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Methods of Mmax Estimation East of the Rocky Mountains

By Russell L. Wheeler

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Conversion Factor

SI to Inch/Pound

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	mile (mi)

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Abstract

Several methods have been used to estimate the magnitude of the largest possible earthquake (Mmax) in parts of the Central and Eastern United States and adjacent Canada (CEUSAC). Each method has pros and cons. The largest observed earthquake in a specified area provides an unarguable lower bound on Mmax in the area. Beyond that, all methods are undermined by the enigmatic nature of geologic controls on the propagation of large CEUSAC ruptures. Short historical-seismicity records decrease the defensibility of several methods that are based on characteristics of small areas in most of CEUSAC. Methods that use global tectonic analogs of CEUSAC encounter uncertainties in understanding what "analog" means. Five of the methods produce results that are inconsistent with paleoseismic findings from CEUSAC seismic zones or individual active faults.

Introduction

Maximum Magnitude and Hazard Maps

Mmax is the magnitude M of the largest earthquake thought to be possible within a specified area, or source zone. For clarity, hereafter Mmax and M will refer to moment magnitude, whereas $m$max and m will denote magnitudes generally. Probabilistic seismic-hazard assessment (PSHA) requires an estimate of $m$max for each source zone to avoid the inclusion of unrealistically large earthquakes. The original formulation of PSHA did not include $m$max because magnitude was assumed to follow an unlimited exponential distribution (Cornell, 1968). However, Cornell noted that $m$max earthquakes were too rare to verify this or any other distribution, and that magnitude might be bounded instead (p. 1602). Chinnery (1979) summarized physical arguments that magnitude must be bounded, perhaps with different $m$max values in different regions of the Earth.

Cornell and Vanmarcke (1969) and Cornell (1971) modified the 1968 formulation to include an upper bound m_l on the magnitude distribution. Algermissen and Perkins (1972) recast Cornell's 1971 results to make a seismic-hazard map that included source zones. Each source zone had its own value of $m$max, which was obtained by converting the largest intensity observed in the zone to magnitude. As far as I know, the first application of $m$max and hazard mapping to the Central and Eastern United States and adjacent Canada (CEUSAC: east of the Rocky Mountains) was the map of Algermissen and Perkins (1976).

Stable Continental Regions and Sparse Seismicity

Johnston and others (1994) coined the term stable continental regions (SCRs) for North America east of the Rocky Mountains and its global tectonic analogs (fig. 1). Johnston and others compiled an SCR catalog of earthquakes having M at least 5.0. The catalog includes the seismological properties of

each earthquake and charateristics of its tectonic settings. The North American SCR consists of the region east of the Rocky Mountains, and approximately the southern half of the SCR is CEUSAC.

Seismicity is sparse and recurrence intervals are long in most of the North American SCR, including CEUSAC. CEUSAC earthquakes of approximately M 7.0 or larger are known historically only from the New Madrid seismic zone in 1811–1812 (Nuttli, 1973a; Johnston, 1996c; Hough and others, 2000; Bakun and Hopper, 2004), the Charleston, South Carolina, seismic zone in 1886 (Bollinger, 1977; Johnston, 1996c; Bakun and Hopper, 2004), the Charlevoix, Quebec, seismic zone in 1663 (Basham and others, 1979; Ebel, 1996), and the Grand Banks area in 1929 (Bent, 1995). Paleoliquefaction studies have yielded chronologies of large prehistoric earthquakes only in the New Madrid, Charleston, and Wabash Valley seismic zones (Munson and others, 1997; Obermeier, 1998; McNulty and Obermeier, 1999; Tuttle and others, 1999, 2002, 2005; Talwani and Schaeffer, 2001). Less complete chronologies are available for two locales in eastern Arkansas (Tuttle and others, 2006; Cox and others, 2007). Additionally, the humid climates of the more populous eastern half of the North American SCR foster rapid erosion and forests, which together would tend to mask the surface ruptures of large prehistoric earthquakes. Indeed, the only known surface ruptures in the SCR occurred prehistorically on the Cheraw fault in sparsely vegetated eastern Colorado (Crone and others, 1997) and the Meers fault in southwestern Oklahoma (Madole, 1988; Crone and Luza, 1990), and in 1989 on an unnamed fault in northern Quebec (Adams and others, 1991a, 1991b, 1992). In 1812 a fourth earthquake warped the ground surface on the Reelfoot fault in the New Madrid seismic zone, but fault strands did not rupture the surface (Kelson and others, 1996).

Consequently, historical earthquakes that are large enough for their magnitudes to be strong candidates for $m$max are rare in CEUSAC. Elsewhere, CEUSAC Mmax must be estimated indirectly. The forced reliance on indirect methods results in differing estimates of Mmax, as described later in "Assessments Using Multiple Methods". The differences increase uncertainty in PSHA. The uncertainty can have a substantial impact on CEUSAC hazard (C.S. Mueller, U.S. Geological Survey, written commun., August 22, 2008). Because most Mmax earthquakes in CEUSAC have long recurrence intervals, differing estimates of Mmax have their largest effects at the low annual probabilities that are of particular interest for nuclear powerplants and other critical facilities. The uncertainty in PSHA increases design and construction costs of these large critical structures. Accordingly, it is desirable to identify the indirect methods that may be the most likely to be valid.

Purposes

This paper has three purposes that are pursued in later sections. (1) "Assessments Using Multiple Methods" is a compilation of the indirect methods or groups of methods of estimating Mmax in CEUSAC. (2) "Pros and Cons of Individual Methods" summarizes the evidence or arguments for and against each method. The compilation and summary can provide a common starting point for further discussion. For example, a draft of this report was distributed to invitees of the workshop on Mmax that is mentioned in the Acknowledgments. (3) "Observations" extracts conclusions from the previous sections to aid in assessing the modern-day utility of the various methods. Although the motivation for the assessments is the needs of seismic-hazard computations in CEUSAC, the assessments apply to other SCRs worldwide and to northern Canada.

Assessments Using Multiple Methods

Overview

Most of the literature on $m$max estimation in CEUSAC was reviewed and used in three large hazard assessments that were performed by the Lawrence Livermore National Laboratory (LLNL), contractors for the Electric Power Research Institute–Seismicity Owners Group (EPRI–SOG), and the U.S. Geological Survey (USGS). The LLNL and USGS assessments have gone through several iterations to incorporate new information and improved methodology. The USGS reviewed the EPRI–SOG report (Appendix B of Risk Engineering Inc. and others, 1988). The Senior Seismic Hazard Analysis Committee (SSHAC) evaluated the expert-elicitation procedures that were used by LLNL and EPRI–SOG (Budnitz and others, 1997), and the SSHAC report itself was reviewed by the National Research Council (Panel on Seismic Hazard Evaluation, 1997).

The LLNL, EPRI–SOG, and USGS hazard assessments used various combinations of eight methods to estimate $m$max within individual source zones (tables 1–3). Five of the methods are seismological and three are geological. Most of the seismological methods use some aspect of the historical and instrumental record of seismicity of a source zone. The geological methods focus on source zones having distinctive geological, structural, or geophysical properties that distinguish them from adjacent zones. The distinctive properties are assumed to control $m$max. The geographic extent of the properties is taken to define the source zone. For example, the features might be large igneous bodies, continental rifts, structural divisions of the Appalachian or Ouachita Mountains, or areas having faults of a particular style and age. Tables 1–3 list all eight methods for ease of comparison, even though the LLNL and USGS assessments did not use all the methods.

Lawrence Livermore National Laboratory Project 1983–1993

The Nuclear Regulatory Commission funded LLNL to use written questionnaires to elicit estimates of seismological and seismotectonic variables from individual experts in seismology, geology, and ground-motion attenuation relations. Each seismology or geology expert divided CEUSAC into source zones and estimated values of several variables for each zone, including the m_b equivalent of Mmax. For example, figure 2 shows one expert's choice of source zones. LLNL used the responses to calculate hazard curves for 69 CEUSAC sites.

The LLNL methodology went through three iterations from 1983 through 1993 (Bernreuter and others, 1984; 1985a, b; 1989a, b; Savy and others, 1986a, b; 1993). Appendix A of Bernreuter and others (1989b) contains each expert's written descriptions of how he estimated the elicited values, and Appendix B contains the values themselves. The estimated uncertainty of each $m$max value is represented by a probability distribution.

Table 1 summarizes the descriptions of how each expert estimated $m$max. The number of different methods used by a single expert varied from one to four. The most widely used estimation method was to set $m$max equal to the largest observed earthquake within each source zone. The only other method that was used by more than half of the eight experts was inference of $m$max from the local seismicity rate. Three of the experts considered a source zone's geologic analogs elsewhere in North America or the world.

Electric Power Research Institute Project 1983–1986

The Electric Power Research Institute–Seismicity Owners Group (EPRI–SOG) funded the development of a more elaborate elicitation process than that used by LLNL (Risk Engineering Inc. and others, 1988). The EPRI–SOG project assembled six teams of four to nine seismologists, geologists, and related specialists per team. Each team produced a map of CEUSAC source zones and alternatives and estimated values of several seismological variables for each source zone, including the m_b equivalent of Mmax. For example, figure 3 shows one team's choice of source zones. The estimated uncertainty of each value is represented by a probability distribution. The 11-volume report includes one volume from each team, in which their methods and results are summarized (Bechtel Group Inc., 1986; Dames & Moore, 1986; Law Engineering Testing Company, 1986; Rondout Associates Inc., 1986; Weston Geophysical Corporation, 1986; Woodward-Clyde Consultants, 1986). EPRI-SOG used the responses to compute hazard curves for CEUSAC sites.

