Draft Report of the *Independent Expert Panel on NMSZ Earthquake Hazards*

Executive Summary

We have briefly but broadly reviewed the current national hazard maps and the process of their generation, for the area around the New Madrid Seismic Zone (NMSZ), on the occasion of the bicentennial of the 1811-1812 earthquakes, soliciting input from scientists, engineers, and the public. The review was called by the National Earthquake Prediction Evaluation Council and motivated by a recommendation from the Advisory Committee on Earthquake Hazards Reduction and in part by the underlying controversy about the current high earthquake hazard assigned the NMSZ.

The hazard is sensitive to several geological parameters that are not certain, and which remain the focus of scientific research and refinement. The assessment in the current hazard map represented a reasonable consensus of the Earth sciences community at the time of its generation, 2006 through 2008. The panel concludes that the New Madrid Seismic zone is an area of significant seismic hazard that must be accounted for in urban planning and development.

The dominant uncertainties that affect the hazard estimates are (i) the ground motions that are generated as a function of magnitude, source-to-site distance, and site conditions; (ii) the magnitudes, and (iii) the recurrence rates of future earthquakes in the NMSZ. Other important factors are the random uncertainty in the shaking estimates and whether or not enough time has passed for the area to be "ripe" for more large NMSZ events. A fundamental problem is the lack of knowledge concerning the physical processes that govern earthquake recurrence in the Central US, and whether large earthquakes will continue to occur at the same intervals as the previous three clusters of events. Evolution in our knowledge in several of these factors will change, and likely reduce, the estimated hazard in the next round of seismic hazard calculations.

Several models for NMSZ earthquake occurrence have been proposed, including sequences initiated by erosion of Mississippi sediments, glacial unloading, thermal events from the upper mantle, and unsteady earthquake clustering across the Central US. The observed very low deformation rates might constrain models, although some models predicting continued earthquake activity are broadly consistent with the observed deformation rates. It has been proposed that the apparent lack of current deformation indicates that the process driving NMSZ earthquakes has ceased, but experts do not commonly share this view.

Additional research would be helpful in reducing uncertainties. More refined estimates of ongoing geodetic strains are needed to understand the underlying processes. Interpretations need to be specific, with testable mechanical models tied to fault locations and with potential reloading processes. Improved ground motion prediction equations, a better understanding of regional ground motion characteristics necessary to induce liquefaction, more geological surveys of active faults, and better surveys of analogous regions elsewhere will also improve our knowledge of the hazard.

In the meantime, continued iteration of the seismic hazard evaluation process used to produce the national seismic hazard maps, which represents stable consensus-based science, is the best means available to refine hazard estimates.

Full Report

The science behind estimation of earthquake hazard around the New Madrid Seismic Zone (NMSZ, Figure 1) is steadily advancing. Studies of geological and ground motion processes are more refined than even just a few years ago. It is natural that the hazard estimates evolve with improving scientific knowledge. The USGS hazard estimation methods are working well. It is likely that the estimated NMSZ hazard may decline moderately in the next hazard assessment due to improved knowledge of past earthquakes and current deformation.

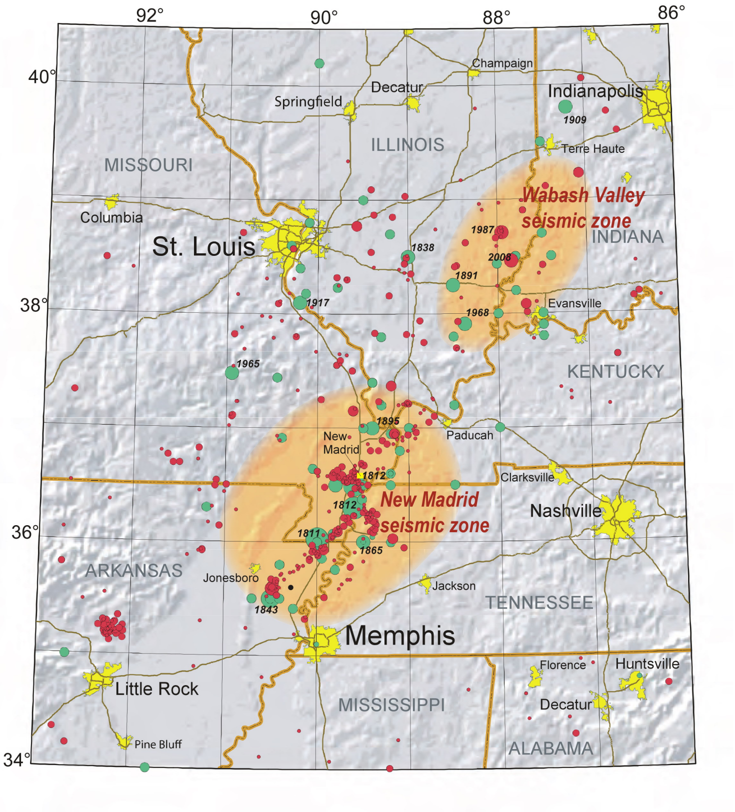


Figure 1. Map of the New Madrid and Wabash Valley seismic zones, showing earthquakes as circles. Red circles indicate earthquakes that occurred from 1974 to 2002 with magnitudes larger than 2.5. Green circles denote earthquakes that occurred prior to 1974. Larger circles represent larger earthquakes (thanks to Rob Williams).

Panel Process

The Panel was convened in early 2011 to respond to the Charge from NEPEC (the National Earthquake Prediction Evaluation Council) that *" ... there are substantial uncertainties regarding the size, location and frequency of both past and future earthquakes in the region, and regarding the underlying causes of earthquakes in this intraplate setting. Consequently, there has been debate in scientific and engineering circles on the level of earthquake hazard in the NMSZ. ... NEPEC recommended that an independent expert panel be convened to consider the diverse evidence and views pertaining to the level of seismic hazard in the NMSZ. ... ".* The Charge was partly in response to the recommendation from ACEHR (Advisory Committee on Earthquake Hazards Reduction) that *" ... it will be advantageous to examine the high hazard levels in USGS maps via an independent review for the New Madrid area ... "*.

Expertise within the Panel includes tectonics, intraplate earthquakes, Earth structure, GPS strain monitoring, liquefaction, paleoseismology, postglacial rebound, strong ground motion, lithospheric mechanics, geodynamics, hazard mitigation and probabilistic seismic hazard analysis.

We met by conference calls between late January and late March 2011, and held a two-day meeting in Memphis, Tennessee in mid-March, in which we interviewed a number of key experts having different perspectives on the issues. Two members attended a March 4th workshop in Boston examining implications of geodetic deformation on seismic hazard near the NMSZ.

We also solicited written comments from the broader community by an invitation sent by Terry Tullis, chair of NEPEC, to the ~600-member CEUS Earthquake Listserv and subsequently forwarded to many others. We received over 40 letters from scientists, engineers, public officials and members of private businesses and trade groups. We greatly appreciate these contributions, which added considerably to our knowledge of previous work, and to our understanding of the way in which seismic hazard information is viewed and acted upon in the region.

