are inevitably highly subjective, especially with sparse and/or old reports. Although no one interpretation–including the one that we will present–can claim to be unique and definitive, we argue that a revisitation of the original data is timely and appropriate given both the importance of the issue and our current appreciation for the the dramatic role that site response can play in controlling ground motions at regional distances.

We address the magnitude determination for the New Madrid mainshocks in two ways. First we reconsider intensity assignments for the reports compiled by *Nuttli* (1973) and *Street* (1984) (Table 1). In our reinterpretation, we focus on two types of information that are considered relatively objective: the extent to which people were woken up by events NM1 and NM3, and descriptions of damage to structures. The former information can provide important differentiation between moderate Modified Mercalli Intensity values, III-V [see *Richter*, 1952; *Stover and Coffman*, 1983]. The latter, in turn, can help differentiate between MMI values of V-VII. We focus on data away from the immediate New Madrid region, in an attempt to better constrain the isoseismal contours for moderate MMI values IV-VII.

Using the reinterpreted MMI values, we then draw new isoseismal contours using subjective as well as systematic approaches. Uncertainties are explored using a bootstrap technique. We use our new isoseismal contours to obtain moment magnitude estimates following the procedure and calibration established by *Johnston* (1996).

In the following section we discuss a suite of representative examples of original felt reports that we have interpreted differently than *Nuttli* (1973) and/or *Street* (1984).

3 Intensity Reports

3.1 Original Sources

All of the MMI values used to construct the original isoseismal maps [*Nuttli*, 1973] are presented in Table 2 and shown in Figure 1. MMI assignments from *Street* (1984) are also included in Table 2. In our reading of the felt reports, we find the original MMI assignments to be 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 a failure to take site response issues into account.

Many of the accounts simply do not appear to support values as high as those originally assigned. In St Louis, Missouri, *Fuller* (1912) describes reports (from the Louisianna Gazatte, 12/21/1811) of people having been woken up by NM1, and furniture and windows having been rattled. He notes that "several chimneys were thrown down," and a few houses, "split." The interpretation of word "split" is open to interpretation, but it seems to have been used in a couple of contemporary accounts to mean "cracked" rather than destroyed. Consistently, as in the above example, the phrase "thrown down" is used to describe more complete damage to either chimneys or entire houses. The Louisianna Gazette account goes on to note that "no lives have been lost, nor has the houses sustained much injury." Based on these reports, we conclude that a MMI of VI-VII is more appropriate than the value of VII-VIII that *Nuttli* (1973) assigns for NM1.

At many locations, including Columbia, South Carolina; Detroit, Michigan; Washington DC; Knoxville, Tennessee; Lebanon, Ohio; and Norfolk, Virginia, 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 woken up by the event. Such descriptions are consistent with an MMI value of IV-V.

In Ft. St. Stephens, Louisiana, the only report of disturbed objects states that the event "shook fowls off of their roosts," but one might fairly suppose the fowls relocated of their own volition.

In Appendix 1, we present four representative original sources (quoted verbatim from *Street*, 1984) that were interpreted with MMI values of VI or V-VI. Although the ringing of a church bell (Milledgeville) and the unsteadiness of people standing (Edenton) are listed as effects of MMI VI, the reports do not describe the overall effects consistent with this intensity level, which include damage to plaster, broken dishes and windows, and overturning of furniture. In previous studies of intensity data from eastern U.S. earthquakes, MMI values of VI are reserved for locations at which multiple instances of plaster/chimney damage are documented [e.g. *Gordon et al.*, 1970].

Reports from Charleston, South Carolina, do describe the ringing of church bells, some cracking of walls, and the agitation of water in wells by the second major event of the sequence at approximately 8:00 a.m. local time on 12/16/1811. This report stands apart from many others (at comparable distance) in that it does document effects beyond the rattling of objects/houses.

In one critical instance, it appears that *Nuttli* (1973) was simply mistaken in his reading of the original sources. While Nuttli assigns an MMI of VI to the city of Arkport in western New York for NM1, the Pennsylvania Gazette account reports clearly that the observations of ground motion were made around sunrise (which corresponds to the time of a large aftershock). There is no mention of the 2:15 a.m. event having been felt at all in Arkport, implying a MMI of perhaps II-III (i.e., not felt at night) for NM1. Moreover, the shaking described for the sunrise event is a fairly gentle swinging/rocking felt by individuals at rest, also more suggestive of MMI III than VI.

It also appears that a transcription error might have been responsible for the MMI value of VII that *Nuttli* (1973) assigns for Lexington, Kentucky for NM1. *Fuller* (1912) does not mention damage in Lexington at all, and the only original source included in *Nuttli's* compilation mentions the earthquake having done "some inconsiderable injury to several dwellings." The compilation of *Street* (1984) includes a report in the Kentucky Gazette of 12/17/1811 that describes windows having been shaken "equal to what they would have been in a hard gust of wind." This account goes on to note that no material injury was sustained in the area. However, two of the original sources included in the *Nuttli* compilation–the New York Post of 3/11/1812 and the Lexington Reporter–relay a letter that was written *to* an individual in Lexington, *from* an individual who had been in New Madrid at the time of the earthquake. *Nuttli* (1973) ascribes his assigned MMI value to the "2/11/1812 New York Post." However, only two letters from this issue of the Post are included in the compilation, neither of which describe damage in Lexington. (Only one of the letters even mentions Lexington, and then only briefly). There is also no account of effects at Lexington in the 2/11/1812 issue of the Post, which we reviewed. Based on the Kentucky Gazette account, we assign a MMI value of V for Lexington, KY.

In addition to the reassignments discussed above, a number of our MMI "downgrades" derive from a more complete understanding of site response than was available at the time of the earlier studies. As a first-order observation, the intensity data are strikingly sparse and concentrated along rivers and other bodies of water. The latter observation is no surprise; it reflects the distribution of the overall population in the more sparsely-populated parts of the central and southeastern U.S. in the early 1800's. Because the New Madrid sequence predates the construction of railroad lines into the mid-continent, settlements tended to remain clustered in proximity to waterways. As documented by the *Missouri Historical Review* of 1911, westward expansion followed the major rivers and virtually all early 1800's settlements in Missouri (the extent of the western frontier at that time) were within a few miles of the Mississippi River. New Madrid was built so close to the bank that, even before the earthquakes, parts of the town regularly gave way under the continued assault of river currents [*Penick*, 1981]. Much of the "bootheel" of Missouri was known as the Great Swamp, and was generally flooded at least part of the year [*Shortridge*, 1980]. 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 1700's resulted in substantial erosion of the river bank upon which the town had originally been built [*Brackenridge*, 1817].

However, 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]. However, the potential magnitude of site amplifications at regional distances was perhaps not been fully appreciated until it so dramatically demonstrated in a number of destructive earthquakes in recent years [e.g., *Singh et al.*, 1986; *Hough et al.*, 1990].

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. Significant site response along river valleys has been documented [e.g., *Stover and von Hake*, 1982] but is relatively uncommon, perhaps because of modern settlement patterns. That is, in modern times, relatively few people live on the very poor soils that are often found immediately adjacent to river banks. (The town of Sainte Genevieve never did expand back towards the river bank). Such settlements were common in earlier times, and isoseismal maps obtained for events such as the M6.6 1895 Charleston, Missouri earthquake clearly show substantial elongation of MMI contours along major river valleys in the central United States [*Nuttli et al.* , 1979; *Hopper and Algermissen*, 1980].

One should note, however, that very few substantial earthquakes have occurred in the central and eastern United States during the twentieth century. It is therefore unclear how strongly modern cities along major river valleys will be affected by site response.

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 to assign a MMI value of VI-VII for Cincinnati for NM1, yet Drake goes on to write:

> *It seems to have been stronger in the valley of the Ohio [River] than in the adjoining uplands. Many families living on the elevated ridges of Kentucky, not more than 20 miles from the river, slept during the shock; which can not be said, perhaps, of any family in town.*

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. Or, equivalently, this approach corresponds to separate assignments for river valley and hill sites at Cincinnati. (In the absense of location direction of the ridge sites, we assign both values to the same location; see tables 1-3).

Another report, from the Western Intelligencer newspaper of 1/24/1812 [see *Street*, 1984] reports:

> *...it appears that [the earthquakes] were scarcely noticed at Chillicothe [Ohio], except along or near the banks of the largest streams.*

This report provides a cautionary illustration of the potential biases associated with intensity data given a very sparse population density and substantial site response. That is, the damage reported in a town like Chillicothe may not be representative of shaking anywhere except along the riverbanks, but, in the absence of specific information such as the above, there is no choice but to assign an overall intensity level based on the available report.

Of the felt reports from the New Madrid sequence, site response is explicitly documented in a number of cases: Cincinnati, Ohio; Chillicothe, Ohio; Newark, New Jersey; Asheville, North Carolina; and Brownsville, Pennsylvania. In each instance, shaking and/or damage is reported to have been worse within a valley or along a riverbank than on adjacent higher ground. Where such information is available, we 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, we generally 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; we do downgrade some of these values. Along the Mississippi River the felt reports document a number of instances of riverbank slumping and even collapse of islands following NM1. One example is Vicksburg, Mississippi, where a MMI value of VII was assigned, apparently based on a report from one island (Island No. 94) near the city:

> *In the night the earthquake came and next morning when the accompanying haziness disappeared the island could no longer be seen. It had been utterly destroyed as well as its pirate inhabitants.*

Although dramatic, we suggest that the assignment of VII for the city of Vicksburg is problematic in several respects: 1) An MMI of VII involves "considerable damage in poorly built or badly designed structures; some chimneys broken." Yet there are no reports of significant damage from the city itself in the compilations of *Mitchill* (1815), *Fuller* (1912), or *Street* (1984). Also, 2) It appears virtually impossible to know the geology of Island No. 94, the effect that earthquake-generated river disturbances (waves/currents) might have had on its demise, or even the ultimate fate of the "pirate inhabitants." Fuller does describe the overturning of canoes elsewhere along the river in the same vicinity, and original felt reports describe large and sustained disturbances in the Mississippi river currents caused by event NM1. At a point along the river then known as Devil's Race Ground (120 miles below New Madrid), one account reports,

> *...our boat appeared as if alternatively lifted out of the water, and again suffered to fall. The banks above, below, and around us were falling every moment into the river...*

Clearly, differentiating between the effects of river disturbances along the Mississippi and ground shaking is difficult, if not impossible.

In the final analysis, we conclude that some level of bias will inevitably remain in our reinterpreted MMI values. However, we conclude that, in many cases, the available data are sufficient to assign a more representative regional MMI level based not on the maximum effects reported, but on a full consideration of all available reports.

Figure 1 presents a histogram of MMI values for NM1 obtained in this study compared to those determined by *Street* (1984). Overall, we have assigned significantly more MMI 4-5 values and significantly fewer 5-7 ones, although in a few instances our MMI assessments for a given location are higher than those of *Street* (1984).

A final map of reinterpreted MMI values is shown in Figures 3-5 and tabulated in Tables 2-4. These results include MMI values based on data from the following sources: *Mitchill* (1815), *Fuller* (1912), *Nuttli* (1973), *Street* (1984). Additional data are obtained from the *Chillicothe Fredonian* (1811-1812) and the *Raleigh Star* (1812) [see Appendix 2]. Tables 2-4 also includes brief exerpts from original reports that were considered pivotal in the assignment of MMI values.

4 Isoseismal Areas

The reinterpreted MMI values are considerably more spatially variable than those determined by *Nuttli*, (1973). Considering the data shown in Figure 3a, 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.

We use three different approaches to contour the data from NM1. In the first, the contours are drawn by eye (Figure 3a), a procedure that is entirely subjective but for which there is considerable precedence in previous intensity studies.

The second approach (Figure 3b) is based on a modification of the least-squares minimization scheme presented by *Seeber and Armbruster*, 1987 [see also *Armbruster and Seeber*, 1987]. The data are contoured with a suite of best-fitting ellipses, with degree of ellipticity determined by the data. Least-squares residuals are calculated between each data point and the predicted intensity at that distance.

In the third approach (Figure 3c), the MMI values are treated as Boolean data. If a data point falls within the appropriate isoseismal area (e.g., a value of 4 that falls between the MMI 4 and 5 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 fall-off 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. Because NM1 and NM3 occurred at times when people can be assumed to have been asleep, we assume that a NF report implies a bound of MMI < 4 (the shaking level at which "some" people are awakened; [*Stover and Coffman*, 1993]. For NM2, which occurred around 8:00 a.m. local time, a NF report is taken to imply a bound of MMI < 3.