Table 2 summarizes the written descriptions of how each team estimated $m$max. The number of different methods used by any single team varied from two to five, with four of the teams each using four to five methods. The most widely used method was to estimate $m$max from seismicity rate. Only two other methods were used by more than half of the six teams. The first of these was to set $m$max equal to the magnitude of the largest historical earthquake within a source zone. The second was to estimate $m$max from consideration of the geologic features of the zone. Three of the teams considered a source zone's geologic analogs elsewhere in North America or the world.

U.S. Geological Survey National Seismic-Hazard Maps 1976–2008

The USGS produced probabilistic national seismic-hazard maps in 1976, 1982, 1990, 1996, 2002, and 2008, spanning a third of a century. Methods used to estimate $m$max changed over that time. The 1976–1990 maps estimated Mmax, or its m_b or M_S equivalent, by methods similar to those used in the LLNL and EPRI–SOG studies. The 1976 maps estimated $m$max as the magnitude of the largest observed earthquake in each source zone (Algermissen and Perkins, 1976). In preparation for the 1982 maps, a PSHA of the Southeast assigned the entire map area an $m$max of M_S 7.6 to match the magnitude of the 1886 Charleston, South Carolina, earthquake, in "light of the poor knowledge about source sizes, stress drops, and causative structures" (Perkins and others, 1979, p. 13). In 1980, source zones and their $m$max values were discussed at two workshops on the Central and Northeastern United States (Thenhaus, 1983). Large historical earthquakes were taken to define $m$max at the New Madrid, Charleston, and Charlevoix, Quebec, source zones. Three other source zones in the Central United States were assigned $m$max by magnitude-frequency extrapolations of their historical seismicity to the earthquakes in each zone that would have a specified recurrence interval; two of the zones used 1,000 years and the third used 2,000 years (Thenhaus, 1983). Other zones appear to have been assigned $m$max values according to their seismicity rates and the occurrence of moderate earthquakes in some zones. Eventually the 1982 maps used five values of $m$max: M_S 8.5 only in the New Madrid seismic zone, M_S 7.9 along and near the St. Lawrence and Ottawa Rivers of southeastern Canada, M_S 7.3 along the Appalachian Mountains and Coastal Plain from southern New England to Alabama and Florida, M_L 6.7 in northern New England and along Lakes Erie and Ontario, and M_L 6.1 elsewhere between the Appalachian and Rocky Mountains (Algermissen and others, 1982). The values were assigned according to the magnitude of the largest historical earthquake in the more active zones, the local tectonic setting, and opinions expressed at the two workshops in 1980 (Algermissen and others, 1982). The 1990 maps used the same source model as the 1982 maps.

Subsequent national maps have used a different methodology. An integral part of the post-1990 methodology is more-extensive discussions among regional and topical experts at regional workshops (Frankel and others, 1996, 2002; Wheeler and Perkins, 2000; Petersen and others, 2008). The 1996, 2002, and 2008 maps used global analogs to identify Mmax values and the tectonic settings to which they apply worldwide (Johnston, 1994). Each Mmax value was then applied to the same tectonic settings in North America (Wheeler, 1995; Frankel and others, 1996, 2002; Wheeler and Frankel, 2000; Wheeler and Cramer, 2002; Petersen and others, 2008). Most of the tectonic settings that make up the CEUS are larger than typical LLNL or EPRI–SOG source zones. The result was fewer source zones than those of the LLNL experts or the EPRI–SOG teams (fig. 4; cf. figs. 2 and 3). The largest historical CEUS earthquakes were used to set Mmax only in the New Madrid and Charleston seismic zones, where earthquakes of M7.0 and larger occurred historically and repeatedly prehistorically (Talwani and Schaeffer, 2001; Tuttle and others, 2002, 2005).

Table 3 shows the estimation methods that were used in the cited publications. Each publication used one to four of the eight methods. The only method used in all of the publications is to set $m$max at the largest observed magnitude at New Madrid, Charleston, and Charlevoix, where large earthquakes have occurred historically. The only other method that was used in more than half of the publications is seismicity rate. The 1996 and subsequent maps used Mmax estimated mainly from global tectonic analogs.

Comparison of Mmax Estimates

Table 4 lists the Mmax values that the LLNL experts, EPRI–SOG teams, and USGS hazard-map authors selected for eight CEUSAC cities. The cities were chosen to represent various levels of seismicity and tectonic settings. Figure 5 shows the cities and CEUSAC seismicity. Cities were selected in the New Madrid, Charleston, and Charlevoix seismic zones because the zones are the most seismically active in CEUSAC and have had the largest onshore historical earthquakes.

Minneapolis and Anna are in the craton source zone of Wheeler and Frankel (2000) and the 1996–2008 national seismic-hazard maps (figs. 4, 5). The Anna seismic zone has elevated seismicity compared to most of the rest of the craton. Minneapolis is in one of the largest sparsely seismic parts of the craton. The six other cities are in the extended-margin source zone of Phanerozoic contractional and extensional terranes that rim the craton (fig. 4). The New Madrid and Charleston seismic zones, New York City, and Houston are in the part of the extended margin that forms the Mesozoic passive margin and associated rifts, with their abundant Mesozoic normal faults. The Charlevoix seismic zone and Knoxville are in the part of the extended margin that is made of the Cambrian passive margin and associated rifts, which have abundant Cambrian normal faults and higher seismicity than most of the craton.

LLNL did not specify their magnitude scale. EPRI–SOG referred to their magnitudes as m_b. I have assumed that both assessments used m_{bLg} or an equivalent. That magnitude has been the standard in most of CEUSAC since Nuttli (1973b) defined it. The assumption allowed straightforward conversion of the original m_b, M_S, and M_L values that had been used for $m$max into the moment magnitudes that are listed in table 4. Conversions were made by the regression relations of Johnston (1996a). Several of the LLNL experts estimated maximum m_b values well above the level at which the m_b scale saturates (Utsu, 2002), and Algermissen and others (1982) did the same for maximum M_S of the New Madrid seismic zone. These values convert to maximum M estimates that seem unrealistically high. The largest M values that have been calculated directly from SCR data are those that Johnston (1996c) published for the New Madrid seismic zone. He obtained M 8.1 ± 0.31 for the December 16, 1811, main shock. Accordingly, table 4 does not show any converted M values larger than 8.4.

The last three rows of table 4 summarize the preceding rows. Most of the 22 experts, teams, and sets of map authors chose the largest $m$max values for the three cities that are within source zones that are the most seismically active, and which have had historical earthquakes of about M 7.0 or larger. These are the New Madrid, Charleston, and Charlevoix source zones. The ranges of the central halves of the estimates are smallest for New Madrid, Charleston, and Charlevoix, 0.5 units, perhaps indicating that most of the experts, teams, and authors agreed in considering the large historical earthquakes to be approximately $m$max. The ranges of the central halves of the estimates are larger for the other five cities, which are in less active seismic zones that lack large historical earthquakes.

Pros and Cons of Individual Methods

The experts, teams, and authors cited in tables 1–3 explained which methods they used to estimate $m$max, and some of them provided general explanations of how they implemented the methods. However, except for the 1996–2008 USGS national maps, I found little discussion of why we should expect a particular method to give valid estimates of $m$max. The first eight of the following subsections provide such discussions for the methods used by LLNL, EPRI–SOG, and USGS.

In addition, Cornell (1994) and Coppersmith (1994) described an application of Bayesian analysis to $m$max. It postdates the LLNL and EPRI–SOG assessments and has not been used by the USGS either. Chinnery (1979) and Coppersmith and others (1987b) reviewed three other methods and groups of methods that were also not used in the LLNL, EPRI–SOG, or USGS assessments. Jin and Aki (1988) proposed a fourth. The five additional methods are examined in the last five subsections. Table 5 summarizes the more detailed discussions in all of the subsections.

Paleoseismic results at three seismic zones and two faults in CEUSAC allow estimation of Mmax for these zones and faults. The results were too sparse before the middle 1980s to allow Mmax estimation; the first were published by Russ (1979) and Obermeier and others (1985). By mid-2008 sufficient results had accumulated to allow testing of several of the methods that are discussed in this section. The discussions will draw on the following five summaries of paleoseismic results.

The largest historical earthquakes in the New Madrid seismic zone of southeastern Missouri and adjacent States were the three main shocks of December 16, 1811, January 23, 1812, and February 7, 1812 (Nuttli, 1973a). In chronological order of earthquakes, estimates of their sizes are M 8.1, M 7.8, and M 8.0 (Johnston, 1996c); M 7.2–7.3, M 7.0, and M 7.4–7.5 (Hough and others, 2000); and M 7.6, M 7.5, and M 7.8 (Bakun and Hopper, 2004). Prehistoric earthquakes or earthquake sequences produced liquefaction features as large and as widespread as those of 1811–1812 at least three times at intervals of 400–600 years (Tuttle and others, 2002, 2005). The repeating earthquakes of similar sizes have been interpreted as characteristic. The interpretation can be used to infer that a significantly larger earthquake is unlikely in the seismic zone. If this inference is valid, then Mmax for the seismic zone may have been observed historically.

The Charleston, South Carolina, seismic zone generated its largest historical earthquake in 1886. Bollinger (1977) estimated its magnitude as m_b 6.8, which equates to M 7.0; Bollinger's m_b was the m_{Lg} of Johnston (1996a). Johnston (1996c) and Bakun and Hopper (2004) obtained M 7.3 and M 6.9, respectively. Prehistoric earthquakes produced liquefaction features as large and widespread as those of 1886 at intervals of 400–500 years (Talwani and Schaeffer, 2001). The same reasoning as used for the New Madrid seismic zone suggests that the 1886 shock represents Mmax for the Charleston zone.

The Wabash Valley seismic zone of Illinois and Indiana has had at least eight prehistoric earthquakes with magnitudes estimated as M 6.0 or larger in the last 12 k.y. (thousand years) (Munson and others, 1997; Obermeier, 1998; McNulty and Obermeier, 1999; Tuttle and others, 1999). The largest were approximately M 7.1 at 12 ka (thousand years ago) and M 7.5 at 6.1 ka (Obermeier, 1998).