Further process details, including Panel membership, detailed meeting schedule, and list of contributors of input, are given in the Supplement.

Review of 2008 Hazard Map and its Construction

The seismic hazard of the central U.S. (CUS) is regularly assessed via the national seismic hazard maps produced by the USGS. These maps provide the ground-motion input to the building code process, and are also often used for retrofit guidelines, insurance assessments, design of bridges, dams, and landfills, land-use planning, and other purposes. Furthermore, the maps are used in the United States for nationwide earthquake risk assessment and for developing credible earthquake scenarios for planning and emergency preparedness, and earthquake risk and loss assessments.

At the request of the engineering community, the USGS provides maps of index ground motion parameters that are exceeded with probability levels of 10% in 50 years and 2% in 50 years. The index parameters show peak ground acceleration and 5% damped spectral accelerations for specified vibration periods, in which the spectral accelerations, in simplest terms, are proportional to the earthquake-induced lateral force that a building will "feel" depending on its natural period; a 1-to-2 story building has a natural period near 0.2s, while a 10-story building has a period near 1s. The maps give values for a reference "firm-ground" condition, with amplification factors being used to correct the motions for different soil conditions. We note that one needn't wait 2500 years to sample the 2% in 50-year motions; due to variation in earthquake locations and resulting ground motions, on average across the region 2% of sites are expected to exceed the 2%-50-year motions each 50 years, and 15-20% every 500 years.

The maps are produced with a well-tested and widely accepted probabilistic calculation methodology that has been developed over the past 40 years. Thousands of peer-reviewed academic publications attest to this status. While not perfect, we consider it the best currently available approach to quantitatively evaluate the seismic hazard and an essential tool in urban planning, ensuring seismic resiliency of our communities. The real scientific issues in the hazard calculation revolve around the many choices of input parameters (and their interactions), not around the methodology. There are valid differences of opinion on the best value and range of these parameters in light of uncertainties in proper characterization of the hazard in the CUS. Uncertainties in our knowledge are significant, and are generally accounted for in the hazard calculations by performing (and weighting) calculations for alternative branches on a "logic tree" that describes the range of possible input models and their consequences for computed hazard. To ensure that the models reflect the wider scientific community view on hazard, the USGS maps employ a scientifically sound and carefully implemented process that involves input and peer review at both regional and national levels by expert and user communities.

Geology and Paleoseismicity

How do large earthquakes, similar to those in 1811-1812, recur in the New Madrid seismic zone? To address this question, we reviewed the geology and paleoseismology (geologic record of past earthquakes in the region).

The geology provides context for understanding the 1811-1812 New Madrid earthquakes. It is well known that earthquakes occur as a result of slip on faults. Furthermore, strong ground shaking and fault slip leave a permanent record in the geology if the conditions are favorable for preservation. Geologists can read this record like a history book, perhaps with a few pages missing. Active faults, defined as faults that have moved recently (in the Holocene or Late Quaternary geologic time periods), are key players. Geologic data such as evidence of fault slip, liquefaction, and broken stalactites in caves reveal approximately how often strong shaking has occurred in the past, and help to identify areas that are susceptible to future earthquakes.

Geologic data show that several faults in the region have slipped and deformed the ground surface, in some areas lifting it up (e.g., Lake County Uplift) or lowering it (e.g., Reelfoot Lake) relative to surroundings, thus affecting flow of the Mississippi River. For example, the Reelfoot scarp is a 10-meter-high hill formed by at least 3 major earthquakes on the Reelfoot fault in the last 2,400 years. The predominant style of recent faulting in the New Madrid region is strike-slip faulting with horizontal movement nearly parallel to the course of the Mississippi River. Horizontal slip along strike-slip faults is difficult to see at the ground surface unless a stream crosses the fault nearly perpendicular to it. The conditions within the Mississippi River Valley are not favorable for preserving evidence of active strike-slip faulting. Despite these unfavorable conditions, there is good evidence that several northeast-trending faults in the region are active and have generated significant earthquakes in the past. Two of these faults in the New Madrid seismic zone have been located by micro-earthquakes that are probably aftershocks of the 1811-1812 earthquakes. Other faults outside the New Madrid fault zone are roughly parallel to the course of the Mississippi River and are related to an ancient fault zone commonly called the New Madrid Rift. Over the last 20,000 years, the Mississippi River has removed sediments from the ancient rift valley, potentially erasing some records of faulting. However, geologic investigations show that several ancient faults with low long-term slip rates within the New Madrid seismic zone have been "reactivated" and show evidence of recent movement. Any of these faults could potentially generate an earthquake under the right conditions (e.g., a favorably oriented stress field and enough accumulated strain).

Thus, from a geological perspective, the New Madrid seismic zone region has the necessary ingredients for the occurrence of future earthquakes because there are a number of faults with evidence of past slip, as well as evidence of multiple episodes of strong groundshaking in the form of liquefaction features, and new evidence of broken stalactites in caves, that show a history of repeated earthquakes. The liquefaction evidence of earthquakes is difficult to tie to specific faults, but it can be used directly to estimate the magnitude and frequency of relatively recent (Latest Quaternary) earthquakes on faults within the seismic zone.

By studying paleoliquefaction features, insights can be gained into the magnitude, timing, and locations (all with inherent uncertainties) of moderate-to-large paleoearthquakes that occurred in the NMSZ. Several investigators have undertaken such studies. Dr. Tuttle and collaborators found paleoliquefaction features that formed during five paleoearthquakes: 1810 AD +/- 130yrs (i.e., 1811-1812 events); 1450 AD +/- 150yrs; 900 AD +/- 100yrs; 300 AD; 1100 BC, with the occurrence time of the earliest two earthquakes being more uncertain than the others. The time between the three paleoearthquakes whose occurrence times are more accurately known ranges from 200 to 800 years, with an average of 500 years.

Based on the areal extent of paleoliquefaction features, Dr. Tuttle and collaborators estimated the magnitudes of the three 1811-1812 earthquakes to be at least M7.6, with the 1450 AD and 900 AD paleoearthquakes having similar magnitudes. These estimated magnitudes are in line with the estimated magnitude of a large paleoearthquake that occurred near Vincennes, Indiana, in the Wabash Valley Seismic Zone, WVSZ about 6000 years ago. Based on detailed, site-specific analyses, the Vincennes paleoearthquake was estimated to have a magnitude about M7.3-M7.5. The areal extent of paleoliquefaction features formed during the Vincennes paleoearthquake is smaller than that of the 1811-1812 New Madrid earthquakes. The ease with which the soil liquefies in the WVSZ is similar to that in the NMSZ, which implies that the magnitude of the 1811-1812 New Madrid earthquakes were larger than that of the Vincennes paleoearthquake, in agreement with the independent magnitude estimations.