We do not attempt a subjective contouring of the data for events NM2 and NM3. Given the sparsity of the data for these events, we also fix both the ellipticity and the shape of the distance-decay 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 solutions that we consider unstable.

Figures 3-5 present the results of the least-squares and Boolean regressions for all three events. We estimate M_ω values from each individual isoseismal contour using the equations derived by *Johnston* (1996). For MMI of 6 and below, we use the regression results derived specifically from eastern North American data. For MMI 7 and 8, we use the regression results derived by *Johnston* (1996) from a global data set of stable continental region earthquakes.

Johnston (1996) presents so-called western correction factors for extrapolation of isoseismals from the New Madrid sequence to the west. *Johnston* (1996) uses 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. We apply these same correction factors to our results.

The M_ω values implied for each isoseismal (MMI 4-8) from each event are summarized in Figures 6a and 6b. To obtain an average M_ω for each regression, we estimate seismic moment, M_o using the standard formula

$$log(M_o) = 1.5M_\omega + 16.05 \tag{1}$$

and compute an average M_o value that we then translate to M_ω using equation (1) (Figure 6). The variability of the results for NM2 and NM3 (with isoseismal level) are a direct result of the western reduction factors, which vary substantially with MMI level. If one instead applies the set of reduction factors derived by *Johnston* (1996) for NM1, the inferred magnitude estimates from individual isoseismal levels are more consistent, but not significantly different on average.

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 shown in Figures 6a and 6b.

5 Interpretation

For NM1, the range from both regressions is approximately 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 approach for each event, one obtains uncertainties of approximately a full magnitude unit for all three events.

We suggest, though, that the available data do constrain the magnitude of each event to better than +/− 0.5 magnitude units. Returning to the Boolean contouring results for events NM1 (Figure 3c) and NM3 (Figure 5b), we argue that the isoseismal contours are contradicted by a key subset of the observations: for both events, the MMI 4 contour extends to the northeast well beyond the limits of the (positive) felt reports for both events. The northeast was the most densely populated part of the country at the time. If the MMI 4 contour for NM3 truly bisected Massachusetts, then surely the event would have been felt throughout southern New York and New England. Similarly, the Boolean MMI 4 contour for NM1 suggests that this event would've been felt throughout eastern Pennsylvania.

The MMI 4 contours from the least-squares regressions for both NM1 and NM3 are, we suggest, considerably more reasonable. For both events, the MMI 4 contours nicely separate the felt from the NF reports. Although the data from NM2 are more ambiguous, the MMI 4 Boolean contour for this event does include a number of MMI 3 values in the northeast.

We conclude that while the Boolean approach would be preferred given a sufficiently complete set of felt reports, it is yielding over-estimates of isoseismal areas for the New Madrid events because of the significant remaining site response biases. The least-squares regressions, on the other hand, result in contours that are closer to what one would draw subjectively based on one's assessment of site response. Although the isoseismal contours for NM2 are less well constrained than the other two events, we consider it likely that the data would be biased by the same factors that bias the data from the other events.

We therefore consider the least-squares results for events NM2 and NM3 to be our preferred magnitude estimates. For event NM1, our preferred estimate is the one resulting from the subjective contouring. Although we do not consider it possible to quantify the uncertainties precisely, we conclude that the bootstrap results do provide a good general indication of the appropriate error bars. Our final, preferred estimates for the three events are, respectively as follows: $M_\omega 7.2-7.3$, $M_\omega \approx 7.0$, and $M_\omega 7.4-7.5$, with uncertainties of approximately 0.3 units in each case. Interestingly, as shown in Table 5, these estimates are quite close to the m_b values originally determined by *Nuttli* (1973).

Given a prolonged sequence of events, one might suppose that the damage from NM2 and NM3 was exacerbated by the pre-existing damage from the earlier event(s). However, damage to weakened structures would only be reflected at MMI levels large enough to cause damage (¿ V), and there is no evidence that the larger MMI values are disproportionately elevated for the second and third events.

In addition to inferences drawn from the intensity data from each event, the above magnitude and uncertainty estimates are also guided in part by a consideration of the relative shaking levels reported for the different events. That is, intensities for NM2 are somewhat–but not enormously–smaller overall than for NM1. The January event was described as being stronger than NM1 at some locations, which may have reflected 1) the more northerly epicenter of NM2 and 2) the fact that NM2 happened during daylight hours, when people's perceptions were likely to have been more keen. Based on the overall intensity fields, we conclude that NM2 was somewhat smaller than NM1, although, as the bootstrap uncertainties show, this magnitude estimation is the least certain of the three. (A significant cold spell in the weeks preceding NM2 reportedly slowed boat traffic into the mid-continent and may have served to impede reporting of this event more than the others).

NM3, on the other hand, is widely described as having been the largest event, in terms of both amplitude and duration of ground motions. Although this event was also farther north than NM1, we consider it unlikely that the modest difference in location would have accounted for the documented differences in shaking as far away as Ohio, Pennsylvania, Virginia, and South Carolina. It is tempting to speculate that, as the one thrust event, perhaps NM3 was of comparable magnitude to NM1 (assumed to be a strike-slip event) but had a higher stress drop. Clearly, we cannot conclude with certainty that this was not the case. However, the felt reports are remarkably consistent in describing NM3 as having had the longest duration of shaking, which suggests the event had a larger magnitude–rather than, or in addition to–a larger stress drop than the other events.

5.1 A Note on Demographic Issues

An important consideration in the interpretation of sparse felt reports is the population density of the towns from which the data are derived. Fortunately, such data are available in the 1810 Federal Census, which included both states and territories. Unfortunately, the data are incomplete in some instances, with population tallied only by county or district, not by individual town.

The total population of the United States was approximately 7,000,000 in 1811, including sizable numbers in Tennessee, Kentucky, and the territories, including present-day Missouri and Louisiana.

The 1810 Census documents the population for several districts for which felt reports are considered, including the District of Saint Louis (pop. 5667), Natchez (10,002), Cincinnati (2540), New Orleans (24,552), and Detroit (2227). What is noteworthy about these figures is that they are comparable to, or in some cases greater than, the populations of districts for which damage from NM1 is documented: Cape Girardeau (3888), Louisville (1357), and New Madrid (2103).

Although present-day Missouri was relatively sparsely populated in 1811, available contemporary accounts [e.g. *Bradbury* (1819); *Brackenridge* (1817)] provide a fairly thorough documentation of demographic and related information. These sources reveal that cities such as Saint Louis and Sainte Genevieve were far more than simple villages by 1811, with solidly constructed houses appearing by the turn of the century. In Sainte Genevieve, *Anderson* (1937) describes the typical house of the time as being a one-storied dwelling with plastered walls and front and back porches. The oldest brick building west of the Mississippi was built in Sainte Genevieve in 1804. This house, and approximately 50 others that predate the New Madrid sequence, are still standing today.

Moreover, while the New Madrid sequence predated even telegraph communications, a perusal of the contemporary sources reveals that news did circulate between towns. A weekly Saint Louis newspaper, the Louisiana Gazette, printed over a dozen separate reports on the New Madrid earthquakes between 12/21/1811 and 5/2/1812. These reports included observations from various midcontinent locations. Additional information was carefully compiled by the naturalists and historians of the time: Mitchill, Brackenridge, Bradbury. We conclude that, had there been substantial damage in towns such as Saint Louis, Sainte Genevieve, or Cincinnati, it would have been documented.

6 Discussion and Conclusions

The results presented in this study show that a plausible reinterpretation of the intensity data yields magnitude estimates nearly a full unit below those previously inferred. Our preferred estimates for the moment magnitudes of the three principal events are M_ω7.2-7.3, ≈7, and 7.4-7.5, respectively.

Considerable uncertainly clearly remains in the assignment of magnitudes for all three of the New Madrid mainshocks because of uncertainties associated with both the assignment of MMI values and with the estimation of isoseismal areas. Interpretation of felt reports is inherently subjective. Our approach has been to assign MMI values based more on descriptions of damage and other specific effects, and less on vague qualifiers regarding the perceived severity of shaking. Ground motions–the long-period waves in particular–from large (M7+) earthquakes at regional distances can be surprisingly powerful without being damaging, presumably all the more so to people with no prior (first-hand) experience with earthquake ground motions. In some cases we also base our MMI assignment not on a single effect indicating the highest intensity, but rather on an overall assessment of effects described.

Because the isoseismal area-M_ω regression results of *Johnston* (1996) were calibrated with similarly subjective data, the critical question is the extent to which our assignments are consistent with those on which the regressions were based. In general, there is some precedent for keying an MMI assessment on the most dramatic effects described, such as MMI values of VI for Edenton, N.C., because of the single report that people "could scarcely keep their feet" and for Milledgeville, GA, because the bell in the State House was set ringing (see Appendix 1, and associated discussion earlier in the text).

However, considering the MMI assignments made for the 1968 m_b5.3 South-Central 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.

We also note, that, in some cases (including those from Edenton and Milledgeville), the specific report suggesting a high MMI value 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 1900's (1925 onward). They are thus more recent by upwards of 100 years than the New Madrid sequence, and so the collection of felt reports from the New Madrid sequence is considerably sparse than the others. Density of data depends on both the density of population and on the completeness of reporting. Both factors could conceivably bias the inferred intensity data, but no systematic bias–either positive or negative–has yet been documented.

However, systematic differences in spatial sampling 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 19th century, the introduction of ground 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 19th century than those from the 20th century (or even the mid-19th century). Although we recognize this possible bias in the 1811-1812 intensity data, we do not correct for it systematically in our assignment of MMI values. We have, however, addressed the issue of site response in two ways: 1) by revising the MMI assignments where contemporary accounts do document significant site response, and 2) by using judgement in choosing preferred isoseismal contours. *Nuttli et al.* (1979) argued that "protuberances in the isoseismals are due to the enhancement of the intensity by surficial geology" and should not be used to constrain contours. We use this very consideration to reject the Boolean regression results in favor of the least-squares contours. The least-squares regressions essentially allow high MMI values (such as those along coastal South Carolina) to become outliers.

A systematic site response correction could be done via a careful consideration of intensity distributions from more recent data. *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. We note, however, that site corrections for the 1811-1812 data would require an very detailed analysis because settlement patterns changed so drastically in the decades following the New Madrid sequence.

We also note that the MMI values predicted in the *Hopper et al.* (1983) study are grossly inconsistent with our inferred values. For example, their MMI VII contour stretches well into Georgia and South Carolina. These contours result from their methodology, in which observed MMI data from smaller earthquakes are scaled up by maximum reported intensity of NM1. This equates to the assumption that the shape of the intensity fall-off is the same for earthquakes of all magnitudes (in a given source region), an assumption that is not necessarily valid. For example, a very large event might have a very steep decay with distance from MMI XI to VIII, as these intensities tend to be controlled by near-field effects, while the distance decay of MMI for a smaller, deeper event can be more gradual. However, if one were to use the shape of the intensity contours from *Hopper et al.* (1983), which do reflect expected site response patterns, with rescaling using our revised MMI values, the resulting isoseismal areas could be appreciably smaller still than those determined here.

We have 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, as noted by *Newman and Stein* (1999) interpretation of these reports is greatly complicated by the vast extent of poorly consolidated and largely water-saturated sediments within the Mississippi embayment. And, once again, the natural settlement patterns would have resulted in a strong correlation between population density and proximity to the Mississippi River.

A M_ω of $\approx 7.2-7.3$ for NM1 is consistent with several other lines of evidence, including 1) an extrapolation of the currently observed seismicity distribution, given constraints on the repeat time as determined from paleoseismic studies; 2) the available area of the inferred causative fault as constrained by the extent of the southern limb of the New Madrid Seismic Zone and the observed depth of microseismicity [e.g., *Gomberg*, 1993]; and 3) a long-term slip rate recently inferred from GPS data to be less than 2 mm/yr [*Newman et al.* 1999]. That is, the low strain rate recently determined from GPS data is inconsistent with M_ω of 8+ for the 1811-1812 events if they occur as often as has been inferred from paleoseismic data [e.g., *Tuttle and Schweig*, 1996]. *Newman et al.* (1999) therefore argue that either the repeat time is longer than previously estimated or the magnitudes are smaller. Although interpretation of short-term GPS data is fraught with fundamental uncertainties regarding tectonic processes–in intraplate regions especially–M_ω7.3 is consistent with the most straightforward interpretation of both deformation and seismicity data.