Accordingly, Mmax for the zone has been taken to be M 7.5 (Wheeler and Frankel, 2000; Wheeler and Cramer, 2002).

The Cheraw normal fault in Colorado has a scarp 45 km long (Crone and others, 1997). If the entire fault broke at once, the scarp length indicates that the resulting earthquake would be of M 7.0 ± 0.34 (Wells and Coppersmith, 1994). Because the earthquake would have broken the entire known length of the fault, it would be a reasonable candidate for Mmax of the fault. The standard deviation of the calculated magnitude is the computational uncertainty of the regression equation and does not include geologic uncertainties in scarp length. Additionally, slip is uncertain and rupture width is unknown. Prehistoric surface ruptures occurred on the fault at 8 ka, 12 ka and 20–25 ka. The dates define recurrence intervals of at least 8 k.y., 4 k.y., and 8–13 k.y.

The southeastern section of the strike-slip Meers fault of Oklahoma has a scarp 35 km long (Madole, 1988; Crone and Luza, 1990). Two surface ruptures have been recognized at several locations along the section (Crone and Luza, 1990; Kelson and Swan, 1990), which could indicate that both earthquakes ruptured the entire section. If that happened, the shocks could represent Mmax for the section and they would be of M 6.9 ± 0.28 (Wells and Coppersmith, 1994). As for the Cheraw fault, the standard deviation does not include geologic and other uncertainties. The surface ruptures occurred at 1.1–1.3 ka and 2.0–2.9 ka (Crone and Luza, 1990; Kelson and Swan, 1990). The dates define recurrence intervals of at least 1.1–1.3 k.y. and 0.7–1.8 k.y.

Mmax equals Largest Observed M in a Source Zone (Mobs)

Pro:
This method has an intuitive appeal because it is simple and can be applied anywhere. It provides an indisputable lower bound on Mmax.

Con:
Probability calculations imply that probably most parts of CEUSAC have not had their Mmax earthquakes during historical time (Coppersmith, 1994). Mobs is most likely to approximate Mmax if the historical record is long compared to the recurrence interval of Mmax, or if the seismicity rate is high enough that Mobs is close to Mmax. Neither condition can be shown to be valid without knowing Mmax beforehand. In fact, likelihood functions and numerical simulations show that the CEUSAC historical record is too short for Mobs to provide a useful constraint on Mmax (McGuire, 1977; Bender, 1988). Mobs has a higher probability than any single larger M of being the true Mmax, but this higher probability may still be low and will generally be lower than the total probability of all M larger than Mobs (McGuire, 1977). For instance, the two likelihood functions that are graphed by Coppersmith (1994, figs. 6–2, 6–4) have at least 98 percent of the areas under their graphs above Mobs, indicating a probability of at least 0.98 that Mmax exceeds Mobs. At best, Mobs provides a lower bound on Mmax. Additionally, each occurrence of a CEUSAC earthquake larger than its local Mobs would increase Mmax and, therefore, the computed hazard (Yeats and others, 1997, p. 456–457). The increase of Mobs and hazard with time is more likely for small Mobs than for large Mobs.

A magnitude-frequency analysis of the Eastern Tennessee seismic zone illustrates the effect of short CEUSAC historical records on Mobs. On the basis of moment-release rate per unit of upper-crustal volume, the zone has a seismicity level second only to that of the New Madrid seismic zone east of the Rocky Mountains (Powell and others, 1994). However, the largest historical earthquake in the zone was M 4.6 in 2003 (*http://www.eas.slu.edu/Earthquake_Center/MECH.NA/20030429085937*, accessed December 5, 2008). Chapman (2002) estimated that the zone's catalog is complete down to m_{bLg} 5.0 back to 1870. If Mobs provides a useful estimate of Mmax, then the historical record of eastern

Tennessee may be more likely to show a statistically significant absence of earthquakes of m_{bLg} 5.0 and larger than would the record of any similar-sized part of CEUSAC except the New Madrid seismic zone. Chapman calculated that the Eastern Tennessee catalog would have to be complete down to m_{bLg} 5.0 back to 1693, and would have to contain no earthquakes larger than m_{bLg} 5.0, to achieve 0.90 significance that larger earthquakes cannot occur in the Eastern Tennessee seismic zone. Chapman's calculations were done in 1996 (Savy and others, 2002). The year 1693 was 2.4 times as far before 1996 as 1870 was. Thus, even the historical record of the Eastern Tennessee seismic zone appears to be too short by a factor of 2.4 for us to be surprised if an m_{bLg} 5.0 or larger earthquake occurred there tomorrow. Extending the record to the end of 2007 decreases the factor only to 2.3. The factor will be still larger for other less seismically active parts of CEUSAC.

The Mobs method does poorly when compared to the five areas in CEUSAC in which paleoseismic studies have documented chronologies of large historical and prehistoric earthquakes (see summary at the start of "Pros and Cons of Individual Methods"). In the New Madrid and Charleston seismic zones, Mobs is large enough and is similar enough to the sizes of repeating prehistoric earthquakes that it may be a reasonable estimate of Mmax. However, the Wabash Valley seismic zone has Mobs 5.4 (Johnston, 1996a), yet the paleoseismic record contains eight earthquakes of approximately M 6.0–7.5. The Cheraw fault has an estimated Mmax of M 7, but the largest historical earthquake within 50 km had a maximum intensity of IV (M 3.8, Johnston [1996b]) in 1955 (*http://www.neic.cr.usgs.gov*, accessed December 5, 2008). The southeastern section of the Meers fault has an estimated Mmax of M 6.9, but the largest historical earthquake within 50 km was m_{bLg} 4.2 (M 3.8, [Johnson, 1996a]) in 1998 (*http://www.neic.cr.usgs.gov*, accessed December 8, 2008). Thus, in three of the five CEUSAC areas with paleoearthquake chronologies, Mmax is known to exceed Mobs by roughly 2.1 to 3.2 units.

Mmax equals Mobs plus an Increment

Pro:
This method is appealing because, like that using only Mobs, it is simple and can be applied anywhere. The simplicity is most apparent in a region with many small source zones, each having its own Mobs. A handful of different increments, each applied to several source zones, can produce Mmax estimates that are tailored to each zone's Mobs and are large enough to provide some protection against earthquakes larger than Mobs. For example, LLNL expert 5 used an increment of 1.0 throughout CEUSAC, and then adjusted it in an unspecified manner according to each zone's geological and geophysical properties (Bernreuter and others, 1989b, Appendix B). Expert 7 used increments of 1.0, 0.75, or 0.5, respectively, for increasingly larger Mobs. One EPRI–SOG team used two increments per source zone, 0.3 and 0.6, with equal weights (Bechtel Group Inc., 1986). Another team used the same four-point distribution for all source zones (Woodward-Clyde Consultants, 1986). The distribution extended upward from Mobs and it peaked at an increment of 0.5 unit above Mobs.

Con:
For most of CEUSAC where Mobs is small, an increment larger than 0.5–1.0 magnitude unit may be required to provide adequate protection against the occurrence of an earthquake significantly larger than any known historically. Risk Engineering Inc. and others (1988) and Budnitz and others (1997) pointed out that the increment method can be thought of as the Mobs method applied to a longer historical record. They observed that for b equal to –0.9 to –1.0, which are common values in CEUSAC, using an increment of 0.5 would be equivalent to extending the historical record by a factor of 2.8–3.2; an increment of 1.0 would imply a record extended by a factor of 7.9–10.0. If the latter factor were

applied to the historical record of CEUSAC, the result would be roughly the length of the Japanese, Middle Eastern, and Chinese historical records (Allen, 1975). Therefore, it does not appear that an increment large enough to be useful could be tested by comparison to the short CEUSAC historical record.

Computational experiments argue strongly that the increment varies significantly from source zone to source zone (Risk Engineering Inc. and others, 1988, Appendix B, p. 42). Additionally, and as described next, recent paleoseismic findings in five parts of CEUSAC imply that increments vary so much within CEUSAC as to undercut severely the defensibility of the increment method.

Paleoseismic evidence summarized at the start of this section indicates that increments appear to be approximately zero in the two highest-hazard parts of CEUSAC, the New Madrid and Charleston seismic zones. The summary explains why, in each zone, large Mobs may be a reasonable estimate of Mmax. In contrast, paleoseismic evidence from the Wabash Valley seismic zone and the Meers and Cheraw faults points toward much larger increments that differ among themselves. As noted at the end of the earlier subsection on Mobs, increments for these three features are 2.1, 2.7, and 3.2 magnitude units, respectively.

Mmax from Seismicity Rate

The seismicity-rate method consists of qualitatively estimating Mmax from the observed frequency of small earthquakes within a specified area, with higher frequency taken to imply larger Mmax. Some consistency between source zones has been introduced in some hazard assessments by one or more of (1) allowing only a few values of Mmax, from which each source zone must be assigned only one value; (2) specifying the minimum magnitude of the small earthquakes whose frequency is counted; and (3) defining "frequency" as the a-value of a magnitude-frequency line that is fit to the small earthquakes.

Pro:

In favor of the seismicity-rate method is that the larger the moment-release rate in a region, the faster earthquakes of any size are likely to recur, and the more frequently large ruptures should occur. In general, we would expect that the more seismically active faults will have higher slip rates, and that they will mature faster: they are likely to break through asperities, smooth geometric and strength irregularities, and link together (Cowie and others, 2005). We would expect that more mature faults will allow longer, wider ruptures and larger slips, thereby allowing larger moment-magnitude earthquakes.