From studying the layering of the soil and rocks in the Mississippi River flood plains and ancient river channels, Dr. Holbrook and collaborators found that the Mississippi River abruptly changed course upstream of the Reelfoot scarp around the same time that paleoearthquakes occurred on the Reelfoot fault, with the timing of the paleoearthquakes independently determined from paleoliquefaction features and fault scarp trenching. It appears that the meandering river straightened as a result of changes in the ground elevation due to movement of the fault. However, Dr. Holbrook and collaborators also found evidence of abrupt changes in the course of the Mississippi River that occurred before the earliest paleoearthquake identified from paleoliquefaction evidence and fault trenching of the Reelfoot scarp. Assuming these earlier river course changes were also caused by large, paleoearthquakes, stratigraphic data provide insights into the timing of large, previously unidentified paleoearthquakes on the Reelfoot fault.

Of particular relevance to the seismic hazard of the NMSZ, the stratigraphic data presented by Dr. Holbrook and collaborators implies that large earthquakes occur in the NMSZ in groups or clusters, with intervening periods of thousands of years with no large earthquakes. The 1811-1812 earthquakes, the 1450 AD earthquakes, and the 900 AD earthquakes would constitute one cluster*,* or the start of one cluster, for example. While this finding may have significant implications on the timing of future, large earthquakes in the NMSZ, the findings are not certain. For example, the evidence of river straightening found by Holbrook and collaborators was due to movement on the Reelfoot fault, which is a reverse fault (i.e., one side of the fault move vertically relative to the other side of the fault). It is unlikely that movement on the strike-slip faults in the NMSZ would result in significant changes in the course of the Mississippi River. Note that two of the three earthquakes that occurred between December 1811 and February 1812 are believed to have occurred on strike-slip faults in the NMSZ. As a result, the lack of evidence of abrupt changes in the course of the Mississippi River upstream of the Reelfoot fault may only indicate that no large earthquakes occurred on the Reelfoot fault during the “quiescence times” between identified earthquake clusters, while large earthquakes may still have occurred on strike-slip faults in the NMSZ during this time.

Magnitude and Intensities

Estimates of the seismic intensities and magnitudes of the 3 mainshocks (largest earthquakes) of the New Madrid sequence of 1811-12, on December 16th, 1811, January 23rd, 1812, and February 7th, 1812, have improved over the last 15 years as a result of several major calibration studies. Previously, the magnitude estimate of at least one the 3 mainshocks has been greater than 8. However, none of the recently published work that we reviewed indicates mean values larger than 7.8 and several are smaller (Table S1 in Supplement).

In summary, magnitudes estimated for the three largest shocks of 1811-12 have been reduced, but measures of their uncertainty such as standard deviations are large, about 0.5 magnitude units. Estimation of the shaking during future large earthquakes in the Mississippi embayment is complicated by the above uncertainties in the magnitudes of the 1811-12 shocks, assumptions about stress drop, and conversion between magnitude scales used in various studies. We describe the recent results in greater detail in the Supplement.

Recent work agrees that the third main earthquake in the series, NM3 of February 7, 1812, was the largest. Its location along the WNW-striking Reelfoot fault and Lake

County uplift and its mechanism, reverse faulting, are the best known of the three mainshocks. The magnitude of the first main event, NM1 of December 16, 1811, was somewhat smaller than NM3; its mechanism and location are widely viewed as strike slip along the Cottonwood Grove fault to the south of NM3. More felt reports are available for NM1 than for the other two main events. The location and magnitude of NM2, which occurred on January 23, 1812, are less certain although it clearly was a large earthquake somewhere to the north of NM3. Several workers place it along the zone of modern small earthquakes that strikes NNE immediately to the north of the western end of NM3. Other work suggests a location farther north in southern Illinois. Additional studies are needed to resolve its location. If it, in fact, occurred farther north, the region between its rupture zone and that of NM3 may not have broken in 1812, may not have ruptured in many hundreds of years and may be a candidate for the site of a future major earthquake. Large aftershocks of NM1 on the same day may have occurred beyond the southwestern end of present-day activity to the west of Memphis and the other near its northeastern end. Hough and coworkers report magnitudes that are considerably lower than estimates by Bakun and coworkers and Cramer, although many estimates overlap at 95% confidence.

GPS Data

GPS data in NMSZ show very low rates of deformation, with deformation across the entire network less than 10^{-9} per yr (equivalent to less than 0.5 mm/yr). High-precision GPS data are increasingly used to constrain seismic hazard analysis in plate boundary zones, either through direct incorporation of surface strain rates or through integration of model-based inferences of fault slip rates. The low deformation rates in the NMSZ have been invoked by some as an argument for reducing the estimated earthquake hazard in the region.

The integration of GPS data in NMSZ seismic hazard analysis is limited by two main factors: (1) limitations of the existing GPS data; and (2) lack of physical understanding of how stress accumulation on faults is related to surface deformation in intra-continental regions. The GPS data only have a predictive power of future earthquake activity in the NMSZ through a mechanical model. As reviewed below, we note that there are mechanical models of earthquake activity in the NMSZ that are broadly consistent with the low observed strain rates.

We have recognized three main limitations of the existing GPS data:
1: The location and distribution of the current continuous GPS network are not optimal for tectonic and earthquake strain studies, particularly in comparison to dense geodetic networks in fault systems near plate-boundary zones (e.g., Japan and on the west coast of the US).
2: Although the GPS position time series are fairly long (up to 10 yr), they are relatively noisy and non-linear, with potential contamination by non-tectonic signals.
3: The very low rates of deformation are at the limit of resolution, and the formal uncertainty of the data may not be well resolved.

Because of these limitations, GPS data interpretations can vary depending on the analysis strategy. Two strategies have been pursued:
1: Individual site velocities are independently estimated from position time series. In this case, all site velocities in the NMSZ are within the estimated uncertainties, and the average scatter of site velocities is at most 0.2 mm/yr across the network.
2: Differential velocities between selected sites are estimated directly from differences in position time series. In this case, differential velocities of about 0.4 mm/yr between a few sites near the faults may be statistically significant and spatially coherent, although the significance is difficult to assess with only a few stations.

Earthquakes and Tectonic Models

Several mechanical models have been proposed to explain the deformation and loading of faults leading to large earthquakes in the NMSZ. Some of the models are broadly consistent with the observed low deformation rates in the NMSZ; however, several of the models were proposed prior to the recent GPS observations and have not been tested against those observations. Additionally, many models have not been evaluated in light of more recent estimations of the magnitudes of past earthquakes. In terms of their implications for seismic hazard analysis, models can be separated into two main categories: (1) Those in which the NMSZ is continuing to reload, and (2) those in which the NMSZ is not being reloaded. In the first class, reloading through external forcing results in a quasi-periodic recurrence of large earthquakes. In the second class, the lack of reloading results in a decrease with time of the frequency or magnitude of large earthquakes.

No mechanical model specifically adapted to the central US or NMSZ has predicted an abrupt end of earthquake activity in the NMSZ. Several models in class (2) predict a gradual decrease in the occurrence of large earthquakes in the NMSZ; however, none are corroborated by the observed paleoseismic data. Several models show that clustering of large earthquakes in both space and time is possible in a system loaded very slowly relative to its characteristic relaxation time; thus a certain degree of space-time clustering of large earthquakes is expected in the central US. However, in the absence of testable predictions adapted to the central US fault systems, it is difficult to assess the model significance.