The revised MMI contours obtained for event NM1 are not too different–perhaps 20% larger–from those obtained for the largest earthquake to have occurred in eastern North America in the twentieth century–the 1929 M_ω7.2 Grand Banks, Canada event. For this event, teleseismic data has been used to obtain an instrumental estimate of M_ω as well as a finite fault rupture model [*Bent* (1995)]. The inferred model involves complex strike slip faulting, with an overall fault length of $\approx$ 100 km. *Gomberg* (1993) infers a similar dimension for the southern limb of the New Madrid seismic zone. We therefore suggest that the Grand Banks and (first) New Madrid event were in fact fairly similar, with the latter perhaps a bit bigger than the former.

Event NM2 is difficult to analyze in any detail because the inferred causative fault, the northern strike-slip limb of the New Madrid Seismic Zone, 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 3-4) field, a strong cold spell in January had slowed boat traffic, and therefore the flow of information, in the mid-continent.

However, recent investigations have provided significant constraint of the Reelfoot fault, the thrust fault in between the two strike-slip limbs of the New Madrid seismic zone 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.* (1996) infer an overall fault length of at least 30 km and constrain the dip to be approximately 40 degrees.

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.* (1996), 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. One observer by name of Mathias Speed described them as similar to the rapids of the Ohio, a 23-foot descent over a distance of 2 miles [*Penick*, 1981]. Another observer, W. Shaler, described a height of "at least six feet" [see *Street*, 1984]. In light of these reports and the established geometry of the Reelfoot fault, we assume an average slip of 4-5 m. Further assuming a fault length of 30-40 km and a down-dip width of 28 km, one obtains a M_ω of 7.3-7.5 for NM3.

The above rupture parameters are generally consistent with scaling relationships established using data from events worldwide [*Wells and Coppersmith*, 1994]. Their relation between rupture length and magnitude yields M6.9 for a rupture length of 40-km, but their relationship between average slip and magnitudes yields M7.5 for a slip of 4.5 m, perhaps lending a measure of support to the hypothesis that the 2/7/1812 event was a high stress drop event.

As a final note, we address two arguments that have been made against "downgrading" the magnitudes of the 1811-12 events: 1) That if the New Madrid events were M_ω7.0-7.4 instead of 8, then the magnitudes of other large historic eastern events, such as the 1886 Charleston, South Carolina (and other smaller events in turn), must be reduced correspondingly; and 2) That a repeat of the *ground motions* from the 1811-12 sequence would be equally destructive whether they were M_ω8 events with typical ground motions for their size or M_ω7 events whose ground motions were anomalously high because of the regional near-surface geology.

We first note that the logic behind argument (1) is not necessarily valid. For one thing, it is possible that the magnitude of the other eastern events have also been overestimated. However, even by 1843 (the year of the M6.3 Marked Tree, Arkansas earthquake), the eastern United States was considerably more populated than it had been just 30 years earlier. Isoseismal contours for the 1886 Charleston, SC, and 1895 Charleston, MO, events are better constrained still. As mentioned earlier, increased population density (especially away from the immediate vicinity of waterways) would reduce site response biases by providing a more representative sampling of site conditions.

The second argument is a more valid one. Assuming the paleoseismic constraints on repeat times for 1811-12 events to be correct, it makes an enormous difference for long-term probabilistic hazard assessment whether these events were M_ω7-7.4 or M_ω8. However, as others have noted, 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.

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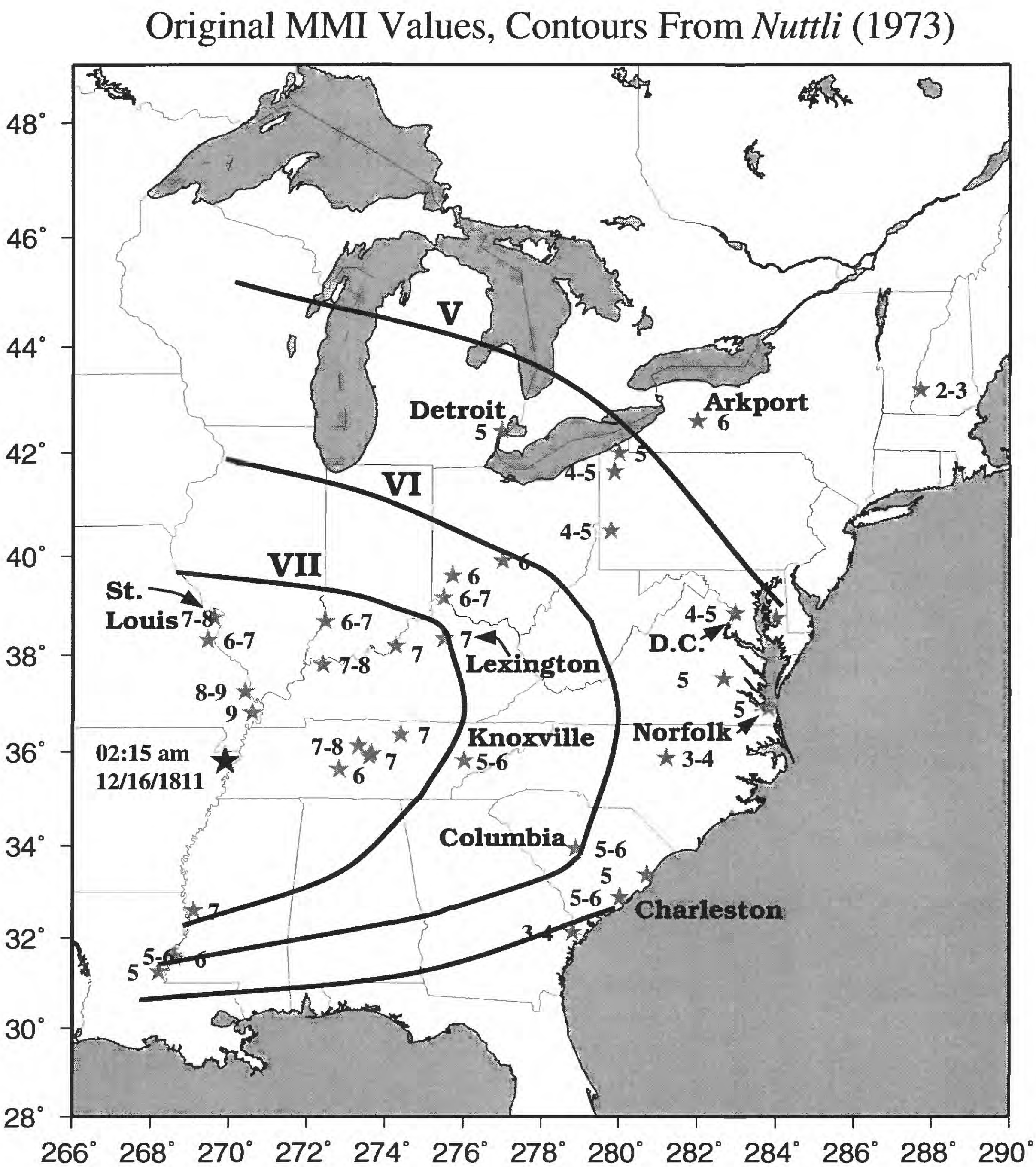

Figure 1. Original MMI values assigned by *Nuttli* (1973) for the 02:15 a.m. (local time), 12/16/1811 earthquake. Approximate original contouring is also shown

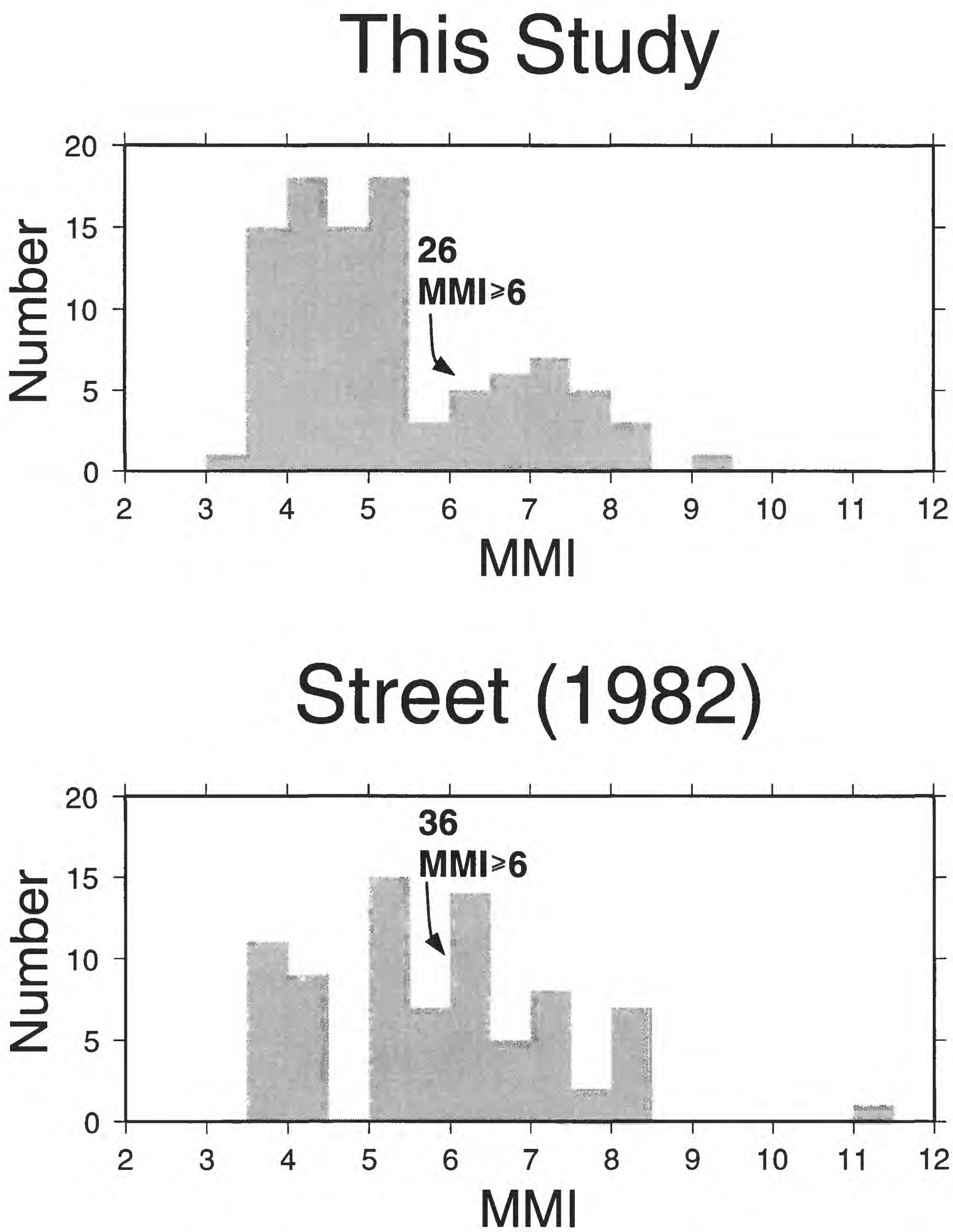

Figure 2. Histogram binned by 0.5 MMI units showing distribution of assigned values for NM1 from this study (top) as compared to those of *Street*, 1984 (bottom). "Not felt" reports are included in the MMI 3.5 bin in both cases.