Con:

This is a valid qualitative description of why we would expect the largest earthquakes in plate boundaries, where the moment-release rate is large and varies greatly. The description may be less valid or less useful in SCR, where moment-release rates are small and so is their range. For example, it is unclear whether the rate at which SCR faults mature exceeds the rate at which fluid flowing through the faults can foster mineral crystallization and recrystallization that could seal and heal the faults (Gratier and Gueydan, 2005; Person, 2005; Tullis, 2005; Yardley and Baumgartner, 2005). Absent a better understanding of rates of fault healing and of their effect on fault strength it is not clear why the seismicity rate should bear any systematic relationship to Mmax in SCRs. Coppersmith (1994) made a similar point about strain rate and Mmax, and fault slip-rate and Mmax. Specifically, Coppersmith (p. 6–6) noted "the lack of a physical basis for linking the *rate* at which crust deforms (or a fault slips) with the *maximum* coseismic slip that may occur in that crustal volume (or along the fault)." Cornell (1994)

compared Mobs of the tectonic subdivisions of SCRs worldwide to their rates of earthquakes with M at least 5, and found no evidence of a relation between the two.

Additionally, at least some SCR earthquakes occur in the middle or lower crust. Their magnitudes may be unrelated to the observed frequencies of earthquakes in the upper crust. For example, three instrumental CEUSAC earthquakes of M 5–6 occurred at midcrustal depths of 20–30 km (Wheeler and Johnston, 1992 and references cited there). For another example, Lin (2008) used textural and petrologic relations to infer that pseudotachylites in central Australia formed under lower-crustal granulite-facies conditions. Lin concluded that seismic ruptures had nucleated above the brittle-ductile transition and propagated downward through it. For a third example, Lund and others (2004) reported pseudotachylites and brittle faults that formed at depths of 60–70 km in lower continental crust, which is now exposed in coastal Norway of the Eurasian SCR (Broadbent and Allan Cartography, 1994). Textural and petrologic data indicate that the faulted rocks had remained brittle for tens of millions of years or longer because of their exceptionally low volatile contents. The interpretations of Lund and others suggest that persistently brittle lower-crustal masses might be large enough to contain the rupture zone of an SCR earthquake of M 7–7.5 (Wells and Coppersmith, 1994; Somerville and others, 2001).

Finally, as summarized at the start of this section, at each of three CEUSAC areas and two CEUSAC faults, the historical and prehistoric records contain two or more earthquakes of approximately M 7.0 or larger whose sizes approximate Mmax. Figure 6 shows graphs of seismicity rates against these Mmax estimates.

Rates were determined from the USGS Preliminary Determination of Epicenters (PDE) catalog, because it is entirely instrumental, and it may be presumed to be fairly complete and of uniform quality for the five features having Mmax estimates and their surroundings. The PDE has these advantages because it began in 1973. If CEUSAC seismicity is cyclic over centuries or many decades near any of the five features, rates derived from the PDE could depart from long-term average rates. However, catalogs much longer than that of the PDE are likely to be incomplete in their early parts, particularly near the Cheraw and Meers faults in the comparatively recently settled western Great Plains. Incompleteness would lead to erroneously low rates.

Mmax values were obtained as follows. For the New Madrid seismic zone, the graphed value and uncertainty are the mean and standard deviation of three estimates of the magnitudes of the three main shocks of 1811–1812 as listed at the start of this section (Johnston, 1996c; Hough and others, 2000; Bakun and Hopper, 2004). For the Charleston seismic zone, the plotted value and uncertainty are the mean and range of three estimates of the magnitude of the 1886 earthquake (Bollinger, 1977; Johnston, 1996c; Bakun and Hopper, 2004). For the Wabash Valley seismic zone, the largest of eight prehistoric earthquakes had an estimated magnitude of 7.5. The uncertainty is set arbitrarily here at 0.5. For the Cheraw fault, the scarp length of 45 km implies Mmax of M 7.0 with a standard deviation of 0.34 (Wells and Coppersmith, 1994). For the southeastern section of the Meers fault, the scarp length of 35 km indicates Mmax of M 6.9 with a standard deviation of 0.28 (Wells and Coppersmith, 1994).

Figure 6a shows rates calculated from earthquakes of M 3.0 and larger and from M 4.0 and larger. Figure 6b combines the two sets of rates to provide an uncertainty estimate for the rates. Both figures show unconvincing indications that Mmax decreases with seismicity rate. The indications are unconvincing because of the small number of features and the large Mmax uncertainties. For example, the indications would vanish if a sixth feature were found to have a rate of 0.4 and Mmax of 7.0. Log-log graphs show similar trends and are not shown here.

Another aspect of figure 6b undercuts the usefulness of seismicity rate. The data extend down to negligible rates because of the low seismicity near the Cheraw and Meers faults. Rate cannot be negative. Therefore, the graphs cannot extend beyond their left edges to suggest Mmax values smaller

than M 6.8–7.0. This observation could support one or more of three interpretations, all of which argue against use of the seismicity-rate method. (1) Perhaps future paleoseismic results will add several points with nearly zero rates and Mmax around 6.5. The resulting graph would indicate a steep drop in Mmax at very low rates. However, the large uncertainties in rates and Mmax values would imply that, in such a steep part of the graph, seismicity rate would not give reliable estimates of Mmax. (2) Perhaps rate is not a valid indicator of Mmax in SCR. The uncertainties of the five data points are consistent with a horizontal line on the graphs. (3) Perhaps Mmax is no smaller than approximately M 7.0 anywhere in the North American SCR.

Thus, even if seismicity rate were a valid indicator of Mmax, paleoseismic and instrumental magnitudes suggest that the utility of seismicity rate is restricted to approximately M 7 and above. This is the range in which accepted paleoseismic methods can also provide a basis for Mmax estimation, regardless of the validity of the seismicity-rate method.

Mmax from Magnitude-Frequency Extrapolation of Historical Record

Nuttli (1981) proposed that $m$max for an area should be set at the magnitude that would recur in 1,000 years, as predicted by extrapolation of a magnitude-frequency graph of the area's seismicity. He applied the method to the New Madrid and Charleston, South Carolina, seismic zones and showed that it yielded approximately the m_b magnitudes of the 1811–1812 New Madrid and 1886 Charleston earthquakes.

Pro:

Like the Mobs and increment methods, the magnitude-frequency method is simple and can be applied anywhere. Additionally, it is reproducible in that if two seismologists were given the same earthquake catalog of the same area, they would obtain the same Mmax value.

Con:

It is not clear why Mmax should have a recurrence interval of 1,000 years everywhere (Coppersmith, 1994; Budnitz and others, 1997, Appendix H). In fact, although the magnitude-frequency equation indicates the recurrence interval of any specified M, the equation itself provides no guidance as to which M to specify. The estimated magnitude varies with the size of the areal zone considered. Nuttli used 30,000 km^2 and 100,000 km^2, but cautioned that the most appropriate size is unknown.

The paleoseismic work summarized at the start of this section shows that large CEUSAC earthquakes have widely varying recurrence intervals in small areas or on individual faults. The 1811–1812 New Madrid and 1886 Charleston earthquakes, and prehistoric earthquakes of similar sizes, have had recurrence intervals that average only 400–500 years. The Cheraw fault has had apparent Mmax earthquakes at intervals of 4 k.y., at least 8 k.y. and 8–13 k.y., and the Meers fault has done the same at an interval of 0.7–1.8 k.y. For the Wabash Valley seismic zone, Nuttli (1981) calculated that the 1,000-year earthquake would be of m_b 6.2–6.4. Paleoseismic work revealed that the zone has had much larger paleoearthquakes of approximately M 7.1 and 7.5 at 12 ka and 6.1 ka, respectively.

Mmax from the Saturation Magnitude of m_b, Approximately 7.5

Pro:

It is true that saturation precludes measurement of an m_b larger than 7.0–7.5.

Con:

The sizes of moderate and large earthquakes are now routinely expressed as seismic moment M_0 or moment magnitude M (Hanks and Kanamori, 1979), which do not saturate. Important older earthquakes, whose magnitudes may have been measured as m_b or on another scale that saturates, are being converted to M, either by regression relations (for example, Johnston, 1996a) or by recalculation from the original data (for example, Bent, 1992, 1995, 1996, 2002). Thus, the saturation method of estimating Mmax is no longer pertinent.

Mmax from Local Geologic Features

The local-geology method involves estimating Mmax of a specified area from the geological, seismological, and other geophysical properties of the area.

Pro:

An area with distinctive geology, faults, hypocentral depths, or gravity and aeromagnetic anomalies might include rocks and faults with physical properties that differ significantly from those of adjacent areas. The map dimensions of the distinctive area (source zone), or the length of its longest known fault, could constrain the length of the largest likely rupture zone (Budnitz and others, 1997). If the factors that set the source zone apart from its neighbors extend to hypocentral depths, then the width and area of the largest likely rupture zone might be estimated as well (Bollinger, 1981; Woodward-Clyde Consultants, 1986, p. 6–12, 6–13, 6–18; Bernreuter and others, 1989b, p. A–8, A–14, A–49–50, A–68). Maximum rupture length or maximum rupture area would allow estimation of Mmax (Johnston, 1993; Wells and Coppersmith, 1994; Somerville and others, 2001). Mmax might also be estimated from the area of a tabular zone of hypocenters, or from the volume of a crustal block that is more seismically active than its surroundings (see summary by Coppersmith, 1994)

Con:

The Charleston seismic zone illustrates the central flaw in the local-geology method. In general, it is unclear which geologic properties control Mmax in CEUSAC. Therefore, in general it is unclear which aspects of pre-Quaternary history and geologic structure are pertinent to historical and near-future seismicity (Allen, 1975). The source fault or faults of the 1886 Charleston earthquake and its similarly large prehistoric predecessors remain unknown. Even the young fault that was reported by Chapman and Beale (2008) and Chapman and others (2007) in the 1886 meizoseismal area will require additional geophysical and paleoseismic study to determine whether or not the fault broke coevally with the 1886 earthquake or one of its predecessors. Within the Atlantic Coastal Plain, only the Charleston area has been shown to have had such large, repeated, Holocene earthquakes at intervals of a few centuries (Amick and Gelinas, 1991). However, similarly large earthquakes cannot be ruled out in the similar tectonic settings that cover most of the Atlantic and Gulf of Mexico Coastal Plains, although they might recur at much longer intervals than at Charleston.