Here we discuss the two classes of mechanical models that have been constructed to explain earthquake activity in the NMSZ:

1: Models in which the faults are reloaded result in a quasi-periodic recurrence of large earthquakes. These models assume that the time-scale over which the NMSZ continues to be reloaded is much longer than the characteristic recurrence time of large earthquakes. From a hazard analysis perspective, these models imply that the probability of earthquake recurrence should continue to be high for the near future (> 1000 yr). In the simplest models, the NMSZ faults are anomalously weak or optimally oriented, and are reloaded through large-scale regional stress in the North American plate. Mechanisms that may result in localized reloading include postglacial rebound from the Laurentide ice sheet, sinking of a high-density rift pillow in the lower crust, or the sinking of the Farallon slab in the mantle. Reloading may also be focused in the NMSZ region due to rheological weakening of the lower crust or uppermost mantle.

2: Models in which the faults are not reloaded through time predict that occurrence of large earthquakes should decrease with time. These models assume that at some time in the past the NMSZ was either stressed or weakened, resulting in the initiation of a sequence of large earthquakes. As these models do not include a mechanism to reload the faults, they predict that the occurrence of large earthquakes will decrease through time; however, sufficient stress to generate large earthquakes may well be present on nearby faults in the Mississippi embayment. Most recently, it has been proposed that flexure of the crust due to unloading of sediments in the Mississippi embayment has resulted in an unclamping of the NMSZ faults, which are presumed to have been very close to a failure condition. In this model, each fault only fails once, as there is no mechanism to reload the faults that ruptured in 1811-12. It might be possible for recurrence to be triggered by diminishing fault strength, which should produce a decreasing trend in earthquake rate over time in the NMSZ.

Estimation of the Background Seismicity Across the Central US region also matters for hazard, but less debate exists over this issue and fewer new developments have arisen since the experts were last polled. Accordingly, we examined background seismicity less closely. The possibility exists that there are more locales similar to the NMSZ, in addition to the couple that are already identified. The difficulty in recognizing big earthquakes in the more distant past makes it possible that so far we are underestimating their frequency elsewhere in the Mississippi embayment and the Wabash Valley.

Sensitivity of Hazard Maps to Changes in Knowledge

The national hazard maps are an evolutionary product that changes as new information on the hazard is obtained, with significant updates being produced about every 5 years. Our panel looked at current trends in thinking on some of the major issues that may impact the hazard maps in the near-future, such as the latest ideas on the magnitude and repeat times of large earthquakes in the New Madrid seismic zone, ground motion prediction equations, and site amplification.

Sensitivity calculations to give a sense of the relative importance of these issues – without meaning to suggest recommended values – were requested from the USGS and presented here. The choice of requested sensitivity calculations, as briefly outlined below, was motivated by the presentations, written comments, and literature that the Panel examined (see Appendix A). We emphasize that the purpose of this exercise is only to show sensitivity, with the goal of highlighting those areas where future research efforts may be most fruitful in improving the hazard maps.

We requested calculations to provide values of peak ground acceleration (PGA) and 5% damped spectral accelerations at 0.2 and 1 s, at 2% probability of exceedence (PE) in 50 years and 10% PE in 50 years. We use the national seismic hazard model as a basis for the following sensitivity cases, in which all other parameters aside from the one being varied are held fixed at the values used in the 2008 national seismic hazard maps, for 4 cities: New Madrid, MO, Memphis, TN, St. Louis, MO, and Paducah, KY.

The changes made in the model for the sensitivity calculations, relative to the 2008 hazard maps, are summarized in Table 1. Figure 2 shows representative results of the calculations for PGA. The rest of the results and the logic tree for the 2008 hazard map are listed in the supplement. The calculations are all for the reference hard-rock condition. The appropriate evaluation of site response factors, by which to modify the hazard maps, is also a crucial issue, as important as those evaluated here, but was beyond our scope to examine.

Table 1 – Sensitivity Cases Examined

Case	Parameter	Description
1	*Maximum magnitudes for New Madrid earthquakes*	Reduce all maximum magnitudes for New Madrid earthquakes by 0.5 magnitude units, leaving all weights the same
2	*Uncertainty in the ground motion prediction equations (sigma)*	Reduce the assigned "sigma" (expressing random variability) for all GMPEs to an optimistic "single-station sigma" of 0.4 natural log units at all periods
3	*Median ground motion prediction equations (GMPEs)*	Use the following newer GMPEs and weights: AB06' (from Atkinson and Boore, 2011) (finite-fault stochastic method) (B/C): 0.15 A08' (from Atkinson and Boore, 2011) (referenced empirical method)(B/C): 0.3 Pezeshk et al., 2010) (hybrid empirical method)(rock converted to B/C): 0.25 Somerville et al, 2001 (broadband simulations) (rock converted to B/C): 0.15 Silva et al, 2002 (stochastic single corner, variable stress) (rock converted to B/C): 0.15
4	*NM recurrence intervals*	Change weights on the NM recurrence intervals, for both the unclustered and clustered models, to 500 years (0.1), 1000 years (0.9): this has the effect of lengthening the average recurrence intervals
5	*Extreme Model*	Make all the changes (1 to 4) simultaneously
6	*Western GMPEs*	Show the effect of using the CUS model but assuming GMPEs that apply to the western U.S. (as implemented in the maps for California)