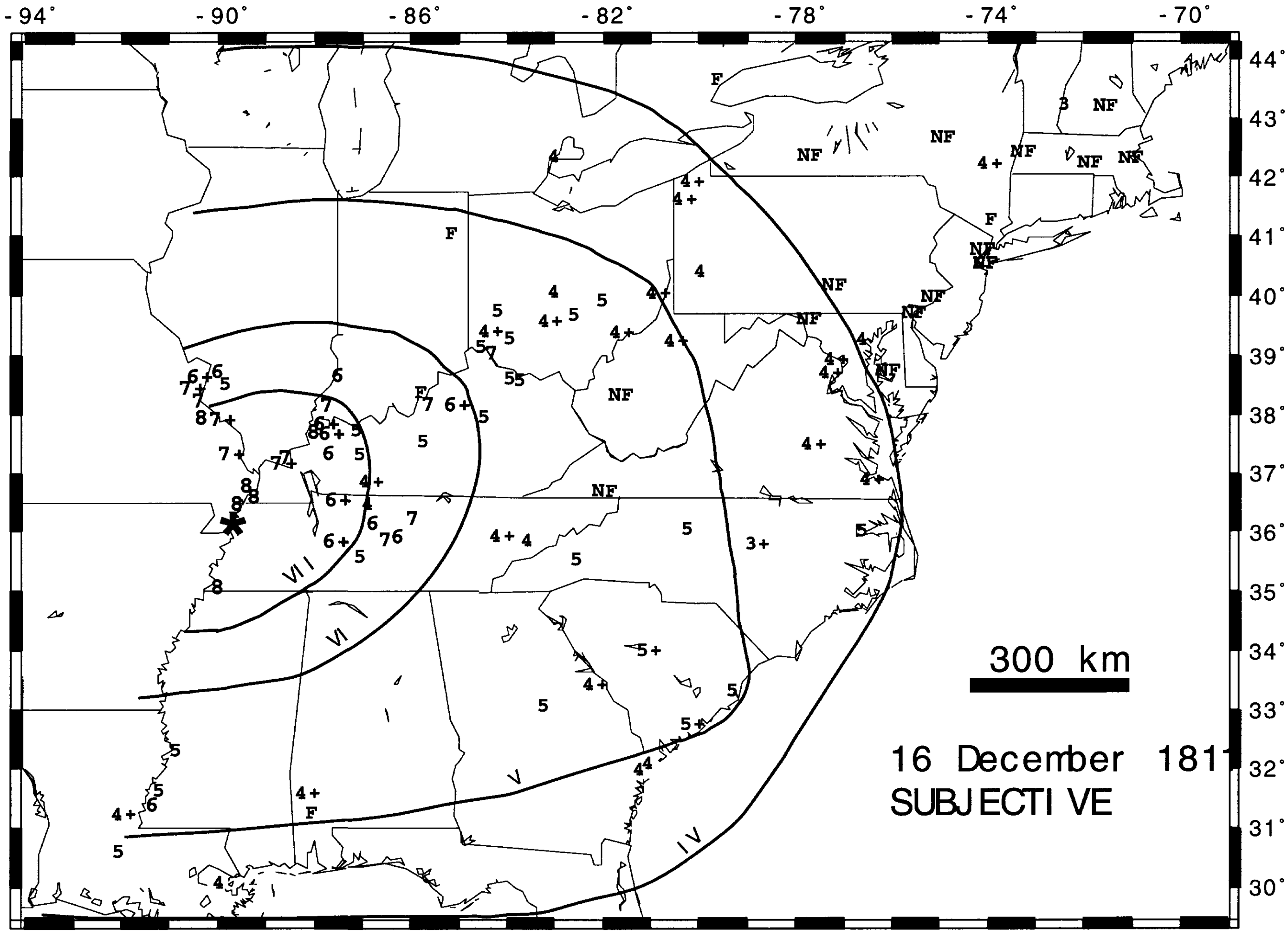

Figure 3a. MMI values based on reinterpretation of original felt reports as documented by *Nuttli* (1973) and *Street* (1984). In some instances, MMI values are shifted very slightly for clarity. Also, in some cases where we have assigned an intermediate value or a range of values for a given site, only the average is shown. Half MMI units are denoted with "+" signs. Contours are drawn subjectively and yield Mw using the regression results and western correction factors from *Johnston* (1996).

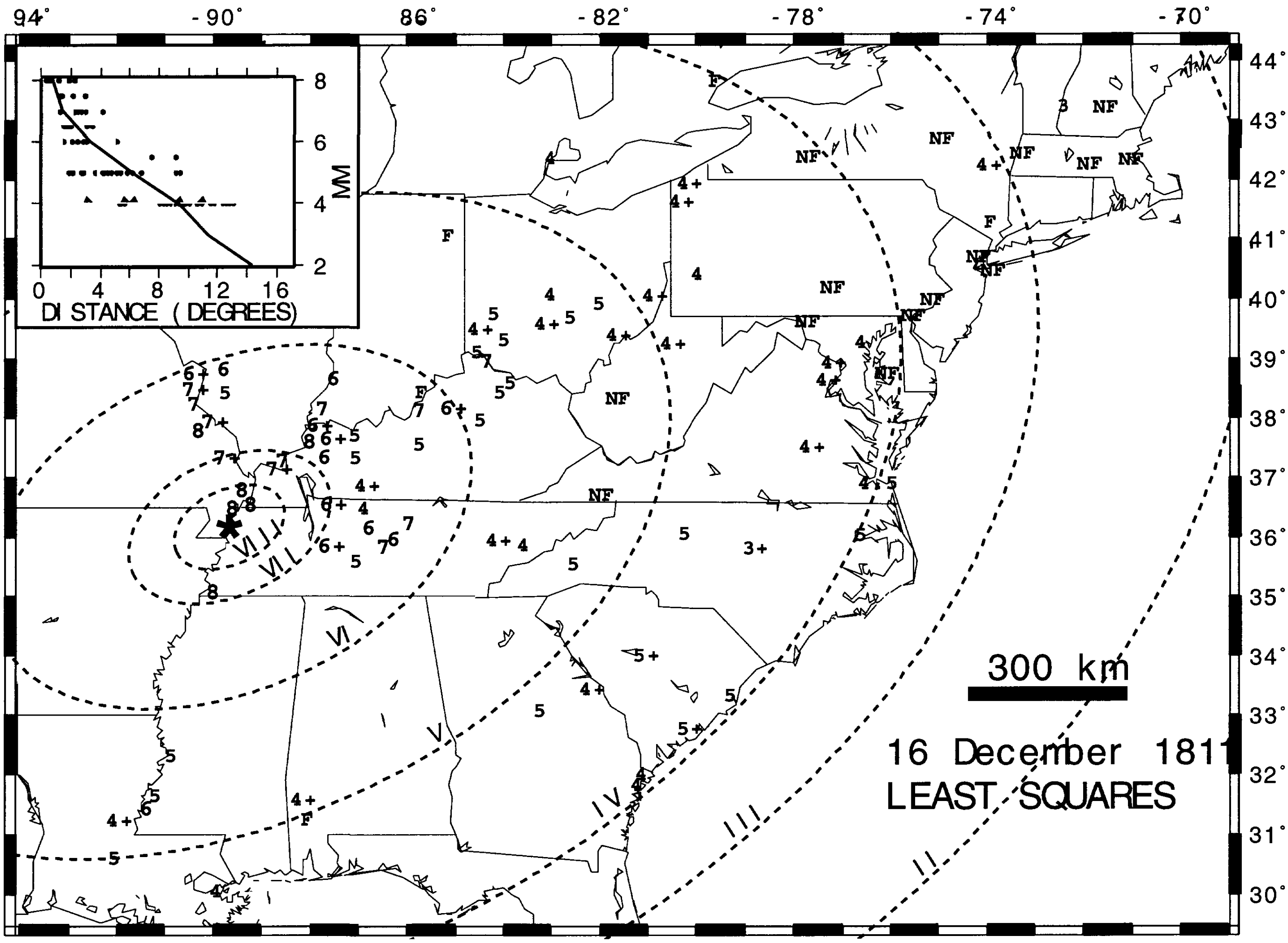

Figure 3b. MMI data for event NM1; least-squares contouring results. Inset shows observed intensity values as a function of distance from the epicenter shown (symbols) and predicted values (smooth line). "Not felt" results are shown with inverted triangles; a report that the event was "felt" (i.e., with no other information) is shown with an upright triangle. Small circles show results from felt reports that include enough information to determine a numerical MMI value.

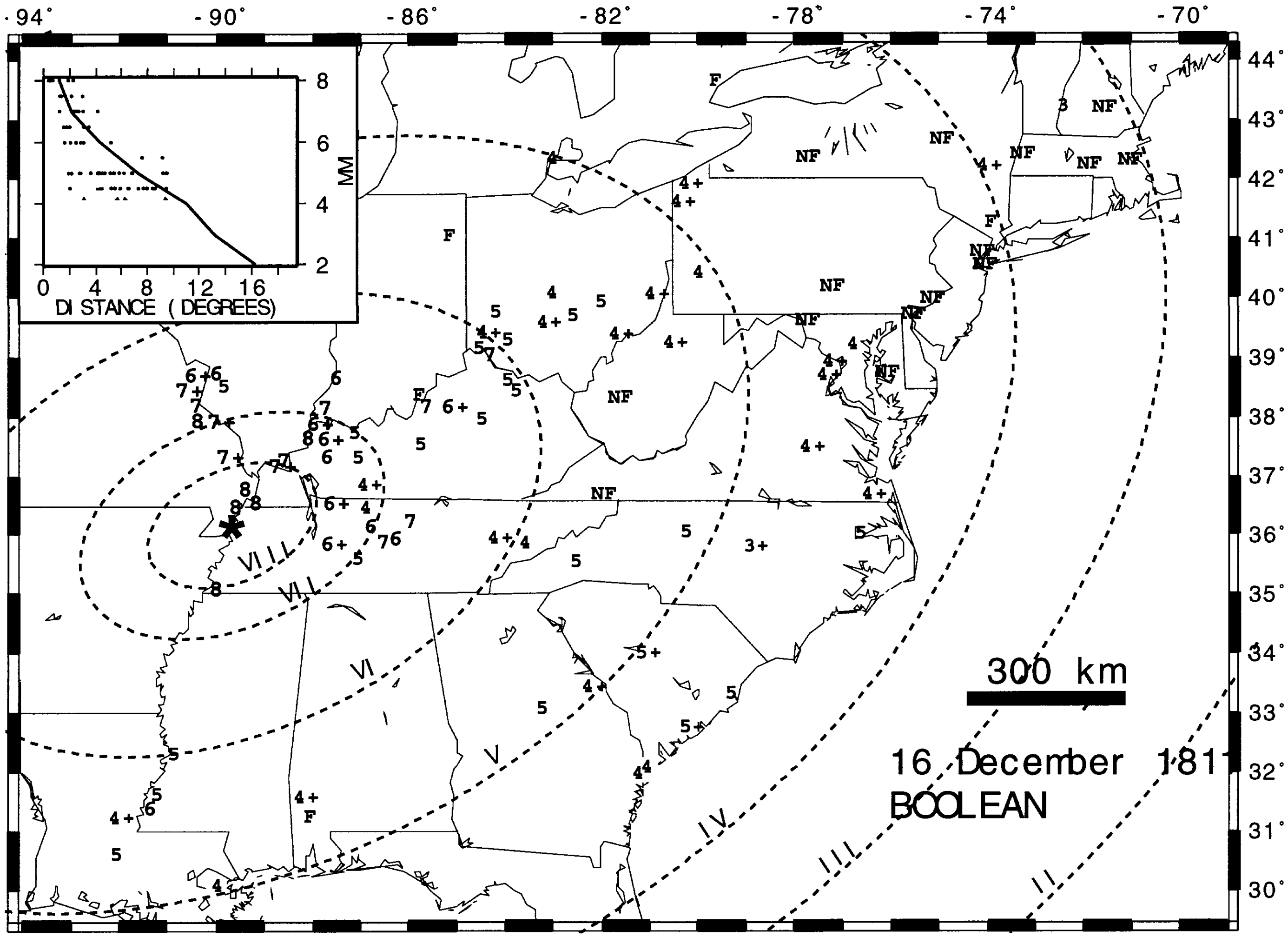

Figure 3c. MMI data for NM1; Boolean contouring results. Inset plotting conventions same as in Figure 3b.