The local-geology method encounters three similar problems with enigmatic geologic controls elsewhere in CEUSAC. (1) Nearly all source zones contain too few historical earthquakes to clearly reveal interpretable spatial associations between local geologic features and large earthquakes. (2) Large CEUSAC earthquakes are too rare for their seismological study to identify the geologic controls on the length, width, and displacement of propagating ruptures. (3) Nearly all CEUSAC hypocenters are within metamorphic and igneous basement, or near the bottom of overlying Paleozoic sedimentary rocks (Wheeler and Johnston, 1992). Most geologic features in CEUSAC basement or the overlying deep sedimentary cover formed tens of millions to billions of years ago. However, I do not know of any

evidence of large cumulative Quaternary deformation in CEUSAC basement or its deep cover rocks. The apparent lack of large, young tectonic deformation implies that a geologic feature that produces large earthquakes cannot have done so for a geologically long period of time (Schweig and Ellis, 1994). Production of large earthquakes by the feature must turn off and on at unknown time intervals (Coppersmith, 1988). Therefore, there must be at least one control in addition to the geologic feature and its rate of historical seismicity. This conclusion may increase the difficulty of resolving the enigma of geologic controls on CEUSAC seismicity and Mmax.

We might not need to understand geologic controls on the propagation of CEUSAC seismic ruptures if we could identify the individual faults whose slips generate present-day earthquakes. Unfortunately, attribution of individual CEUSAC earthquakes or groups of them to individual faults is hindered by generally sparse seismicity, rarity of surface ruptures, and uncertain locations of earthquakes and faults at hypocentral depths. The clearest links between individual CEUSAC earthquakes and individual faults are prehistoric surface ruptures on the Meers and Cheraw faults, and surface warping on the Reelfoot fault in 1812. As noted earlier in the introduction, the only historical surface rupture east of the Rocky Mountains occurred in 1989 far north of CEUSAC. Less clearly, in the New Madrid, Charlevoix, and Wabash Valley seismic zones, abundant accurate and precise hypocenters, numerous single-earthquake focal mechanisms, and tight geophysical and well-log constraints on the locations and orientations of subsurface fault systems, taken together, identify systems of contractionally reactivated rift faults as sources of modern-day seismicity. The rift faults had their largest extensional slip during the Cambrian Period (McKeown and Pakiser, 1982; Anglin, 1984; Himes and others, 1988; Johnston and others, 1992; Rhea and Wheeler, 1994, 1995, 1996; Wheeler and others, 1994, 1997a, 1997b; Nelson, 1995; Lamontagne and Ranalli, 1997; Lamontagne and others, 2000; Kim, 2003). Beyond these examples, few individual faults have been linked to individual earthquakes through precise hypocenters and well-controlled focal mechanisms.

Absent understanding of the geologic controls on rupture propagation in SCR, the map dimensions of a source zone and the length of its longest known fault are difficult to relate to Mmax and may not be reliable estimates of it (Risk Engineering Inc. and others, 1988, p. 4–13). The longest fault might never rupture entirely in a single event. Because much of CEUSAC is covered with Paleozoic and younger sedimentary rocks, and because CEUSAC earthquakes tend to nucleate in underlying basement (Wheeler and Johnston, 1992), a basement fault beneath the masking sedimentary cover might be much longer than is known. Even if the entire fault has been mapped, if the rupture zone penetrates more deeply than usual then the resulting earthquake could be larger than expected from the mapped rupture length, as happened during the 2001 Bhuj, India, earthquake (Bodin and Horton, 2004; Mandal and others, 2004). Even if the geologic factors that control SCR rupture propagation were known, it would still be necessary to devise methods to detect their presence or absence at focal depths.

Finally, some moderate CEUSAC instrumental earthquakes have occurred deeply enough that geologic features at their hypocentral depths may be unrelated to exposed aspects of the local geology, as noted earlier in the discussion of the seismicity-rate method.

Mmax from North American Tectonic Analogs

The method involves identifying parts of the North American SCR that are thought to share geologic controls on Mmax with the CEUSAC source zone that is being analyzed.

Pro:

The suggestions that support the local-geology method apply here as well. The local-geology method implies that for a specific source zone, one can specify a small set of recognizable and

detectable geologic factors that are likely to control Mmax. However, the set of likely controlling factors also can be used to identify other North American source zones that have the same set of factors. The other source zones may be considered to be tectonic analogs of the original zone. Some of the analog source zones might have had larger historical earthquakes than any observed in the original zone. If Mobs in each of the analogous source zones is assumed to be possible in all the other analogs, then the largest Mobs may be taken as Mmax in all the zones, including the original one. In fact, Johnston (1994), Coppersmith (1994), and Cornell (1994) applied this strategy within North America and globally.

Con:

The arguments against the local-geology method apply here as well, although less strongly because the North American analogs taken together would supply a larger sample of earthquakes and a larger geographic area in the specified tectonic setting. The larger sample should provide a higher lower bound on Mmax, as well as more data with which to test inferences as to geologic controls on Mmax. However, care needs to be taken to define "analogs" in terms of geologic factors that can be expected to influence Mmax (Coppersmith, 1994, p. 6–7—6–8). Coppersmith additionally noted that defining Mmax as the largest Mobs in all the analog zones should be justified.

Mmax from Global Tectonic Analogs

The global-analog method uses a worldwide catalog of Earth's moderate and large historical SCR earthquakes (Johnston and others, 1994). To use the global-analog method, the historical record of the moderate and larger earthquakes that have occurred in a specified SCR tectonic setting worldwide are taken as an approximation of the future magnitudes to be expected in the tectonic setting under the present-day stress regime (Coppersmith, 1994; Wheeler and Frankel, 2000). If the tectonic setting exists in CEUSAC, then the setting's global historical record can characterize the CEUSAC Mmax. Johnston (1994) examined the global SCR catalog and observed that historical SCR earthquakes reached larger magnitudes in Mesozoic and Paleogene extended terranes (rifts and passive margins) than in nonextended terranes such as cratons.

Two versions of the global-analog method are in current use. The first to be developed is a Bayesian analysis that is the subject of the next subsection (Cornell, 1994; Coppersmith, 1994). The second version is that used in the 1996 and subsequent USGS national seismic-hazard maps (Frankel and others, 1996, 2002; Wheeler and Frankel, 2000; Petersen and others, 2008). The USGS version is the topic of this subsection. The fourth-generation seismic-hazard maps of Canada use the same Mmax values as the USGS maps in most parts of CEUSAC (Adams and Halchuk, 2003; Fenton and others, 2006). The main difference is that the Canadian maps use Mmax 7.0 in most of the northern Appalachians, whereas the USGS maps use 7.5. Because both the Bayesian and USGS versions of the global-analog method use the global SCR catalog, the rest of this subsection and the next identify advantages and disadvantages that apply to both versions.

Pro:

The reasoning that justifies the use of North American tectonic analogs applies here as well. Additionally, the earthquakes of a single source zone, or even of all similar source zones within the North American SCR, are but a sample of the global population of similar source zones and their SCR earthquakes. This realization is at least two decades old (Coppersmith and others, 1986, 1987a, b; Coppersmith, 1994). Accordingly, Johnston and others (1994) compiled the global SCR catalog.

Because of the large sample size, inspection of the global catalog can reveal aspects of SCR seismicity that may not be detectable from study of smaller areas or any individual SCR.

The USGS version of the global-analog method has the advantage of simplicity. The version uses Johnston and others' (1994) observation that large SCR earthquakes have occurred preferentially in young extended terranes globally, in contrast to nonextended terranes globally. The observation is applied to CEUSAC to divide it into two large background source zones with different Mmax values, the craton and extended margin (fig. 4; Wheeler and Frankel, 2000).

An additional advantage of the global-analog method is that it brings with it the possibility of using recent paleoseismic results from the Australian SCR. Scores of late Quaternary fault scarps have been found in the Precambrian cratons of western Australia. The scarps have lengths that imply formation during prehistoric earthquakes with magnitudes that may have reached as high as roughly M 7.5 (Clark and McCue, 2003; Clark, 2005, 2006; Leonard and Clark, 2006). At present the Australian results have not been incorporated into the USGS hazard maps.

Con:

As for the method of North American tectonic analogs, the use of global analogs requires care in defining "analog" and justification for taking Mmax as the largest Mobs in all of the analog zones (Coppersmith, 1994). The definition and the justification remain unsolved problems.

Mmax from Bayesian Method

Cornell (1994) suggested the use of Bayesian analysis for examination of the global SCR catalog of Johnston and others (1994). Coppersmith (1994) described the details of such an analysis. It has been applied to eastern Tennessee (Geomatrix Consultants Inc., 2004), and to Switzerland in the PEGASOS project (K.J. Coppersmith, Coppersmith Consulting, Inc., written commun., March 17, 2008, containing section 4.1.2 on Assessment of Maximum Magnitude [NAGRA, 2004]). The Bayesian analysis involves multiplication of a prior probability distribution by a likelihood function, to form a posterior probability distribution (fig. 7). The prior distribution summarizes existing knowledge of large SCR earthquakes that occurred in tectonic settings that are similar to the region under consideration for the hazard assessment. Cornell (1994) and Coppersmith (1994) described construction of the prior distribution. Construction follows Johnston's distinction between a group of young extended terranes and a second group of nonextended terranes. Each group of terranes has its own prior distribution. The prior distribution for the young extended terranes is a normal distribution that has been fit to a histogram of the Mobs values of all the individual young extended terranes on Earth. Construction of the nonextended prior distribution is analogous. Thus, the priors are developed by dividing Johnston's two large groups of terranes according to tectonic characteristics of the individual terranes. The likelihood function expresses the fact that Mmax for an area cannot be smaller than Mobs in the area. The posterior distribution gives the probability distribution of Mmax.