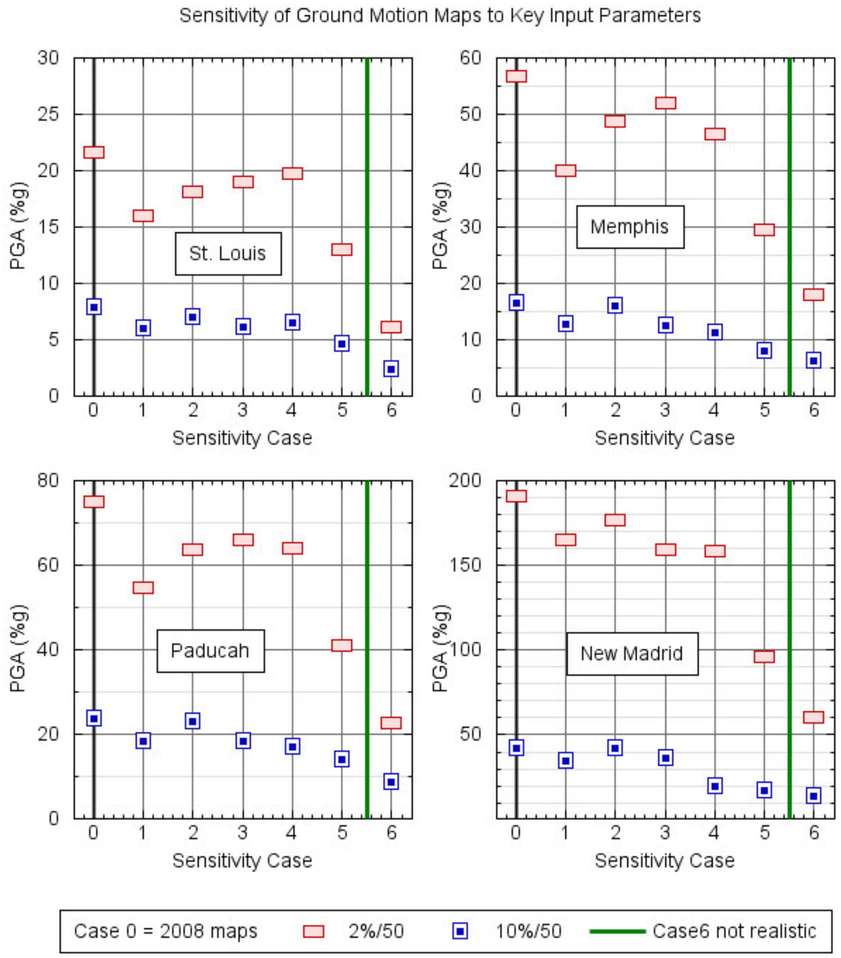


Figure 2– Sensitivity of PGA to Various Uncertain Parameters. Case 0 uses the 2008 national seismic hazard model. Cases 1 to 4 show the effects of other possible assumptions (Table 1); 1=lower maximum magnitudes; 2=lower sigma; 3=new GMPEs; 4=lower recurrence rates for large events; 5= combined effect of 1 to 4. Case 6 is not realistic, as it assumes western ground-motion propagation, but is shown for illustration.

The sensitivity calculations of Figure 2 illustrate the importance of the ground motion prediction equations, and in particular the role of eastern ground-motion characteristics in controlling the mapped values. The ground motions calculated at all cities would drop dramatically for short periods if western GMPEs were used (Case 6). However, it is known that eastern motions have richer short-period content, and decay more slowly with distance, than do western motions. Thus it would be incorrect to assume western GMPEs, which is why the maps use GMPEs developed for the CUS (and why Case 6 is marked as "not realistic" on the figure). Sensitivity case 6 illustrates that the GMPEs for the CUS are, in large part, the reason why the ground motions may seem high relative to California.

We now turn to the other sensitivity cases, 1 to 4, which are reasonable alternative interpretations based on current data. We note that lower maximum magnitudes with longer recurrence rates for major events and new GMPEs are both important trends that may tend to lower the calculated motions in the next version of the national seismic hazard maps. Further refinement of random uncertainty estimates for the GMPEs (sigma) would also be beneficial. If we consider, in the extreme case, the combined effect of all these possible changes (case 5), the chosen input parameters of the national seismic hazard maps might reduce the calculated PGA by nearly a factor of two. But there could be other factors that tend to increase the calculated motions, and we have not justified the choices made in these sensitivity calculations; rather, we seek a crude estimate of the current amount of uncertainty in the hazard.

The engineering community determines the uses of the national seismic hazard maps in building codes. It is important to note that while the building codes use the maps as input, the "design maps" in the codes do not exactly mirror the mapped ground motions, as "deterministic caps" and other factors have been used to modify the hazard maps to produce design maps. This process and its results are evolutionary, and have recently shifted from a hazards-based formulation to a risk-based formulation. The recent change to a risk-based approach recognizes that design provisions should account for different recurrence rates of events and different ground motion attenuation in the seismic zones of the CUS versus California that result in different hazard curve shapes, despite similar levels of high frequency motions at low probabilities. Thus, new building code provisions (in ASCE 7-10 and in IBC 2012) integrate entire hazard curves (including probability levels from 2% in 50 years to 10% in 50 years) with building fragility curves to provide, wherever deterministic caps do not govern, seismic design provisions that result in a relatively uniform collapse probability on the order of 1% in 50 years. An example of these "design spectra" is given in the supplementary material. This level has been chosen to be the engineering reliability target for safe new buildings.

Our Panel has concentrated on the scientific issue of hazard assessment; we did not evaluate engineering or policy issues in our review. Those questions are best left for professionals and politicians who are qualified and/or positioned to make informed societal-risk decisions.

Possible Future Evolution of Hazard Estimates

Hazard estimates will evolve, and likely diminish, because of further analysis and better data. The recurrence interval might lengthen because some models have slowing recurrence as the sequence of events progresses. That the last burst of earthquakes was only 200 years ago might mean we are not yet in the time window where more earthquakes are expected. The hazard in the NMSZ region would be lower using a time-dependent model of seismic hazard, in which the fault at depth requires reloading; such models are not yet sufficiently mature for use in the national seismic hazard maps. Studies continue to re-examine previous data and produce new data that can be used to constrain a new set of hazard models. These updated models may tend to reduce the estimated hazard in the NMSZ. On the other hand, reevaluation of background seismicity may well work in the opposite direction, increasing estimated hazard across a broader area.

The next round of USGS National Hazard maps are a logical and effective method to include this new information, along with improved information on ground motions and their variability, to provide an improved estimate of the seismic hazard.

Recommended Future Research Directions
(not in priority order)

1. **More resolved GPS deformation studies**. Better site distribution and some redundancy in nearby stations may lead to better estimations of deformation amplitude and pattern. The GPS velocity field should be open to the research community for validation, which would aid the integration of GPS with seismic hazard analysis in the central and eastern US. With a higher station density, it may be possible to constrain vertical deformation around the Feb 1812 shock, despite poor GPS vertical sensitivity.
2. **Testable mechanical models**: It is crucial to have testable mechanical models for NMSZ earthquake recurrence. These models must be consistent with the sequence of events over the last several thousand years, finite offsets of the faults, and present-day GPS surface deformation. Models that were proposed prior to the recent GPS results should be re-evaluated in light of the tighter constraints on surface deformation. For hazard analysis, mechanical models must include the time-scale of cessation or continuation of earthquake activity in the NMSZ. Mechanical models of clustering of large earthquakes in space and time within the broader central and eastern US region are necessary.
3. **Improve ground motion prediction equations**, and the representation of their uncertainty, as the available data and interpretation context continues to improve.
4. **Study liquefaction evidence in adjacent regions**, such as those to the NE and SW of the presumed rupture zones of 1811-12 earthquakes, in order to assess the wider distribution of earthquake sources and source region migration patterns. Also, a better understanding is needed regarding the regional ground motion characteristics (e.g., amplitude, frequency content, and duration) potential to induce liquefaction, as compared to motions from shallow crustal active tectonic regimes.
5. **Use further study of faults** with paleoseismology, neotectonic geomorphology and stratigraphy, including high-resolution subsurface imaging, borings, trenches and CPTs, to improve our tectonic interpretations.
6. **Compare the NMSZ with analog regions** with similar tectonics and known earthquake history to assess geologic and geodetic factors that are relevant to hazard.
7. Obtain measurements of the **magnitudes of principal stress in boreholes** in Tertiary and older rocks to help in constraining mechanical models.