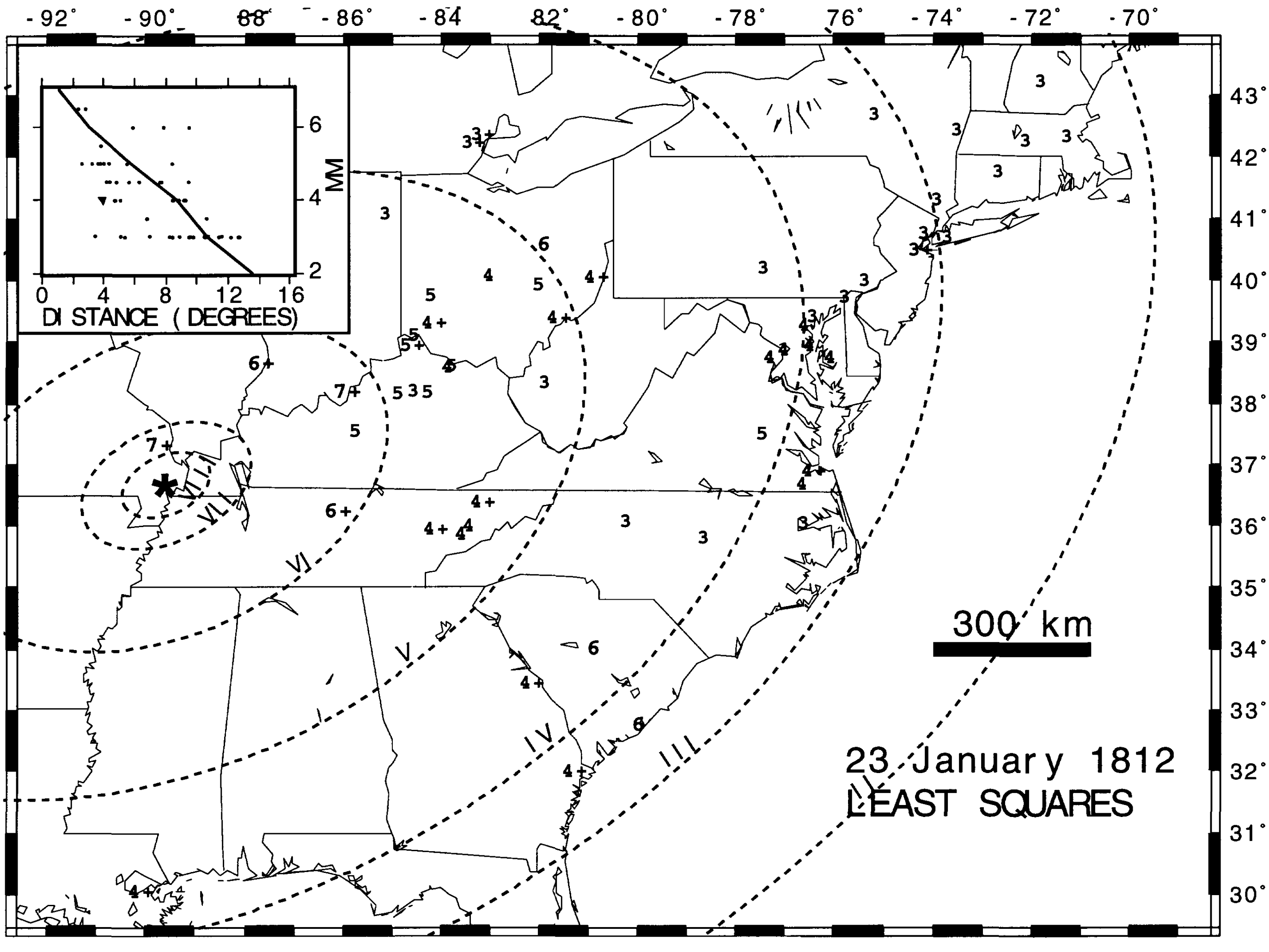

Figure 4a. Reinterpretted MMI data for event NM2; least-squares contouring. Inset plotting conventions same as for Figure 3b.

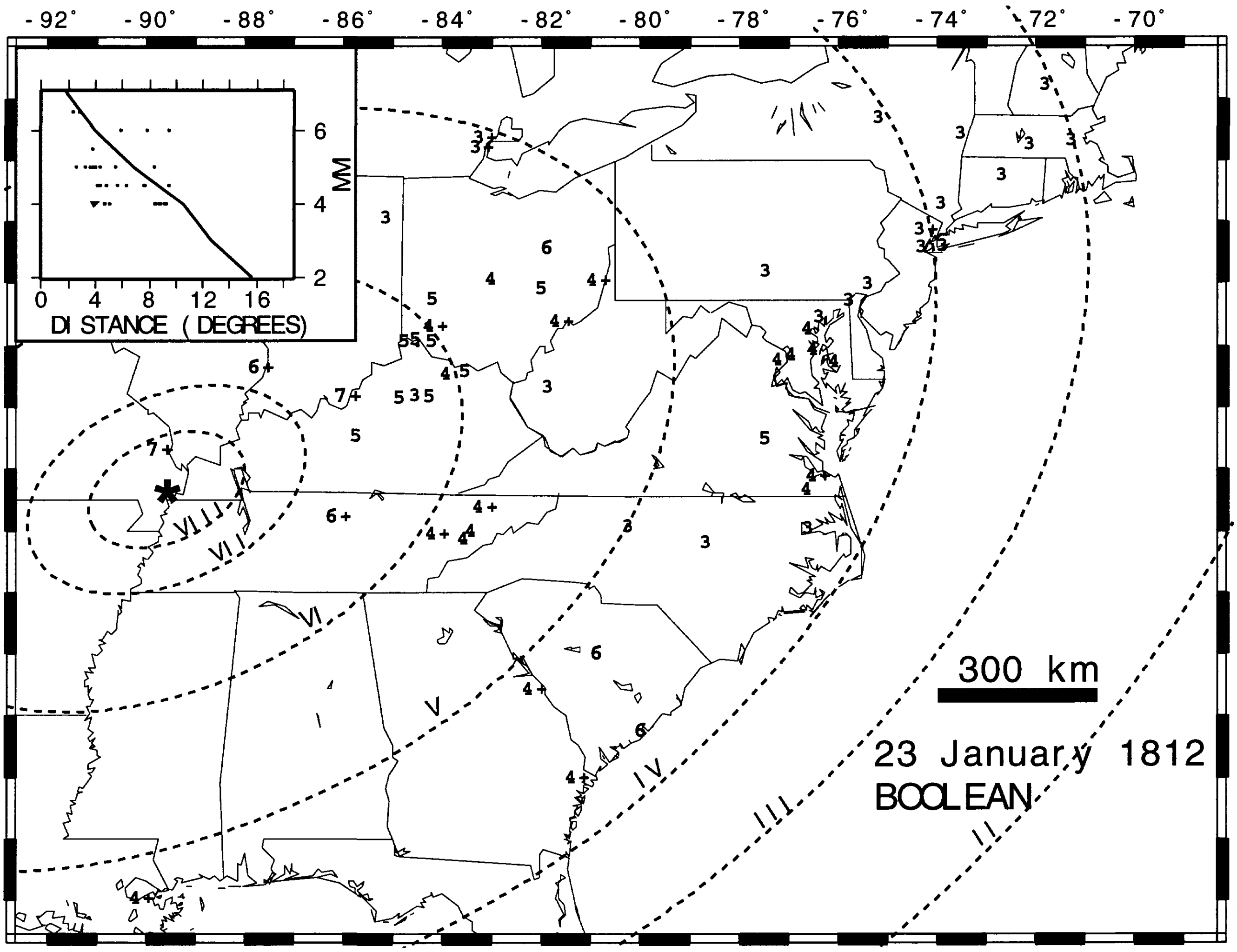

Figure 4b. Reinterpreted MMI data for event NM2; Boolean contouring results. Inset plotting conventions same as for Figure 3b.

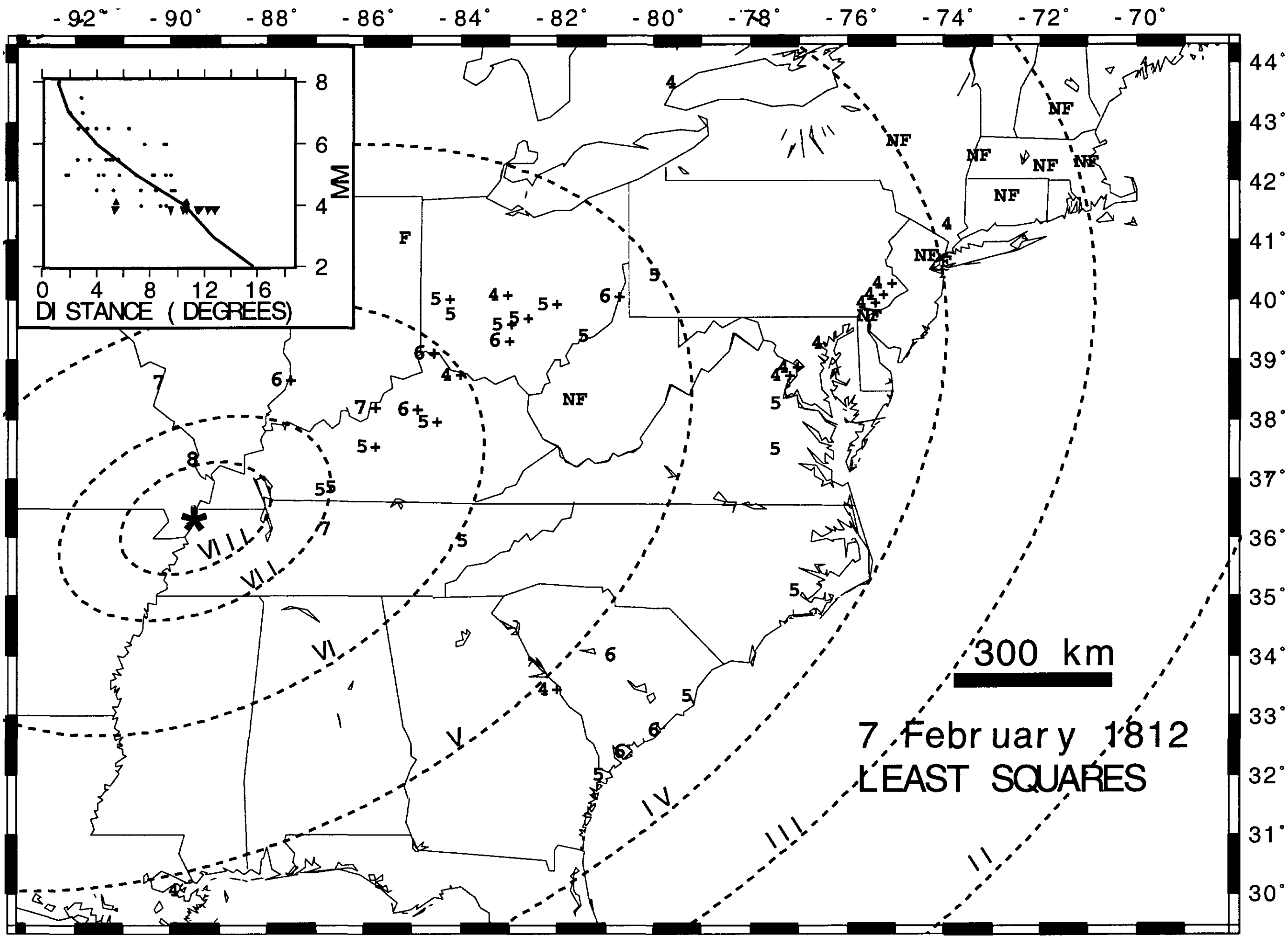

Figure 5a. Reinterpreted MMI data for NM3; least-squares contouring results. Inset plotting conventions same as for Figure 3b.

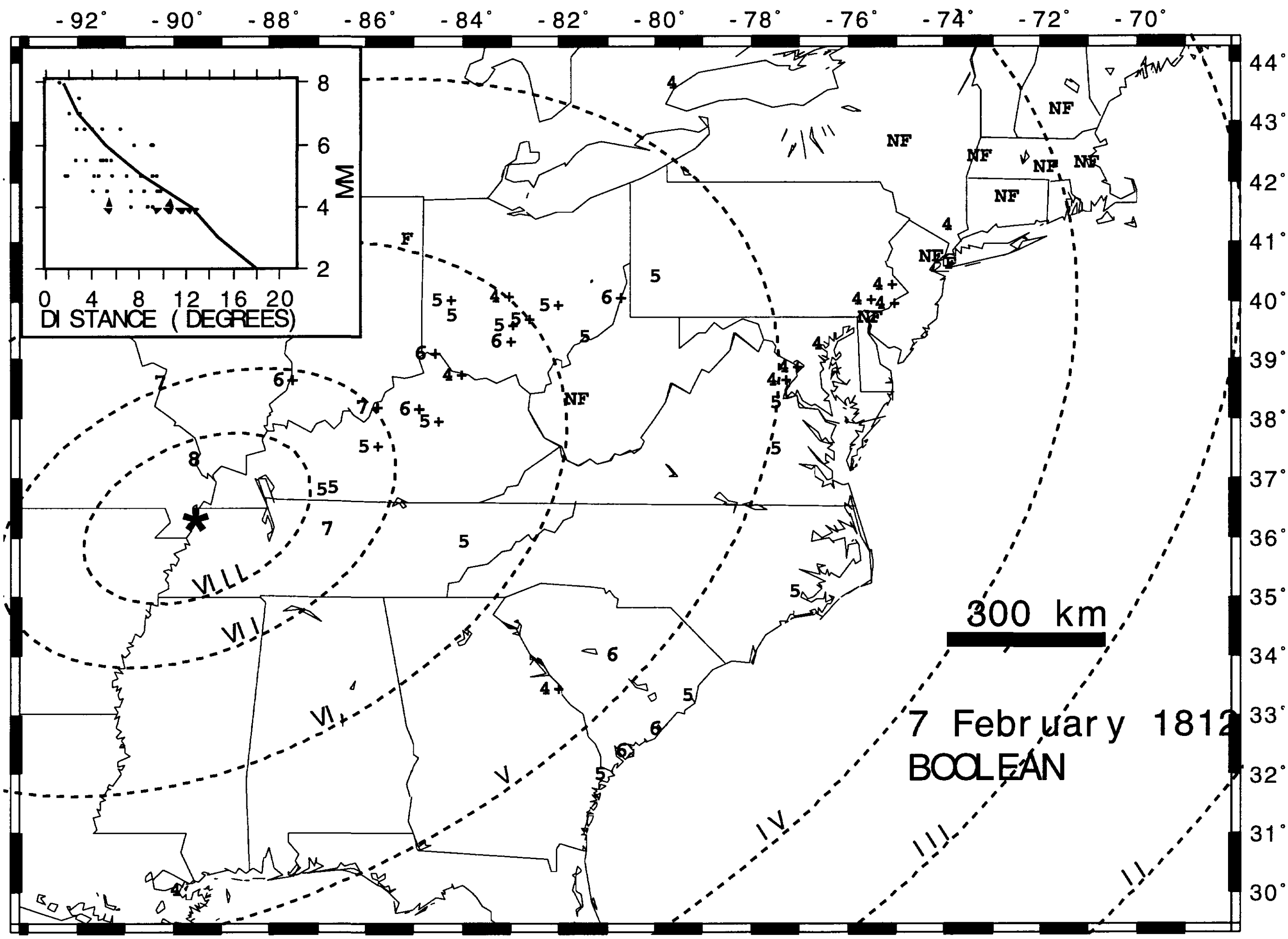

Figure 5b. Reinterpreted MMI data for event NM3; Boolean contouring results. Inset plotting conventions same as for Figure 3b.