Pro:

The two introductory paragraphs and the first paragraph under "Pro" in the subsection on the global-analog method apply here as well. Just as for the USGS version of the global-analog method, the recent Australian results have not yet been applied to the Baysian version. Bayesian analysis could use a catalog from a smaller region than the whole of Earth's SCRs, but then the analysis would lose some of the benefit of the largest sample. The Bayesian approach has the added advantage of dividing the process of estimating Mmax into development of a prior distribution and development of a likelihood

function. The prior and the likelihood may be evaluated separately, which can simplify the understanding and critiquing of the analysis.

Con:
       The counterarguments of the global-analog method apply here as well. The Bayesian approach has the added disadvantage of a more complex process that requires justifying the choices of both the prior distribution and the likelihood function. The choice of a prior distribution has an inherently subjective component (Vere-Jones and Ogata, 2003).

Mmax from Physical Principles

Pro:
       Physics-based arguments support the existence of a maximum magnitude that might vary regionally or even locally (Chinnery, 1979; Coppersmith and others, 1987b; Kijko and Graham, 1998).

Con:
       Quantitative understanding of the geologic controls on the propagation of seismic ruptures in SCR was insufficient to permit assigning values to Mmax in 1978 and 1987 (Chinnery, 1979; Coppersmith and others, 1987b). I am not aware of evidence that this has changed, at least for the old, cold crust and long recurrence intervals of SCRs. Additionally, small samples of seismicity and historical intervals that are shorter than several cycles of Mmax earthquakes hinder testing of the assumptions of physics-based estimates of Mmax (for example, Main, 1995).

Mmax from Statistical Approaches

       Bayesian analysis is a statistical method. However, the Bayesian method is treated in its own subsection because it is already being used in hazard assessments.

Pro:
       Numerous papers have applied magnitude-frequency statistics and the theory of extremes to estimating Mmax (Chinnery, 1979; Coppersmith and others, 1987b; Kijko and Graham, 1998). Purely statistical approaches do not require understanding of the physics or the largely enigmatic geologic controls of rupture propagation in SCR crust.

Con:
       Early statistical approaches were undercut by saturation of the M_S magnitude scale, by small seismicity samples, and by rarity of earthquakes large enough that their sizes would make them reasonable candidates for Mmax (McGuire, 1977; Chinnery, 1979; Bender, 1988; Cornell, 1994). Since Chinnery's and Coppersmith's reviews, a global moment-magnitude catalog of moderate and larger SCR earthquakes removes the ambiguity introduced by saturation (Johnston and others, 1994). The LLNL, EPRI–SOG, and 1996 and subsequent USGS assessments used different versions of the SCR catalog (tables 1–3). However, the problems of small samples and rare large earthquakes continue to hinder testing of statistical models in SCRs (for example, Thompson and others, 2007).

Mmax from Pattern Recognition

Pro:

Pattern recognition might be able to identify the combinations of geologic and geophysical properties that are most strongly associated with the occurrence of large earthquakes. Because pattern-recognition techniques are purely descriptive, they would not require understanding of the controls on SCR rupture propagation. The techniques would not have to satisfy the formal requirements for statistical tests of hypotheses.

Con:

Pattern recognition methods encounter the same barriers as statistical approaches. The most fundamental barrier is the scarcity of SCR areas in which Mmax is known well enough to allow testing of the pattern-recognition results (Chinnery, 1979). Two pattern-recognition studies of the Eastern United States succeeded in distinguishing seismically active areas from inactive areas (Barstow and others, 1981; Jones-Cecil and others, 1981). However, the studies could constrain Mmax only if seismicity rate were a good estimate of Mmax. Evidence of the effectiveness of seismicity rate is lacking, as summarized in the earlier subsection on that method.

Mmax from Crustal Lg Coda Q at 1 Hertz (Q_0)

A map of Q_0 in China shows spatial correlations with epicenters of large historical earthquakes (Jin and Aki, 1988). The earthquakes occurred preferentially in areas of low Q_0. The magnitude of the largest earthquake to have occurred since 1700 within 150 km of each of the recording stations varies inversely with the logarithm of Q_0. Jin and Aki suggested an inverse relation between Q_0 and Mmax that could be useful for hazard assessments.

Pro:

The suggested relation is reasonable in terms of the components of seismic moment. Areas of active or recently active tectonics have low Q_0, whereas most continental areas have higher Q_0 (Mitchell and Cong, 1998). Tectonically active regions will have larger rates of deformation than less active regions, whether the deformation is extensional, strike slip, or contractional. If the deformation involves significant faulting, we would expect faults to have faster slip rates in the more active regions. The faster slip rates may tend to impede and overcome the chemical processes of fault healing (but see the earlier subsection on the seismicity-rate method). If so, then the faster rates will allow faults to mature faster, that is, to smooth out strength and geometric irregularities and to link short faults into long faults. Smooth, long faults should present fewer barriers to rupture propagation, and thus should tend to have larger rupture lengths. Consequently, we may expect the greater rupture lengths in more active, lower Q_0 regions to produce larger Mmax.

Con:

The Chinese and Mongolian SCRs (fig. 1) include large parts of the contour map of Q_0, with the rest of the map area being active continental crust (Broadbent and Allan Cartography, 1994). Thus, the relation suggested by Jin and Aki (1988) is at least partly based on SCR data. Baqer and Mitchell (1998) mapped Q_0 throughout the conterminous United States. Approximate values in CEUSAC range from 750 in New York State to 400 in southern Alabama. Values around the Meers and Cheraw faults are about 500 and 600, respectively. Values at the New Madrid and Charleston seismic zones are about 600 and 425, respectively. Jin and Aki show a graph of the logarithm of Q_0 at each station plotted against the

magnitude of the largest earthquake to have occurred within 150 km of each station since 1700. The graph suggests that New York State could have earthquakes no larger than approximately M 5. That region has had five M 5.1–5.2 earthquakes since 1737 but nothing larger (Wheeler and others, 2001), which is consistent with the prediction from the graph. The graph predicts an Mmax of at least M 6.5 for southern Alabama, which is much larger than any historical earthquake there, and therefore not contradicted by the historical record.

However, the graph performs worse in the five CEUSAC areas that have paleoseismically determined chronologies of large earthquakes. The start of this section summarizes the chronologies. The graph predicts Mmax of approximately 6.1 for the Meers fault and surroundings, and 5.6 for the Cheraw fault and its vicinity. These values are 0.8- and 1.4-M units smaller, respectively, than those implied by scarp lengths. The graph predicts Mmax of roughly 6.1 for the Wabash Valley seismic zone, whereas an earthquake of approximately M 7.5 occurred there 6.1 ka. The graph underpredicts the largest M observed historically at New Madrid and Charleston, estimating approximately M 6.3 for the Charleston seismic zone and 5.6 for the New Madrid seismic zone. Thus, in these five areas the graph underpredicts Mobs or paleoseismically estimated Mmax by roughly 1–2 units.

Observations

Our poor understanding of the physics of geologic controls on the propagation of seismic ruptures in SCR crust forces us to rely on direct observations of Mmax or on indirect methods of estimating it.

Direct observation of Mmax in most of CEUSAC is rare and likely to remain so. Long recurrence intervals of large SCR earthquakes mean that earthquakes of approximately M 7 or larger have been observed historically only in the New Madrid, Charleston, and Charlevoix seismic zones, and in the Grand Banks area offshore from Newfoundland. Smaller values of the largest magnitudes observed in other CEUSAC areas can be harder to justify logically as choices of Mmax, as explained in the preceding section and summarized in table 5.

Direct observation also must include paleoseismic observations and measurements of the geologic records of large prehistoric earthquakes. Paleoseismic work added to the historical record another three areas with prehistoric earthquakes of approximately M 7 or larger: the Cheraw and Meers faults and the Wabash Valley seismic zone. The pace of CEUSAC paleoseismic fieldwork and laboratory analyses is constrained by the small number of experienced CEUSAC paleoseismologists, limited funds with which to train and support more paleoseismologists, uneven availability of exposures of liquefiable sediments or access to them, and field seasons that are often seasonally restricted by extreme heat, or by high stream levels or thick vegetation that obscure outcrops. The uncertainties in magnitudes estimated paleoseismically remain poorly characterized. Accordingly, outside these seven small parts of CEUSAC, additional direct observations are likely to accumulate too slowly to usefully constrain Mmax soon.

Indirect methods have been discussed and used in the EPRI–SOG, LLNL, and USGS hazard assessments (tables 1–3). Long recurrence intervals produce small samples of historical seismicity in most of CEUSAC. The smallness of a sample decreases the resolution of inferences that are drawn from it, the reproducibility of results from one worker to another, and the degree to which analyses and Mmax estimates can be argued to represent the near future and geologically similar areas. In these ways small samples undercut the methods of Mobs, Mobs plus an increment, inference from local geology, physical modeling, statistical analysis, pattern recognition, and Q_0. Probably the problem of long recurrence intervals will persist for the foreseeable future. In addition, paleoseismic findings contradict the results of the methods of Mobs, Mobs plus an increment, seismicity rate, extrapolation from a

magnitude-frequency diagram, and Q_0. Finally, our present inability to locate earthquakes and faults accurately and precisely at hypocentral depths in most of CEUSAC prevents attribution of most individual earthquakes to individual known faults. This prevents us from verifying some of the inferences drawn from local geology. It also slows improvements in our understanding of the physics of SCR rupture propagation. Significant improvements in our ability to demonstrably link earthquakes with faults at hypocentral depths may come from more sensitive and numerous instruments, new analytical tools and computational methods, and new theoretical insights into rupture processes. Improvements like these are foreseeable and some may be predictable, but their actual use may be years in the future.