Supplementary Materials

A. Magnitude estimates
B. Logic tree for 2008 hazard maps
C. Full set of sensitivity calculations
D. Design spectra for selected cities
E. Panel members
F. Panel charge
G. Meeting dates and briefings
H. Those who provided written comments
I. Agenda of Memphis meeting
J. Bibliography

A. Magnitude Estimates

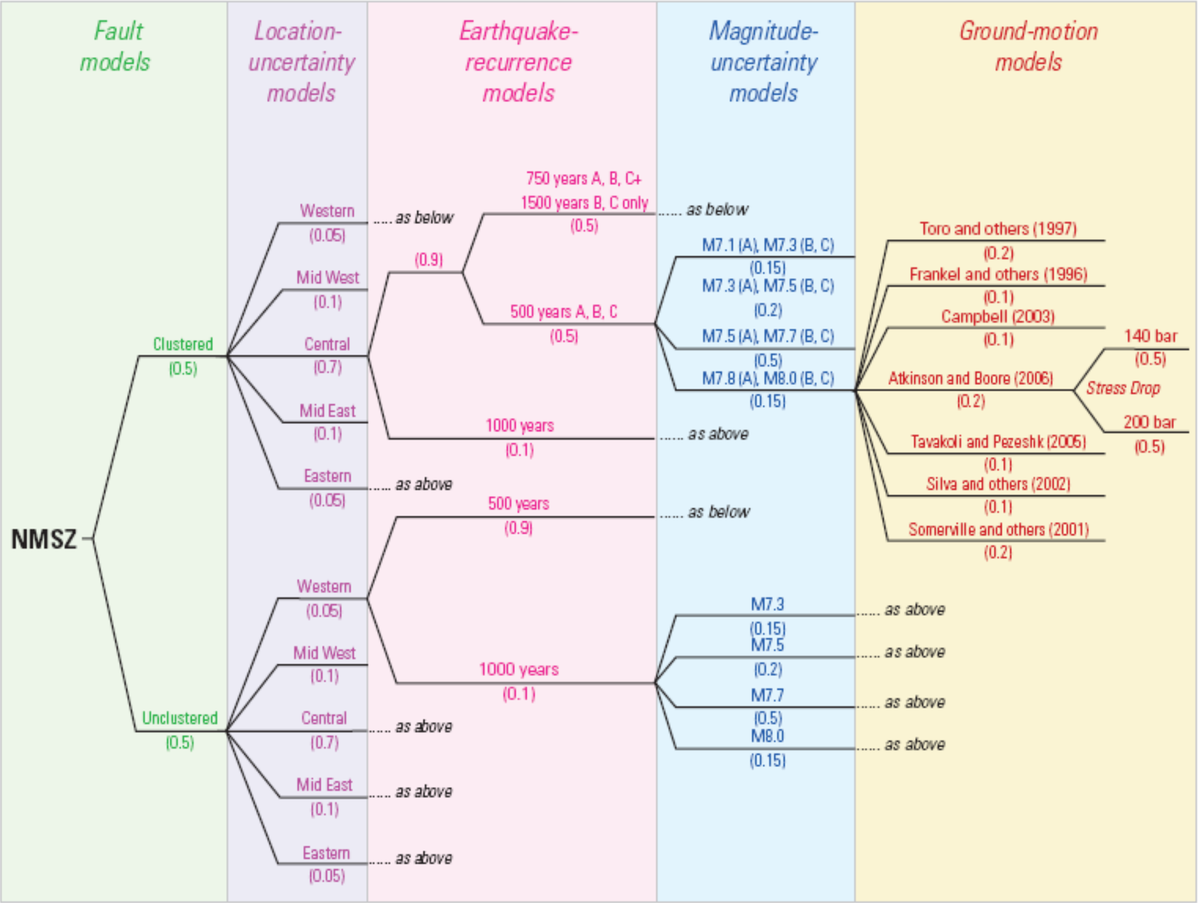
The main differences in the alternative estimates of magnitudes shown in Table S1 below results from the following factors: 1) the near lack of calibration events in eastern North America for large earthquakes since 1900 for which instrumental magnitudes are available; 2) use of intensity data for the 2001 Bhuj, India, earthquake of Mw 7.6 (after correction for attenuation differences between the Indian craton and central/eastern North America); 3) different interpretations of felt reports at large distances in terms of Modified Mercalli intensity, and 4) much of the intensity information in 1811-12 comes from soft sediments within river valleys such as the Mississippi and Ohio rivers. Some other workers merely state that the three main events had magnitudes between 7 and 8.

Known felt reports from 1811-12 are largely lacking from the area to their west. Likewise, use of intensity information from the Grand Banks earthquake of Mw 7.2 is problematic since it was located at sea off the coasts of Newfoundland and Nova Scotia. More work on magnitudes and earthquake risk to the New Madrid region likely could be accomplished using intensity data for the 1925 Charlevoix, Quebec, earthquake of Mw 6.4; perhaps the 1663 shock at the same location; the 1933 Timiskaming, Quebec, earthquake, the 1895 Charleston, Missouri, shock; the 1843 Marked Tree, Arkansas, event, and the 1886 Charleston earthquake--all of which appear to have been greater than Mw 6 from their large felt areas. None of the pre-1900 events, of course, have an instrumentally determined magnitude.

Table S1—Recent estimates of Magnitudes, Mw, of Earthquakes of 1811-1812

S	NM 1--16 Dec. 1811	NM2--23 Jan. 1812	NM3—7 Feb 1812
Bakun, Bakun & Hopper			
Best estimates	7.2-7.6	**7.2-7.5**	7.4-7.8
BB95% Confidence	6.8-7.9	**6.8-7.8**	7.0-8.1
Hough and Page	6.7-6.9	6.9	7.1-7.3
Cramer- using Grand Banks earthquake **and Page**	≥7.2		≥7.2
Cramer- using Bhuj, India earthquake	≥7.6		≥7.6

B. Logic Tree for the 2008 Hazard



The logic tree used to calculate the probable shaking from fault-based sources in the New Madrid seismic zone for the 2008 USGS national seismic hazard maps.. Calculated hazard, including in the included sensitivity calculations, also includes contributions from smoothed seismicity and from uniform background source zones. The seismicity-based component has its own entire, separate logic tree.