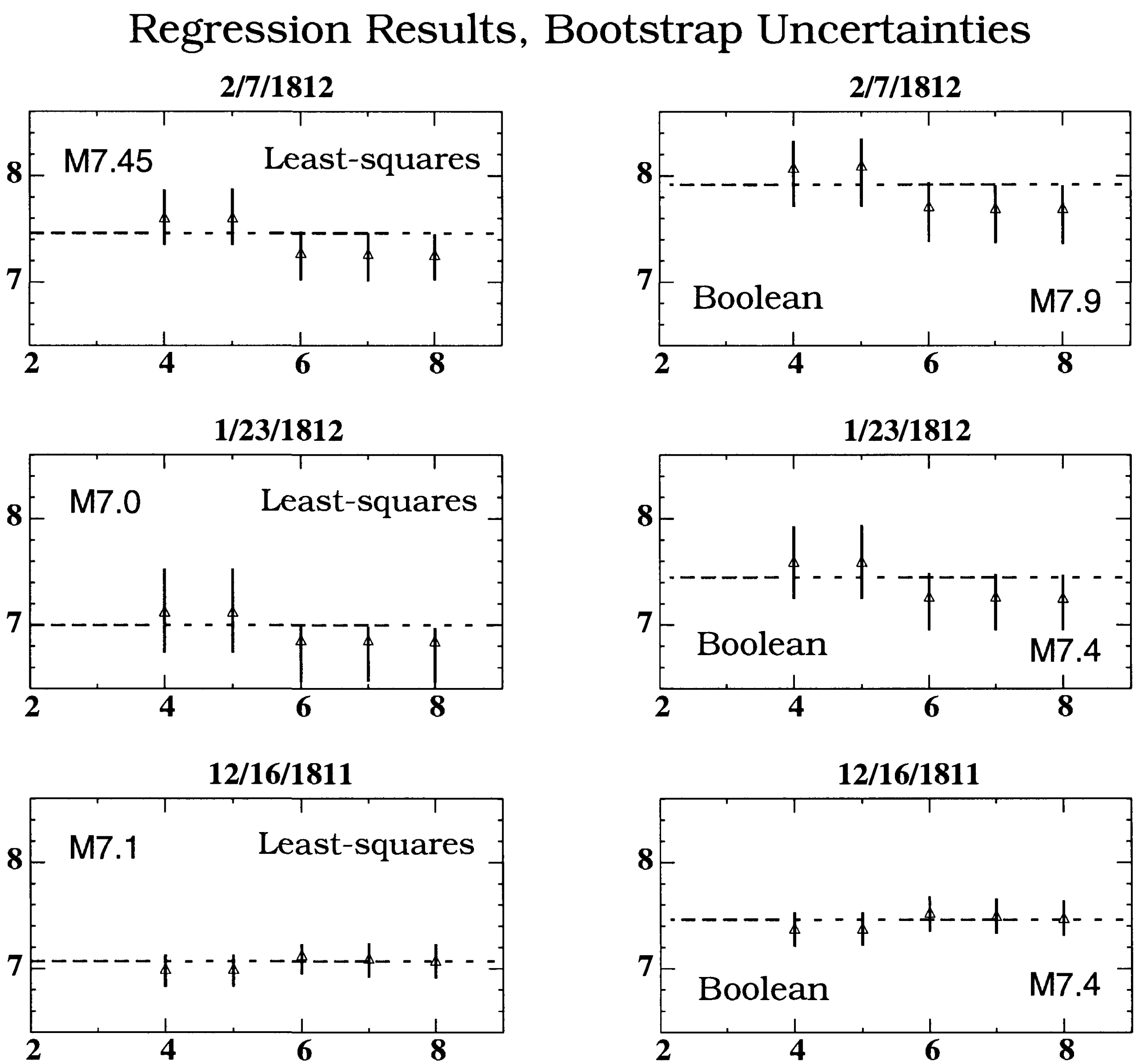

Figure 6. Mw estimates derived from each isoseismal level for least squares results (left set of panels) and Boolean regression (right set) for NM1 (bottom), NM2 (middle), and NM3 (top). For each event, triangles indicate optimal magnitude estimate and error bars reflecting bootstrap uncertainties (the range in values that result from 50 resampled data sets, with the most extreme five values rejected).

Table 1. Available Felt Reports

location	long	lat	NM1	NM2	NM3
Abingdon, VA	-82.00	36.90	Y	N	N
Annapolis, MD	-76.50	38.97	N	Y	N
Alexandria, VA	-77.03	38.85	Y	Y	Y
Arkport, NY	-78.00	42.60	Y	N	N
Asheville, NC	-82.53	35.53	Y	N	N
Augusta, GA	-81.97	33.37	Y	Y	Y
Augusta, KY	-84.00	38.77	N	N	Y
Baltimore, MD	-76.67	39.18	Y	Y	Y
Beaufort, SC	-80.69	32.42	N	N	Y
Birdsville, KY	-88.40	37.20	Y	N	N
Boston, MA	-71.03	42.37	Y	Y	Y
Brownsville, PA	-75.45	40.00	Y	N	Y
Cahokia, IL	-90.18	38.57	Y	N	N
Cape Girardeau, MO	-89.58	37.23	Y	Y	Y
Carlisle, PA	-77.40	40.30	Y	Y	N
Carthage, TN	-85.60	36.35	Y	Y	N
Charleston, NH	-72.30	43.20	Y	N	N
Charleston, SC	-79.97	32.90	Y	Y	Y
Charleston, WV	-81.60	38.37	Y	Y	Y
Chillicothe, OH	-83.00	39.35	Y	Y	Y
Cincinnati, OH	-84.52	39.16	Y	Y	Y
Circleville, OH	-83.00	39.90	Y	N	Y
Clarksburg, OH	-83.15	39.51	Y	N	N
Clarksburg, WV	-80.35	39.27	Y	N	N
Clarksville, TN	-87.37	36.55	Y	N	N
Clinton Hill, IL	-89.85	38.55	Y	N	N
Columbia, SC	-81.12	33.95	Y	Y	Y
Columbia, TN	-87.17	35.63	Y	N	N
Concord, NH	-71.50	43.20	Y	Y	Y
Cooperstown, NY	-74.88	42.67	Y	Y	Y
Coshockton, OH	-81.90	40.60	N	Y	N
Dandridge, TN	-83.42	36.02	N	Y	N
Dayton, OH	-84.22	39.90	Y	Y	Y
Detroit, MI	-83.02	42.42	Y	Y	N
Dorena, MO	-89.24	36.62	Y	N	N
Easton, MD	-76.00	38.75	Y	N	N
Edenton, NC	-76.50	36.05	Y	Y	N
Fort Stephens, LA	-91.80	31.25	Y	N	N
Fort Wayne, IN	-85.14	41.08	Y	Y	Y
Frankfort, KY	-84.87	38.19	Y	Y	Y
Fredericksburg, VA	-77.47	38.30	N	N	Y
Georgetown, KY	-84.55	38.21	N	Y	N
Georgetown, SC	-78.78	33.38	Y	N	Y
Germantown, PA	-75.07	40.30	N	N	Y
Goshen, IL	-89.97	38.80	Y	N	N
Hartford, CT	-72.68	41.77	N	Y	Y
Henderson County, KY	-87.60	37.80	Y	N	N
Herculaneum, MO	-90.55	38.30	Y	N	N
Hodgenville, KY	-85.74	37.57	Y	Y	Y
Jamaica, NY	-73.81	40.69	N	Y	N
Jeffersonville, KY	-87.72	38.18	Y	N	N
Kaskaskia, IL	-89.92	37.92	Y	N	N

Table 1. (continued)

location	long	lat	NM1	NM2	NM3
Knoxville, TN	-83.98	35.82	Y	Y	Y
Lancaster, OH	-82.60	39.72	Y	N	Y
Lebanon, OH	-84.30	39.60	Y	N	N
Lexington, KY	-84.50	38.33	Y	Y	Y
Louisville, KY	-85.73	38.18	Y	Y	Y
Marietta, OH	-81.45	39.42	Y	Y	Y
Meadville, PA	-80.12	41.63	Y	N	N
Milledgeville, GA	-83.24	33.09	Y	N	N
Muhlenberg County, KY	-86.15	37.20	Y	N	N
Mortons Gap, KY	87.47	37.24	Y	N	N
Nashville, TN	-86.68	36.12	Y	N	Y
Natchez, MS	-91.38	31.55	Y	N	N
Newark, NY	-74.17	40.72	Y	Y	Y
New Bern, NC	-77.08	35.12	N	N	Y
New Bourbon, MO	-90.05	37.98	Y	N	N
New Haven, CT	-73.92	41.31	Y	Y	Y
New Madrid	-89.40	36.80	Y	N	Y
New Orleans, LA	-90.25	29.98	Y	Y	Y
Newport, KY	-84.49	39.10	Y	Y	N
New York, NY	-73.94	40.67	Y	Y	Y
Norfolk, VA	-76.20	36.90	Y	Y	N
Nottingham, MD	-76.45	39.36	N	Y	N
Paris, KY	-84.26	38.21	N	Y	N
Philadelphia, PA	-75.13	40.01	Y	Y	Y
Piney River, TN	-86.35	35.95	Y	N	N
Pittsburgh, PA	-80.22	40.50	Y	N	Y
Pittsfield, Mass	-73.26	42.45	Y	Y	Y
Raleigh, NC	-78.78	35.87	Y	Y	Y
Red Banks, TN	-86.40	35.90	Y	N	N
Richmond, VA	-77.33	37.50	Y	Y	Y
Rogersville, TN	-83.01	36.41	N	Y	N
Russellville, KY	-86.89	36.84	N	N	Y
Saint Louis, MO	-90.38	38.75	Y	N	Y
Salem, NC	-80.25	36.08	Y	Y	N
Savannah, GA	-81.20	32.13	Y	Y	Y
Sevierville, TN	-83.58	35.89	Y	Y	N
South Union, KY	-86.66	36.88	Y	N	Y
Springfield, TN	86.88	36.50	Y	N	N
Suffolk, VA	-76.64	36.70	N	Y	N
Troy, OH	-84.22	40.04	N	N	Y
Uniontown, KY	-87.93	37.77	Y	N	N
Vicksburg, MS	-90.90	32.60	Y	N	N
Vincennes, IN	-87.53	38.68	Y	Y	Y
Washington DC	-77.03	38.85	Y	Y	Y
Washington, KY	-83.85	38.62	Y	Y	N
Washington, MS	-91.30	31.58	Y	N	N
Waterford, PA	-80.00	42.00	Y	N	N
Wheeling, WV	-80.70	40.08	Y	Y	Y
White Bluff, GA	-81.20	32.03	Y	N	N
Wilmington, DE	-75.53	39.74	Y	Y	Y

Table 1. (continued)

location	long	lat	NM1	NM2	NM3
Worchester, MA	-71.87	42.27	Y	Y	Y
Worthington, OH	-83.02	40.10	Y	Y	Y
Yellowbanks, KY	-87.12	37.76	Y	N	N
York, Ontario	-79.63	43.68	Y	Y	Y
Zanesville, OH	-82.01	39.95	Y	Y	Y

City and State; longitude and latitude (decimal degrees) estimated from U.S. Census database for modern cities where available. Reports from counties assigned to approximate center of modern county; Y=report available; N=no information.