Direct observation of larger samples than CEUSAC can provide us is the basis of the methods of global analogs, of Bayesian analysis, and, to a lesser extent, of North American analogs. However, these methods suffer from the difficulty of convincingly identifying analogous areas.

Long recurrence intervals, restrictions on the pace of paleoseismic results, and limited ability to link individual earthquakes with individual faults are problems that may be unlikely to be solved soon. However, agreeing on the meaning of "analogous" could be a more quickly tractable problem.

Acknowledgments

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Table 1. Methods used by Lawrence Livermore National Laboratory's experts to estimate $m$max.

[X, method was used by the expert; XX, method was weighted more heavily than others by the expert; --, method was not used; m, magnitude, generally m_b; m-f, magnitude-frequency graph; experts 2, 4, 8, and 9 did not complete the estimation process]

Method	Expert 1	Expert 3	Expert 5	Expert 6	Expert 7	Expert 10	Expert 11	Expert 12
1 Largest observed m (Mobs)	--	XX	--	XX	XX	X	X	X
2 Mobs plus increment	--	--	XX	--	X	--	--	--
3 Seismicity rate	--	X	--	X	--	X	X	X
4 m-f extrapolation of historical record	XX	--	--	--	--	--	--	--
5 m_b saturates at m_b 7.5	--	--	--	--	--	--	--	--
6 Local geologic features	--	X	X	--	--	X	--	X
7 North American analogs	--	--	--	--	--	--	XX	--
8 Global analogs	--	--	--	--	X	--	--	X

Table 2. Methods used by teams of the Electric Power Research Institute–Seismicity Owners Group project to estimate $m$max.

[X, method was used by the team; XX, method was weighted more heavily than others by the team; --, method was not used; m, magnitude, generally m_b; m-f, magnitude-frequency graph]

Method	Bechtel Group Inc.	Dames & Moore	Law Engineering Testing Co.	Rondout Associates Inc.	Woodward - Clyde Consultants	Weston Geophysical Corp.
1 Largest observed m (Mobs)	XX	--	X	X	X	--
2 Mobs plus increment	X	--	--	--	X	--
3 Seismicity rate	--	X	X	XX	X	X
4 m-f extrapolation of historical record	--	X	X	--	X	--
5 m_b saturates at m_b 7.5	X	X	--	--	--	--
6 Local geologic features	--	--	X	X	X	X
7 North American analogs	--	--	--	X	--	--
8 Global analogs	X	--	X	--	--	--

Table 3. Methods used by the U.S. Geological Survey to estimate $m$max or Mmax.

[X, method was used by authors of the cited publication; XX, method was weighted more heavily than others by the authors; --, method was not used; m, magnitude, generally m_b in the first three columns, Ms or M_L in the fourth column, and moment magnitude in the last column; m-f, magnitude-frequency graph]

Method	Algermissen and Perkins (1976)	Perkins and others (1979)	Thenhaus (1983)	Algermissen and others (1982)	Frankel and others (1996, 2002), Petersen and others (2008)
1 Largest observed m (Mobs)	X	X	XX	X	X
2 Mobs plus increment	--	--	--	--	--
3 Seismicity rate	--	X	XX	X	--
4 m-f extrapolation of historical record	--	--	X	--	--
5 m_b saturates at m_b 7.5	--	--	--	--	--
6 Local geologic features	--	--	X	X	--
7 North American analogs	--	XX	--	--	--
8 Global analogs	--	--	--	--	XX

Table 4. Comparisons of Mmax estimates for eight CEUSAC cities.

[Entries are estimated Mmax for the source zones that contain a city. Original m_{bLg}, M_S, and M_L were converted to moment magnitude with equations of Johnston (1996a). If $m$max was expressed as a distribution, the highest-probability point of the distribution was used. For LLNL experts, values are 1993 updates (Savy and others, 1993). EPRI–SOG's Woodward-Clyde team used broad distributions, and $m$max for this table was taken at the 50-percent point of the team's cumulative-probability distribution for each source zone. If several source zones overlap at a city, the highest-probability zone was used. --, this EPRI–SOG team did not zone the Gulf Coast and did not estimate $m$max there; xx, M exceeded 8.4 and was discarded here (see text); Number, count of tabulated M values for the city; Median, median of the tabulated M values for the city; Range, width of the central half of the tabulated M values]

Source[1]	New Madrid, Mo.	Charleston, S.C.	Charlevoix, Que.	New York, N.Y.	Houston, Tex.	Knoxville, Tenn.	Minneapolis, Minn.	Anna, Ohio
LLNL Expert 1	8.0	xx	xx	xx	xx	xx	5.7	6.6
LLNL Expert 2	xx	8.2	8.4	6.6	7.9	6.6	7.9	6.4
LLNL Expert 3	8.0	7.2	7.4	6.4	5.7	6.5	5.7	5.9
LLNL Expert 4	8.2	7.1	6.9	5.5	5.3	5.9	5.3	5.9
LLNL Expert 5	xx	xx	xx	xx	xx	xx	xx	Xx
LLNL Expert 6	xx	xx	xx	8.4	8.4	8.4	5.9	8.4
LLNL Expert 7	xx	7.7	7.5	6.2	5.9	6.6	6.2	5.7
LLNL Expert 10	7.7	7.4	7.4	5.9	5.3	6.2	5.3	5.9
LLNL Expert 11	7.4	7.4	7.4	6.6	5.7	7.4	5.7	6.6
LLNL Expert 12	8.2	7.7	7.5	5.9	4.7	5.9	4.7	5.3
LLNL Expert 13	xx	6.9	8.4	7.7	4.9	6.6	5.9	6.2
EPRI–SOG Bechtel	8.2	7.7	7.1	6.2	5.7	6.2	5.7	5.7
EPRI–SOG D&M	8.2	6.8	7.7	6.1	5.0	5.9	4.8	7.1
EPRI–SOG Law Eng.	8.0	7.1	8.0	7.1	4.2	7.1	4.8	5.2
EPRI–SOG Rondout	8.0	7.4	7.9	5.7	4.4	7.4	4.4	7.1
EPRI–SOG W-C	7.7	7.1	7.1	5.9	--	5.9	4.9	6.2
EPRI–SOG Weston	7.7	6.8	7.7	4.4	5.2	5.9	5.2	5.9
Algermissen and Perkins (1976)	7.9	7.9	7.9	6.1	5.3	6.1	5.3	6.1
Algermissen	xx	7.3	8.0	7.3	5.6	7.3	5.6	5.6

and others (1982)							
Frankel and others (1996)	8.0	7.3	7.5	7.5	7.5	7.5	6.5	6.5
Frankel and others (2002)	7.7	7.3	7.5	7.5	7.5	7.5	7.0	7.0
Petersen and others (2008)	7.7	7.3	7.5	7.5	7.5	7.5	7.0	7.0
Number	16	19	19	20	19	20	21	21
Median	8.0	7.3	7.5	6.4	5.6	6.6	5.7	6.2
Range	0.5	0.5	0.5	1.5	1.6	1.4	0.7	0.7

[1] Abbreviations and references: see text.

Table 5. Summary of pros and cons of methods used to estimate Mmax.

[Mobs: largest historical earthquake within the source zone for which Mmax is being estimated]

| Method	Pros	Cons
1. Mmax = Mobs	The Mobs method is simple. It can be applied anywhere. It provides an unarguable lower bound for Mmax.	(1) Short historical records produce samples of seismicity that are too small to constrain Mmax. (2) Results of the Mobs method are inconsistent with paleoseismic findings, which show Mmax exceeding Mobs by as much as approximately 2.1- to 3.2-M units.
2. Mmax = Mobs + an increment	The increment method is simple. It can be applied anywhere.	(1) Short historical records produce samples of seismicity that are too small to constrain Mmax. (2) Results of the increment method are inconsistent with paleoseismic findings, which imply increments that range from approximately zero to 3.2.
3. Seismicity rates	A high moment-release rate may smooth and link faults faster, and allow larger rupture zones and slips than in less seismically active areas.	(1) The argument from fault smoothing and linking may apply to plate boundaries, but it is unclear whether it applies to stable continental regions (SCRs). (2) Even if the seismicity-rate method is valid in SCR, it does not appear to apply below Mmax of approximately 7.0. (3) Above Mmax 7.0, paleoseismic studies can provide support for Mmax estimates.
4. Extrapolation of the historical record by a magnitude-frequency graph	The extrapolation method calculates the M that would recur at whatever recurrence interval is specified, such as 1,000 years. The method is simple and it can be applied anywhere.	(1) The extrapolation method gives results that vary with the size of the study area and the specified recurrence interval. (2) Results of the method are inconsistent with paleoseismically determined recurrence intervals of large earthquakes.
5. Saturation value of m_b	This is approximately 7.5 globally.	Moment magnitude does not saturate and is preferred for moderate and large earthquakes.
6. Local geologic features	An area with distinctive geology, faults, or geophysical anomalies might have distinctive fault properties that could control rupture-zone size, such as fault lengths, widths, strengths, or orientations.	(1) Short historical records of small source zones produce small samples of seismicity, which can be too sparse to clearly show long-term spatial associations between seismicity and geologic features. (2) Few CEUSAC earthquakes have been linked to specific faults or systems of faults. (3) The geologic controls on SCR rupture propagation are enigmatic.
7. North American tectonic analogs	(1) The arguments in favor of the method of North American tectonic analogs include those favoring the local-geology method. (2) Including all North American tectonic analogs of a CEUSAC source zone could capture larger earthquakes, providing a higher lower bound to Mmax.	(1) The arguments against the method of North American tectonic analogs are the same as those against the local-geology method. However, the arguments are weaker because the seismicity sample of the combined analog areas is larger. (2) The meaning of "analog" is unclear.