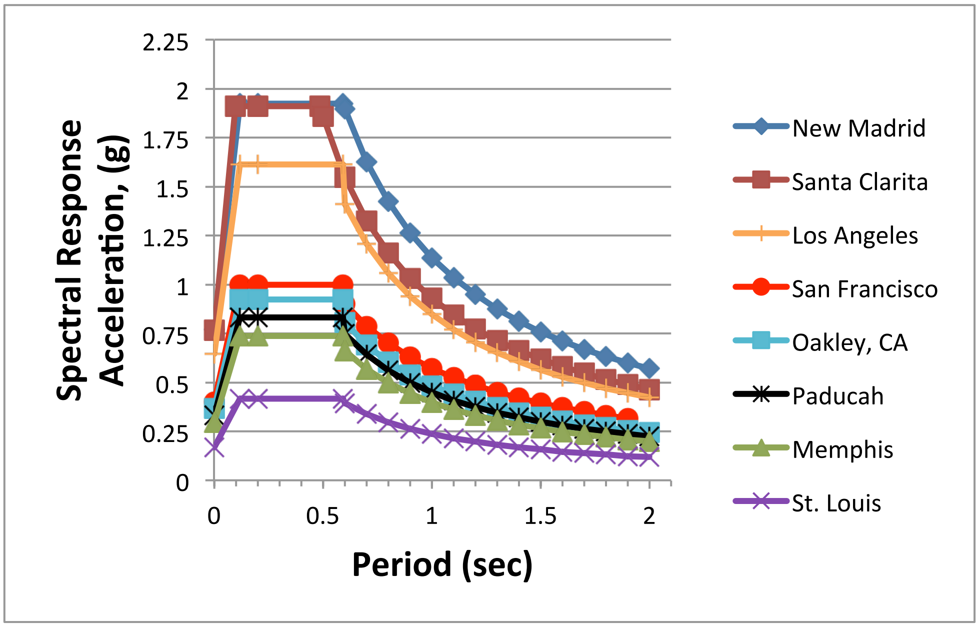
C. Full Set of Sensitivity Calculations

St Louis, MO (38.7°, -90.2°)						
Case*	PGA (%g)		5-Hz SA (%g)		1-Hz SA (%g)	
	10%PE50yrs	2%PE50yrs	10%PE50yrs	2%PE50yrs	10%PE50yrs	2%PE50yrs
2008 Model	7.8	21.6	16.3	43.4	5.0	14.9
1	5.9	16.0	12.4	30.9	3.6	9.8
2	7.0	18.1	14.5	35.2	4.4	11.2
3	6.1	18.9	11.6	33.4	3.4	9.5
4	6.5	19.7	13.6	38.6	3.8	12.3
5	4.6	12.9	9.0	23.0	2.5	5.7
6	2.3	6.1	5.1	13.9	1.7	5.3
Memphis, TN (35.1°, -90.1°)						
Case	PGA (%g)		5-Hz SA (%g)		1-Hz SA (%g)	
	10%PE50yrs	2%PE50yrs	10%PE50yrs	2%PE50yrs	10%PE50yrs	2%PE50yrs
2008 Model	16.3	56.6	31.1	109.3	7.9	32.9
1	12.7	40.0	23.9	74.3	5.9	21.1
2	15.9	48.6	30.4	93.6	7.7	26.4
3	12.5	52.0	20.7	79.3	5.0	19.9
4	11.1	46.5	21.2	88.0	5.0	25.0
5	8.0	29.3	14.5	44.8	3.4	9.9
6	6.2	17.8	13.3	38.1	4.2	14.8
Paducah, KY (37.1°, -88.6°)						
Case	PGA (%g)		5-Hz SA (%g)		1-Hz SA (%g)	
	10%PE50yrs	2%PE50yrs	10%PE50yrs	2%PE50yrs	10%PE50yrs	2%PE50yrs
2008 Model	23.5	74.9	43.6	141.3	10.5	41.0
1	18.3	54.4	33.3	98.6	7.7	26.8
2	22.7	63.5	42.2	117.9	10.4	33.5
3	18.2	66.0	29.1	101.6	6.5	25.0
4	16.9	64.0	30.7	117.0	6.7	33.0
5	13.7	40.7	23.4	62.6	4.9	13.8
6	8.4	22.6	18.2	49.3	5.4	17.6
New Madrid, MO (36.6°, -89.5°)						
Case	PGA (%g)		5-Hz SA (%g)		1-Hz SA (%g)	
	10%PE50yrs	2%PE50yrs	10%PE50yrs	2%PE50yrs	10%PE50yrs	2%PE50yrs
2008 Model	42.1	190.2	71.8	356.6	16.0	118.4
1	35.0	165.2	59.2	294.5	12.7	83.0
2	42.2	176.2	70.3	339.2	15.2	101.2
3	36.6	159.4	47.2	253.4	9.9	69.1
4	19.4	158.3	34.3	289.3	7.1	87.4
5	17.4	96.2	29.7	136.1	6.1	31.2
6	13.5	60.6	30.0	145.4	8.0	49.3

*Descriptions of Cases are listed in Table 1 in the main body of the report.

D. Design Spectra for Selected Cities

The hazard maps for a range of probabilities are used by the engineering community to develop seismic design provisions. The figure below shows the spectra that structures would be designed to resist (as a function of vibration period) under the 2012 IBC, for selected cities. Structures designed to these spectra would have a uniform collapse probability, of the order of 1% in 50 years.



Design Spectra for various cities under 2012 IBC provisions. Provided by USGS.

E. Members of the Independent Expert Panel on New Madrid Seismic Zone Earthquake Hazard

Prof. John Vidale, Chair
Director of the Pacific Northwest Seismic Network, University of Washington; Washington State Seismologist; member, National Earthquake Prediction Evaluation Council.

Earthquakes, Earth structure, numerical simulation, volcanoes, hazard mitigation.

Prof. Gail Atkinson
Professor & Canada Research Chair in Earthquake Hazards and Ground Motions, University of Western Ontario

Seismic hazards; Empirical analysis of earthquake ground motions and study of earthquake ground motions processes; Real-time seismological applications; Ground-motion modeling algorithms

Prof. Russell Green
Department of of Civil and Environmental Engineering, Virginia Tech.

Fundamental and applied research in earthquake engineering: paleoliquefaction analyses; numerical site response analyses; liquefaction evaluation; soil improvement; in-situ characterization of soil properties; dynamic soil-structure-interaction.

Prof. Eric Hetland
Dept. of Geological Sciences, University of Michigan

The mechanics of the earthquake cycle, with focus on strain accumulation on faults and the interpretation of surface deformation near faults; Deformation associated with crustal fluids and volcanic systems; The inference of mechanical properties of the lithosphere from observations; Lithospheric deformation over geologic time scales.

Prof. Lisa Grant Ludwig
Program in Public Health, University of California at Irvine; Associate Director, California Institute for Hazards Research

Natural hazards, earthquake geology, paleoseismology, active faults, San Andreas fault, southern California faults, seismic hazard, environmental health and geology.

Dr. Stéphane Mazzotti
Geological Survey of Canada

Geodynamic study of crustal deformation, earthquake hazards, and tectonic processes in active margins and continental intraplate regions, using geodetic (GPS), seismicity, and other geophysical data.

Dr. Stu Nishenko
Pacific Gas & Electric; member, Scientific Earthquake Studies Advisory Council

Stu: Please provide list of expertise.

Lynn Sykes, Professor Emeritus
Dept. Earth and Environmental Sciences, Lamont-Doherty Earth Observatory, Columbia University

Earthquake Studies, Control of Nuclear Weapons, Tectonics, Natural Hazards.