Table 2. MMI values, 12/16/1811 Event

location	MMI_N	MMI	*report*	*source*
Abingdon, VA	N/R	N/F		S1984
Alexandria, VA	N/R	4-5	furniture shaken; "no portentious effect"	N1973, S1984
Allegany County, NY	N/	4-5	objects visibly swung	S1984
Arkport, NY	6	2-3	2:15 event not felt	N1973
Asheville, NC	N/R	4-6	people awoken; "tanning vats displaced"; worse in valley	CF1811
Augusta, GA	N/R	4-5	family awoken; no damage described	S1984
Baltimore, MD	N/R	4	"felt"	S1984
Birdsville, KY	N/R	7-8	one wall (or possibly chimney) collapsed	S1984
Boston, MA	N/R	N/F	not felt	S1984
Brownsville, PA	N/R	4	"slight" shock felt	S1984
Cahokia, IL	N/R	7-8	liquefaction; damage to brick structures	S1984
Cape Girardeau, MO	8-9	7-8	several houses damaged; chimneys damaged	N1973, S1984
Carlisle, PA	N/R	NF	not felt	S1984
Carthage, TN	7	7	threw bricks from chimneys; cracked brick foundation	F1912, S1984
Charleston, NH	2-3	3	reported as felt	N1973
Charleston, SC	5-6	5-6	church bells rung; clocks stopped	F1912, S1984
Charleston, WV	N/R	NF	not felt	S1984
Chickasaw Bluffs, TN	N/R	F	felt	S1984
Chillicothe, OH	N/R	5	widely felt; no damage	S1984
Cincinnati	6-7	4-6	many familes on elevated ridges slept	F1912, S1984
Circleville, OH	6	4-5	many awoken; no damage	F1912, CF1811
Clarksburg, OH	N/R	5	"sensibly felt"; no damage	S1984
Clarksburg, WV	N/R	4-5	felt	S1984
Clarksville, TN	N/R	6-7	many chimneys injured	F1912
Clinton Hill, IL	N/R	5	"violent shock felt"; no damage described	S1984
Columbia, SC	5-6	5-6	many awoken; plaster fell at one location	F1912, S1984
Columbia, TN	5-6	5	many awoken; no damage	F1912, S1984
Concord, NH	N/R	NF	not felt	S1984
Cooperstown, NY	N/R	NF	not felt	S1984
Dayton, OH	N/R	5	almost everyone awoken	S1984
Detroit MI	5	4	distinctly felt in region; no damage reported	F1912; S1984
Dorena, MO	N/R	8	brick part of one house fell	S1984
Easton, MD	N/R	2-3	morning aftershock felt but mainshock not reported	N1973
Edenton, NC	N/R	5-6	only report from persons on a warfe	S1984
Fort Dearborne, IN	N/R	F	"felt"	S1984
Fort Massac, IL	N/R	7	chimneys fell	S1984
Fort Pickering, TN	N/R	8	liquefaction	S1984
Fort Stephens, LA	5	4	many awoken; "shook fowls off roosts"; no damage	N1973
Fort Stoddert, LA	4-5	4	felt by some	N1973
Fort Wayne, IN	N/R	F	"felt"	S1984
Frankfort, KY	N/R	6-7	bricks thrown from chimneys	S1984
Georgetown, SC	5	5	many awoken; ground at one site settled 1-2 in.	F1912
Goshen, IL	N/R	6-7	strong shaking; chimneys damaged in "American Bottom"	S1984
Hagerstown, MD	N/R	NF	not felt	S1984
Henderson County, KY	7-8	6-7	many chimneys destroyed (ambiguous report)	F1912, S1984
Herculaneum, MO	6-7	7	cracked or destroyed chimneys	F1912
Hodgenville, KY	N/R	5	widely felt; no damage reported	S1984
Hopkins County, KY	N/R	6	utensils thrown down; houses rattled	S1984
Hudson, NY	N/R	4-5	earthquakes felt frequenty staring in December	S1984
Jefferson, KY	N/R	7	"felt very much as in Louisville"	F1912
Kaskaskia, IL	N/R	7-8	liquefaction; damage to brick chimneys	S1984
Knoxville, Tenn	5-6	4-5	many awoken; windows rattled	F1912

Table 2. (continued)

location	MMI_N	MMI	*report*	*source*
Lancaster, OH	N/R	5	motion similar to rolling of ship	S1984
Lebanon, OH	6	4-5	many awoken; no damage	F1912
Lexington, KY	7	5	"no injury sustained"	N1973, S1984
Louiville KY	7	7	damage to gables and chimneys	F1912, S1984
Marietta, OH	N/R	4-5	widely felt; no damage reported	S1984
Meadville PA	5	4-5	distinctly felt; many awoken	N1973
Milledgeville, GA	N/R	5	bell rung; no damage reported	S1984
Muhlenberg County, KY	N/R	5	general fear; no damage reported	S1984
Mortons Gap, KY	N/R	6	crack in brickwork	S1984
Nashville, Tenn	7-8	6-7	"no real injury"; fall of some chimneys	N1973, S1984
Natchez, Miss	6	6	widely felt; minor damage	N1973, S1984
Newark, NJ	N/R	NF	not felt	S1984
New Bourbon, MO	N/R	7-8	damage to chimneys	S1984
New Haven, CT	N/R	F	"barely felt"	S1984
New Madrid, MO	9	9	pervasive ground failure and damage	(various)
New Orleans, LA	N/R	4	felt (some accounts say not felt)	F1912, S1984
Newport, KY	N/R	7	one chimney thrown down	S1984
New York, NY	N/R	NF	not felt	S1984
Norfolk VA	5	4-5	doors swung; clocks stopped; no damage	F1912, S1984
Philadelphia, PA	N/R	NF	morning aftershock felt; NM1 not felt	S1984
Piney River, Tenn	7-8	6	slumping along river	F1912
Pittsburgh PA	5	4	distinctly felt; many awoken	F1912, S1984
Pittsfield, MA	N/R	NF	not felt	S1984
Raleigh NC	3-4	3-4	slight earthquakes were felt (no mention in Raleigh Star)	S1984, RS1811
Red Banks, Tenn	7	7	cracked or destroyed many chimneys	F1912, S1984
Richmond, VA	5	4-5	distinctly felt; bells rung	F1912, S1984
Saint Louis, MO	7-8	6-7	several chimneys thrown down	F1912, N1973, S1984
Salem, NC	N/R	5	many awoken	S1984
Savannah, GA	N/R	4	rattling noise "like carriage on paved road"	F1912, S1984
Sevierville, TN	N/R	4	felt; not noticed by all	S1984
South Union, KY	N/R	4-5	felt; no damage described	S1984
Springfield, TN	N/R	4	felt by two who were awake at time	S1984
Uniontown, KY	N/R	8	every brick chimney damaged/destroyed	S1984
Vicksburg, Miss	7	5	Island No. 94 destroyed; no other damage reported	F1912
Vincennes, Ind	6-7	6	cracked chimneys	F1912, S1984
Washington DC	4-5	4	distinctly felt; furniture rattled	F1912, S1984
Washington, LA	5-6	5	trees shaken; articles thrown	S1984
Waterford, PA	5	4-5	many awoken; no damage	N1973
Wheeling, WV	N/R	4-5	creaked walls, windows	S1984
White Bluff, GA	N/R	4	"felt sensibly", like ship on heavy swell	N1973
Wilmington, DE	N/R	NF	morning aftershock slightly felt; NM1 not felt	S1984
Worchester, MA	N/R	NF	not felt	S1984
Worthington, OH	N/R	4	felt by some but "not generally noticed"	S1984
Yellowbanks, KY	N/R	5	shaking felt; no damage reported	S1984
York, Canada	N/R	F	felt	S1984
Zanesville, OH	N/R	5	many awoken; clocks stopped, "no injury done"	S1984

City and State; MMI_N value assigned by *Nuttli* (1973); reinterpretted MMI value based on reports from towns; summary of firsthand reports on which MMI values are based; source of information (N1973=*Nuttli*, 1973; S1984=*Street*, 1984; CF1811=*Chillicothe Fredonian*, 1811; RS1811=*Raleigh Star*, 1811; F1912-*Fuller*, 1912).

Table 3. 1/23/1812 Event

location	*MMI*	Remarks	*source*
Alexandria, VA	4	"distinctly felt"	S1984
Augusta, GA	4-5	comparable to NM1	S1984
Baltimore, MD	4	felt like ship in heavy swell	S1984
Boston, MA	NF	not felt	S1984
Cape Girardeau, MO	7-8	stronger than NM1	S1984
Carlisle, PA	NF	not felt	S1984
Carthage, TN	6-7	nearly as severe as NM1	S1984
Charleston, SC	6	more severe than NM1; some cracks in masonry	S1984
Charleston, WV	NF	not felt	S1984
Chillicothe, OH (VAL)	5	"considerable shock felt"	S1984
Chillicothe, OH (HR)	4	"barely noticed except along river"	S1984
Cincinnati	4-6	comparable to NM1	S1984
Columbia, SC	6	damage to plaster, worse than NM1	S1984
Concord, NH	NF	not felt	S1984
Cooperstown, NY	NF	not felt	S1984
Coshockton, OH	6	cracked chimneys	S1984
Dandridge, TN	4	felt by almost all	S1984
Dayton, OH	5	worse than NM1, suspended articles swung	S1984
Detroit, MI	3-4	felt	S1984
Easton, MD	4	"sensibly felt"; some pendulum clocks stopped	S1984
Edenton, NC	F	"felt"; "no mischief done"	S1984
Fort Dearborne, IN	F	"felt"	S1984
Fort Wayne, IN	F	"felt"	S1984
Frankfort, KY	5	no damage described	S1984
Georgetown, KY	F	"felt"	S1984
Hartfort, CT	F	"sensibly" felt	S1984
Hodgenville, KY	5	"severe shock"; no damage reported	S1984
Jamaica, NY	F	suspended articles swung	S1984
Knoxville, TN	4-5	lighter than NM1; a few objects thrown from shelves	S1984
Lexington, KY	4-5	almost as severe as NM1	S1984
Louisville KY	7-8	more severe than NM1; damage to chimneys	S1984
Marietta, OH	5	similar to NM1; like rolling of ship	S1984
Newark, NJ (VAL)	3.5	"slight" shock felt	S1984
Newark, NJ (HR)	2.5	shock noticed by persons near river	S1984
New Haven, CT	3	gentle swinging of suspended objects	S1984
New Orleans, LA	4-5	clocks stopped, glassware shaken lightly	S1984
Newport, KY	5-6	strong shaking; no damage reported	S1984
New York, NY	F	felt	S1984
Norfolk, VA	4-5	suspended articles shaken, clocks stopped	S1984
Nottingham, MD	3	felt by some	S1984
Paris, KY	5	suspended articles swung "violently", no damage reported	S1984
Philadelphia, PA	NF	not felt	S1984
Pittsfield, MA	NF	not felt	S1984
Raleigh NC	3	lightly felt	RS1812
Richmond, VA	5	doors/windows "flapped", furniture shaken	S1984
Rogersville, TN	4-5	like motion of ship at sea; no damage reported	S1984
Salem, NC	F	felt	S1984
Savannah, GA	4-5	stronger than NM1, objects vibrated	S1984
Sevierville, TN	4	rattled windows	S1984
Suffolk, VA	4	felt by all; no damage reported	S1984
Vincennes, IN	6-7	shook tops off several chimneys	S1984
Washington DC	4	felt by most, objects rattled	S1984

Table 3. (continued)

location	*MMI*	Remarks	*source*
Wheeling, WV	4-5	nearly equal to NM1	S1984
Wilmington, DE	NF	not felt	S1984
Worchester, MA	NF	not felt	S1984
Worthington, OH	4	felt, no damage reported	S1984
York, Canada	4	felt	S1984
Zanesville, OH	5	as strong as NM1	S1984

City and State (VAL=valley site; HR="hard rock"); reinterpreted *MMI* value based on reports from towns; remarks; source of information (S1984=*Street*, 1984; CF1811=*Chillicothe Fredonian*, 1811; RS1811=*Raleigh Star*, 1811.

Table 4. 2/7/1812 Event

location	*MMI*	Remarks	*source*
Alexandria, VA	4-5	similar to NM2	S1984
Augusta, GA	4-5	generally strongest shaking	S1984
Augusta, KY	4-5	more severe than earlier shocks	S1984
Baltimore, MD	4	sensibly felt by several persons	S1984
Beaufort, SC	6	more severe than earlier shocks	S1984
Boston, MA	NF	not felt	S1984
Brownsville, PA (VAL)	5	articles in cupboards rattled	S1984
Brownsville, PA (HR)	4	"felt more sensibly along river bank"	S1984
Cape Girardeau, MO	8	stronger than NM1	S1984
Charleston, SC	6	longest duration, "quicker" motions	S1984
Charleston, WV	NF	not felt	S1984
Chillicothe, OH	6-7	stronger than others, "sudden jerks"	S1984
Cincinnati	6-7	one chimney toppled, "distinct" shocks	S1984
Circleville, OH	5-6	worse than others	CF1812
Columbia, SC	6	damage to plaster, cracked chimneys	S1984
Concord, NH	NF	not felt	S1984
Cooperstown, NY	NF	not felt	S1984
Dayton, OH	5	worse than NM1, "quicker", 2 shocks	S1984
Fort Wayne, IN	F	"felt"	S1984
Frankfort, KY	6-7	more violent than others	S1984
Fredericksburg, VA	5	3 distinct shocks felt; most awoken	S1984
Georgetown, SC	5	more violent; residents "generally awakened"	S1984
Germantown, PA	4-5	not felt by those sleeping	S1984
Hartfort, CT	NF	not felt	S1984
Hodgenville, KY	5-6	"severe shock"	S1984
Knoxville, TN	5	stronger than NM1; shock furniture	S1984
Lancaster, OH	5-6	rang bells; made other shocks seem "slight and feeble"	S1984
Lexington, KY	5-6	at least equal to NM1; some instances of cracked walls	S1984
Louisville KY	7-8	at least as severe as NM1; damage to chimneys	S1984
Marietta, OH	5	stronger than NM1; no damage reported	S1984
Nashville, TN	7	strongest event; damaged chimneys	S1984
Newark, NJ	NF	not felt	S1984
New Bern, NC	5	violent "rocking/jerking"; no damage reported	S1984
New Haven, CT	4	some awoken	S1984
New Madrid, MO	10	knocked down houses	S1984
New Orleans, LA	4	stronger than others; no damage reported	S1984
New York, NY	F	rattled cups and saucers; felt by many	S1984
Philadelphia, PA	4-5	felt by many; rattled doors	S1984
Pittsburgh PA	5	more sensibly felt than others	S1984
Pittsfield, MA	NF	not felt	S1984
Raleigh NC	4	felt	RS1811
Richmond, VA	5	stronger than others; many awoken	S1984
Russellville, KY	5	stronger than others; no damage reported	S1984
Saint Louis, MO	7	stronger than others; several chimneys toppled	S1984
Savannah, GA	5	felt by many; "no injury done"	S1984
South Union, KY	5	"tremendous"; no damage reported	S1984
Troy, OH	5-6	stronger than others; little damage	S1984
Vincennes, IN	6-7	shook tops off several chimneys	S1984
Washington DC	4-5	not felt by all	S1984
Wheeling, WV	6-7	stone house and chimney cracked	S1984
Wilmington, DE	NF	not felt	S1984
Worchester, MA	NF	not felt	S1984

Table 4. (continued)

location	*MMI*	Remarks	*source*
Worthington, OH	4-5	stronger than others; no material damage	S1984
York, Canada	4	strong than others; no damage done	S1984
Zanesville, OH	5-6	stronger than others	S1984

City and State (VAL=valley site; HR="hard rock"; reinterpreted *MMI* value based on reports from towns; remarks; source of information (S1984=*Street*, 1984; CF1811=*Chillicothe Fredonian*, 1811; RS1811=*Raleigh Star*, 1811.

Table 5. Magnitude Comparison

Study	NM1	NM2	NM3
Nuttli (1973)	7.2*	7.1*	7.4*
Street (1982)	NI	7.1*	7.3*
Johnston (1996)	8.1	7.8	8.0
This Study	7.2-7.3	≈7.0	7.4-7.5

Asterisk indicates m_b, otherwise, M_ω values are shown. NI=no independent determination made.

1 Appendix 1. Sample Sources from compilation of *Street*, 1984 (S1984)

1.1 Lebanon, Ohio (from *Mitchill*, 1815)

"At Lebanon, in Ohio, the alarm was so great, that many persons forsook their houses. The vibration of the shocks seemd to be from east to west." (Assignment by S1984: VI; this study: IV-V)

1.2 Milledgeville, Georgia (from *Poulson's American Daily Advertiser*)

"The earthquake noticed in our last, says the Augusta (Georgia) Herald, was felt in every direction from this place as far as we have yet heard from. In Columbia, South Carolina, several successive shocks were felt in this place, and at about the same hours. In Milledgeville, the state House was shaken as to cause the clapper of the Bell in the Cupola repeatedly to strike. In Savannnah the shock was equally severe, as it was in different places in the country." (Assignment by S1984: VI; this study: V)

1.3 Newbern, North Carolina (*Anonymous*, 1812)

"At four o'clock yesterday morning, a strong and alarming shock of an earthquake was felt in this town. Its duration was, perhaps, two minutes: some think it continued much longer. The rocking, or rather jirking was often repeated and violent. It seemed as if some monstrous weight had rolled, or swung almost out of the power of force which was restraining it, and that that power by desperate tugs and efforts wrenched it back again. It went off with a trembling like the quivering of a vessel at sea, after it has sustained a rugged stroke from an enormous and impetous wave." (Assignment by S1984: V-VI; this study: V)

1.4 Edenton, North Carolina (*Chenango Weekly Advertiser*, 1812)

"At Edenton, N.C. a warehouse on a warfe was so shaken that the persons working therein could scarcely keep their feet; and a new brig fitting at the warfe rolled so much that the hands at work on board immediately left her. The shock was felt in other parts of the town, the whole unattended by any noise." (Assignment by S1984: VI; this study: V-VI)

1 Appendix 2

1.1 From the *Raleigh Star* (Raleigh), NC:

The paper makes no mention of earthquakes in issues between 1/17/1812 and 2/7/1812. The 2/14/1812 issue reports that the "smart shock of an earthquake" was felt in Raleigh around 4 a.m. on 2/7/1812.

1.2 From the *Chillicothe Fredonian*

12/18/1811

"On Monday morning last, between the hours of one and two o'clock, many of the inhabitants of this place were considerably alarmed by a sudden and violent trembling of their houses, which is supposed to have proceeded from an earthquake. The shock was so sensibly felt as to cause many to leap from their beds. About 8 o'clock the same morning, a similar shock was experienced, which continued for the space of half a minute –during which time the houses were considerably agitated. Neither shock was preceded or accompanied by any explosion."

1/26/1812

"On Thursday the 23rd instant, at a quarter past 9 in the morning [illegible] the violent shock of an earthquake was felt in this place. The trembling was so [illegible] as to shake coffee out of the cups [illegible] of some of the inhabitants who were at breakfast. The shock was much more terrible than either of those heretofore mentioned in our paper of the 18th (December)."

2/12/1812

"Several very severe shocks of earthquakes have been felt in this place since our last. That felt on Friday morning, at 45 minutes past 3, was, we believe, much more terrible than any of those which preceded or followed it. It was preceded by a rumbling noise like distant thunder, and the shaking continued with more or less violence for about three minutes."

2/19/1812 – letter from John C. Edwards of Asheville, NC, dated 12/19/1811; reprinted in its entirety, transcribed verbatim

Gentlemen,–I take the liberty to transmit the following account of an earthquake which happened on the night between the 15th and 16th inst.

For several nights previous, the Aurora Borealis brilliantly illuminated the sky with its trembling corruscations; the late appearance of a splendid comet, and the blood-like color of the sun for several days, had alarmed a great many superstitious people. They talked of war; an when the news of Governor Harrison's dear-bought victory arrived, it brought to their recollection all those appearances which are still believed (as these are now) to have been the awful precursors of that bloody war by which we gained our independence.

On Monday morning, about one o'clock, the inhabitants were roused from their peaceful slumbers by a dreadful sound: some waggoners who were up the time it began, said it resembled, but was louder, than if 100 waggons were driven at full speed down the mountain. This gave us considerable alarm: the timid took to prayer, expecting every moment (as they say) to hear the sound of the last trumpet. The more courageous ventured to open their doors to discover what occasioned the noise. A sudden trembling of the earth caused fresh terror and alarm, from which we had not time to recover when we felt a violent shock which lasted about 3 minutes and was attended with a hollow rumbling noise, and ended with a dreadful crash leaving behind a strong sulphurous stench.

For the remainder of the night, all was still and calm, but was spent by us in trembling anxiety. When the wished for morning came, we were happy to find no lives were lost, but while some of us were in the street, congratulating each other on our happy escape, we were again alarmed by a much louder noise than any we had heard before. It was quickly followed by a more violent shock, which gave the earth an undulating motion resembling the waves of the sea. Two of those who were standing with me, were thrown off their feet, the rest of us with difficulty kept from falling, while two or three cows that were near us were unable to stand, and testified their fear by their loud bellowing, which with the cries of the women and children, and the terror that was depicted in the countenances of the men, presented a scene of terror I am uanble to describe.

It is somewhat strange that its effects were more violent in the vallies than on the mountains: a tan yard, in a valley near this place, had several vats displaced–the edges of some were raised 3 feet above their former level, and others were moved partly round, and left in a zig-zag manner. It would far exceed the bounds of this letter to describe all of the phenomena produced by this awful convulsion of nature: rocks moved, hills shook, houses shattered, &c.

A wonderful change has taken place in the manners of the people. I believe so many fervent prayers never were put up in this place as were on that fearful night and morning. I think what has been done may be termed a revival in religion.

I have just seen a gentleman from Knoxville, who passed Sunday night with Mr. Nelson at the warm springs: from his account his situation was more terrifying than ours. For several hours previous to the shock, a most tremendous noise was heard from the neighboring mountains. At intervals it was quiet, but would begin with so much violence, that each repetition was believed to be the last groan of expiring nature. The shock at that place did but little damage, except to a few huts that were built near the springs for the accomodation of invalids. The fulminating of the mountains was accompanied with flashes of fire seen issuing from their sides. Each flash ended with a snap, or crack, like that which is heard on discharging an electric battery, but 1000 times as loud. This induced him to believe that the earthquake was caused by the electric fluid.

In the morning it was observed that a large stream of warm water (temperature Fah. 142 degrees) issued from a fissure in a rock on the side of the mountain, which had been opened the preceding night. While they were examining it, another shock was felt which lasted two minutes. Although perfectly calm, the tops of the trees appeared to be greatly agitated, the earth shook violently, and the water of the warm springs, at that time overflowed by French Broad River, was thrown up several times to the height of 30 or 40 feet.

Several masses of stone were loosed from their ancient beds and precipitated from the summits and sides of the mountains. One in particular, well known to western travelers by the name of the Painted Rock, was torn from its base and fell across the road that leads from hence to Knoxville: it has completely shut up the passage for wagons. A great many people who were moving westwardly, are in a pittable situation at this inclement season, being unable to proceed until a new road is made round the rock (no easy task): in this they are cheerfully assisted by their neighbors.

I have been for three months in those dreary regions, examing a mine of Cobalt. The ore is rich: it abounds with arsenic. In May we intend to calcine the orre and prepare it for exportation, or perhaps manufacture it into smalt. The mine is within a few miles of Mackeysville.

John C. Edwards

Note:

John Clarke Edwards achieved a measure of infamy with a second letter that was published in the *Pennsylvania Gazette* on 2/19/1812. In this letter, Edwards describes an actual volcano–a "western Aetna"–in considerable and outlandish detail. The *Gazette* later printed a retraction. This curious chapter of the New Madrid story is explored in more detail in a separate study [*Hough and Hough*, in prep.]. Although Edwards credibility is clearly open to question, we conclude that several factors do lend credibility to his initial observations: 1) his initial report from the warm springs area clearly does not stem from pre-conceived notions of volcanic eruptions, and 2) Supposing the residents of Asheville were awoken by noise (rather than the shaking) of the P-wave, the timing the first perceived shaking is consistent with the expected S-P time at that distance. The quick subsequent arrival of a second, stronger shake is also consistent with the S-Lg time. Moreover, as of December 19th, it is highly unlikely that Edwards was able to fabricate his account based on reports from elsewhere, as news at that time moved only at the speed of boats and horses.