F. Panel charge

National Earthquake Prediction Evaluation Council (NEPEC) charge to an
Independent Expert Panel on New Madrid Seismic Zone Earthquake Hazard

Although the New Madrid Seismic Zone (NMSZ) lies well within the interior of the North American tectonic plate, hundreds of miles from the nearest plate boundary, it has been the most seismically active area within the Central and Eastern US. In addition to ongoing small- and moderate-magnitude earthquake activity, the NMSZ experienced a three-month sequence of earthquakes during the winter of 1811-1812 that are among the largest on-land earthquakes in US history. The geologic record from the region shows that large earthquakes have occurred before 1811 at least twice within the prior 1,200 years. The U.S. Geological Survey (USGS) National Seismic Hazard Maps, which underlie seismic provisions in the latest model building codes, include a region of elevated shaking hazard surrounding the NMSZ. Due to the low seismic attenuation of the mid-continent, even moderate-magnitude earthquakes will cause strong shaking and damage over a much broader area than similar earthquakes striking the plate-boundary regions of the Western US.

Despite these facts, there are substantial uncertainties regarding the size, location and frequency of both past and future earthquakes in the region, and regarding the underlying causes of earthquakes in this intraplate setting. Consequently, there has been debate in scientific and engineering circles on the level of earthquake hazard in the NMSZ.

The upcoming bicentennial of the New Madrid earthquakes will focus attention on the seismic hazards of the region and will provide a unique opportunity to raise public awareness of earthquake hazards and appropriate preparedness activities. At the same time, it brings increased scrutiny of the USGS statutory responsibility to characterize the seismic hazard of the US as it undertakes revision of the National Seismic Hazard Maps beginning in late 2011. For that reason, NEPEC is exercising its responsibility to advise the USGS Director on issues bearing on earthquake forecasting by convening a panel of independent experts to comment on the level of hazard posed by future large earthquakes in the NMSZ. Topics of particular interest include paleoseismologic records of prior large earthquakes in the central US, main-shock magnitudes of the 1811-12 sequence, the nature and implications of ongoing seismicity in the NMSZ, and implications of geodetic observations. Comment is also invited on priorities for future research to better constrain the hazard in light of major sources of uncertainty.

The panel is asked to transmit its written report to NEPEC by April 4, 2011.

G. Panel meetings and briefings:

The panel met by conference call on the following dates:
February 4, February 14, February 22, March 8, and March 28, 2011.
The panel held a two-day meeting in Memphis, Tennessee on March 14 & 15, 2011, at which they received briefings from, and held discussions with, a number of technical experts and representatives of the user community, as listed in the agenda that follows.
In addition to those listed in the meeting agenda, the panel earlier conducted phone interviews with the following: James Cobb, Kentucky State Geologist; and Nathan Gould, structural engineer with ABS Consulting, St. Louis, MO.

H. Written comments received:

NEPEC chair Dr. Terry Tullis invited the scientific community and general public to submit written comments by email for consideration by the panel. 42 letters were received from those listed below. Some comments were accompanied by detailed analysis, reports, abstracts and/or lists of suggested papers. The panel appreciates the many useful viewpoints and suggestions submitted--which added greatly to the panel's knowledge and to their appreciation of the range of perspectives that exist--and the time taken by those who wrote.

John Anderson	University of Nevada Reno
Ron Belz	Belz Enterprises
Antonio Bologna	Bologna Consultants, LLC
Thierry Camelbeeck	Royal Observatory of Belgium
Clem Chase	University of Arizona
Wang-Ping Chen	University of Illinois
Chris Cramer	CERI, University of Memphis
Jay Crandell	ARES Consulting
Chuck DeMets	University of Wisconsin Madison
Tim Dixon	University of South Florida
Kazuya Fujita	Michigan State University
Zvi Garfunkel	Hebrew University of Jerusalem
John W. Geissman	University of New Mexico
Robert Geller	Earthquake Research Inst., Tokyo Univ.
Don Glays	Memphis Area Home Builders Assn.
Stephen Harmsen	USGS, Golden, Colorado
Rich Harrison	USGS, Reston, Virginia
Todd Hendricks	KY Dept. for Environmental Protection
David Hindle	Friedrich-Schiller-Universität Jena, Germany
John Holbrook	U. Texas Arlington & Steve Marshak; U. Illinois Urbana
Scott King	Virginia Tech
Mian Liu	University of Missouri Columbia
Mark Leonard & Dan Clark	Australia
Cinna Lomnitz	Universidad Nacional Autónoma de México
Dexter Muller	Greater Memphis Chamber
Stephen Obermeier	EqLiq Consultants, Rockport, IN
A. Peresan	U. Trieste, Italy (w/ V. Kossobokov & G. Panza)
James Ni	New Mexico State University
Nicholas Pinter	Southern Illinois Univ. Carbondale
Ben A. van der Pluijm	University of Michigan
Paul Rydelek	Earthquake Research Inst., Tokyo Univ.
Gary Searer et al.	Wiss, Janney, Elstner Assoc., Inc., Burbank
Bruce Shaw	Lamont Doherty Earth Observatory
Zhonghao Shou	Earthquake Prediction Center, New York
Richard Stelitz	Lawrence Livermore National Lab
John Tinsley	USGS, Menlo Park

Joe Tomasello	The Reeves Firm
Kelin Wang	Natural Resources Canada
Shimon Wdowinski	University of Miami
John Weber	Green Valley State University
Russ Wheeler	USGS, Golden, Colorado
David Yuen	University of Minnesota
Zhenming Wang	Kentucky Geological Survey

I. Agenda of the panel's meeting in Memphis:

Independent Expert Panel on NMSZ Earthquake Hazard
Monday & Tuesday, March 14 & 15, 2011
FedEx Institute of Technology, 365 Innovation Drive, Memphis, TN 28152

Monday, March 14:

8:00	Continental breakfast; initial discussions; report from GPS workshop
9:00	Roy Van Arsdale, University of Memphis
10:00	*Break*
10:15	Art Frankel, USGS, Seattle & Nico Luco, USGS, Golden (with Mark Petersen, USGS, Golden (by phone)
11:45	Rick Howe, PE, Memphis, TN (by phone)
12:30	*Lunch*
1:15	Sue Hough, USGS, Pasadena
2:15	Bill Bakun, USGS, Menlo Park (by phone)
2:45	*Break*
3:00	Seth Stein, Northwestern University and Joe Tomasello, PE, The Reeves Firm, Memphis, TN
4:30	Eugene (Buddy) Schweig, USGS, Denver
5:30	Discussion; set Tuesday agenda; Adjourn

Tuesday, March 15:

8:00–12:00 Closed session for discussion, follow-ups and drafting the panel report

Meeting Organizers:

Joyce Costello, USGS, Reston, 703-648-6715, jcostell@usgs.gov
Michael Blanpied, USGS, Reston, 703-851-3011, mblanpied@usgs.gov

J. Bibliography:

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The panel was also provided with letters between James Cobb and Zhen-ming Wang of the Kentucky Geological Survey, and Mark Petersen of the USGS, from 2007 & 2008.