|		
8. Global tectonic analogs	(1) The arguments in favor of the methods of local geologic features and of North American tectonic analogs apply here as well. (2) Including all global tectonic analogs of a CEUSAC source zone produces the largest possible sample of historical seismicity and makes capture of some true Mmax values more likely than with any smaller sample.	The meaning of "analog" is unclear.
9. Bayesian method	(1) The arguments in favor of the methods of global tectonic analogs apply here as well. (2) Including all global tectonic analogs of a CEUSAC source zone produces the largest possible sample of historical seismicity and makes capture of some true Mmax values more likely than with any smaller sample. (3) Separation of the analysis into specification of a prior distribution and a likelihood function can simplify explanation and justification.	(1) The meaning of "analog" is unclear. (2) The prior distribution is partly subjective, which can hinder its explanation and justification.
10. Arguments from physical principles	The arguments support the existence of an Mmax that could vary locally or regionally.	(1) Short historical records produce samples of seismicity that are too small to constrain Mmax. (2) The physics of rupture propagation in SCR crust may be poorly understood. (3) Few SCR areas have had earthquakes large enough to be recognized as Mmax. All three factors impede testing of physical theories.
11. Statistical methods	The methods do not require understanding of the physics or geologic controls on SCR rupture propagation.	(1) Short historical records produce small samples of seismicity. (2) Few SCR areas have had earthquakes large enough to be taken as Mmax. Both factors impede testing of statistical models.
12. Pattern recognition	The method does not require understanding of the physics or geologic controls on SCR rupture propagation.	Few SCR areas have had earthquakes large enough to be taken as Mmax. This impedes testing results of pattern recognition.
13. Q_0	Q_0 varies inversely with Mobs in China.	(1) Results of the Q_0 method are inconsistent with paleoseismic findings. (2) Few SCR areas have had earthquakes large enough to be taken as Mmax.
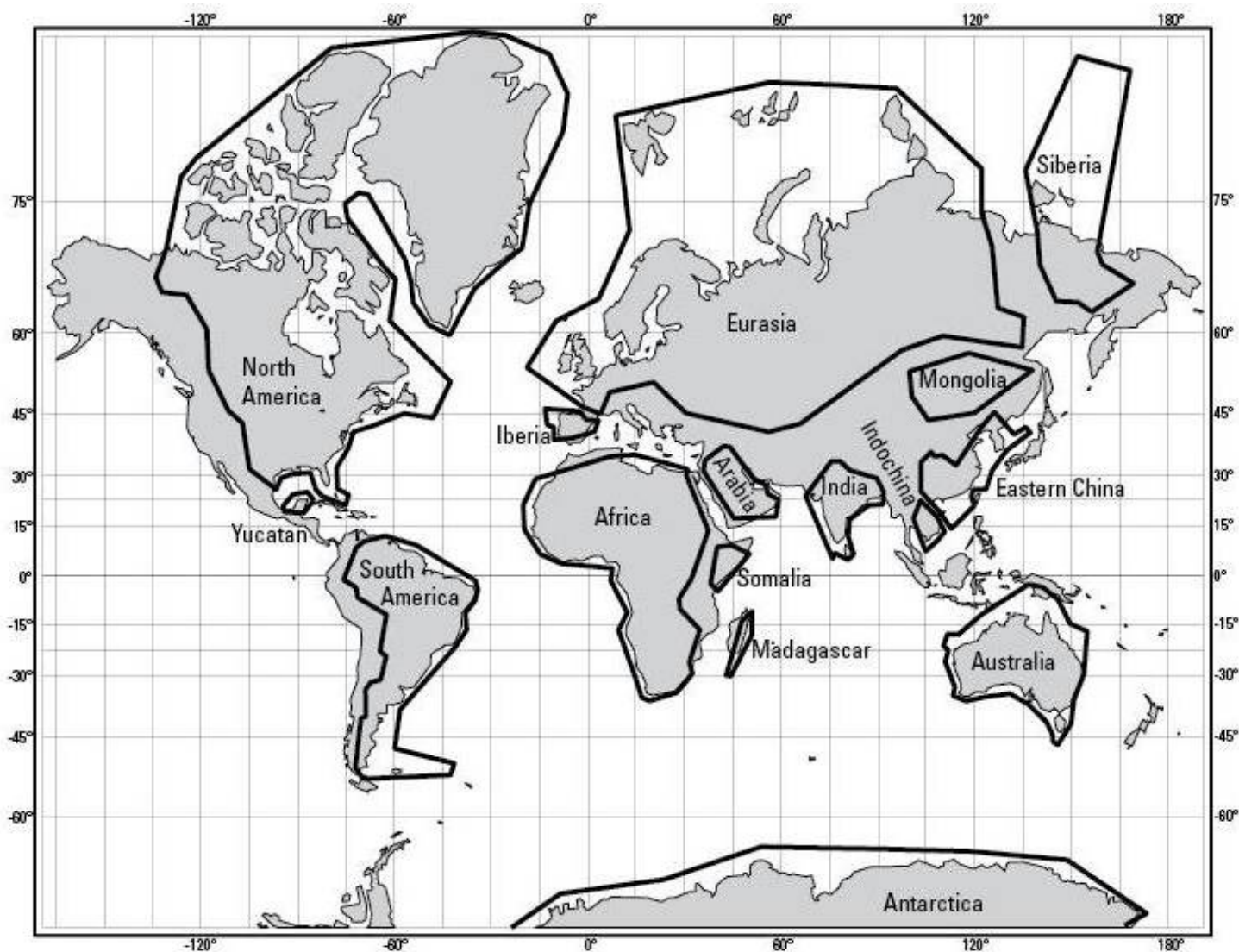
Figure 1. Stable Continental Regions (SCRs) of the Earth. Thick lines outline SCRs (Broadbent and Allan Cartography, 1994). The African, Antarctican, Australian, Eurasian, Indian, North American, and South American SCRs were named by Johnston and others (1994); others are named here.
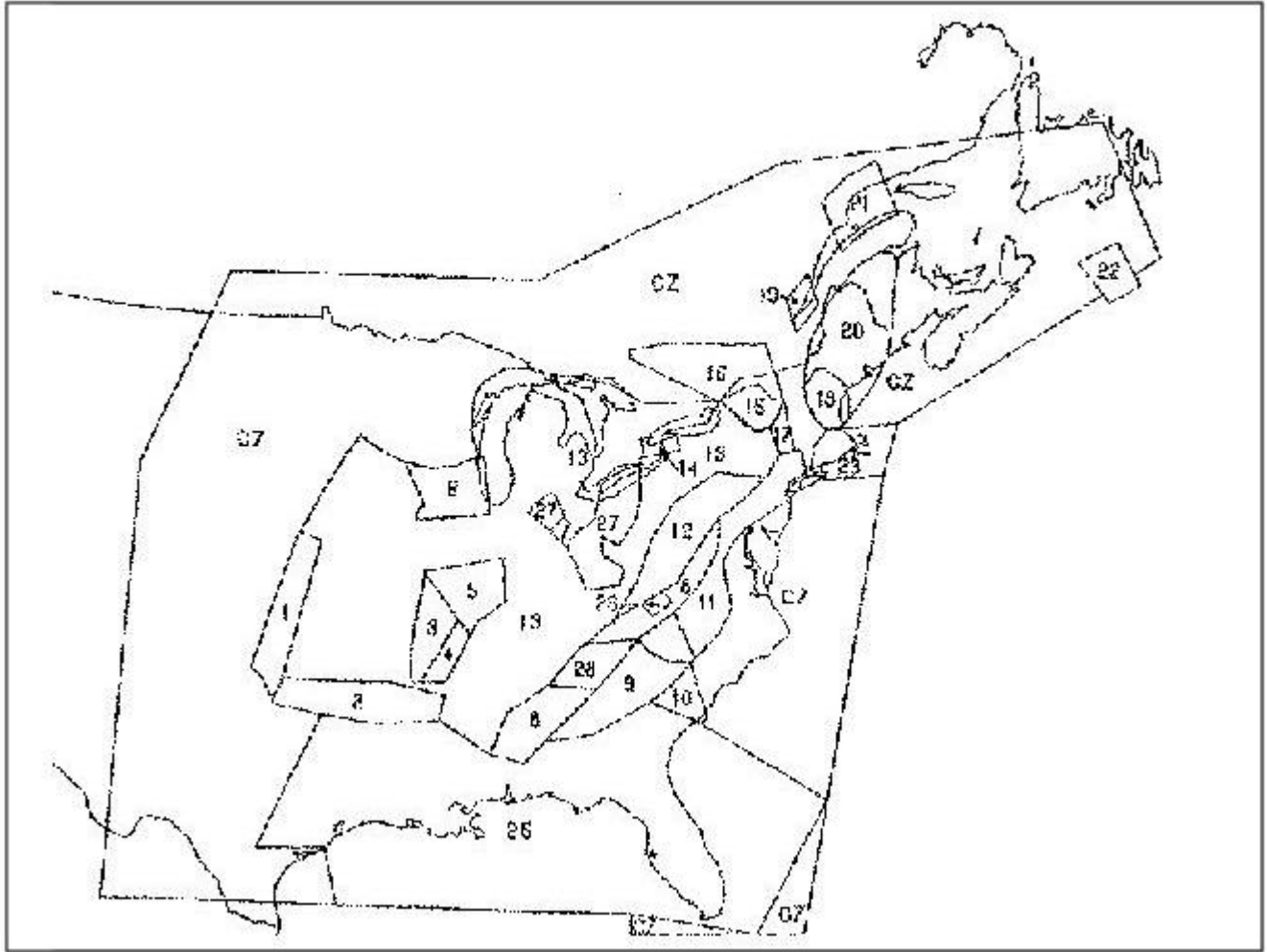
Figure 2. Source-zone map by one of the seismology experts in the project of the Lawrence Livermore National Laboratory. CZ identifies background zones. From figure B4.1 in appendix B of Bernreuter and others (1989b).
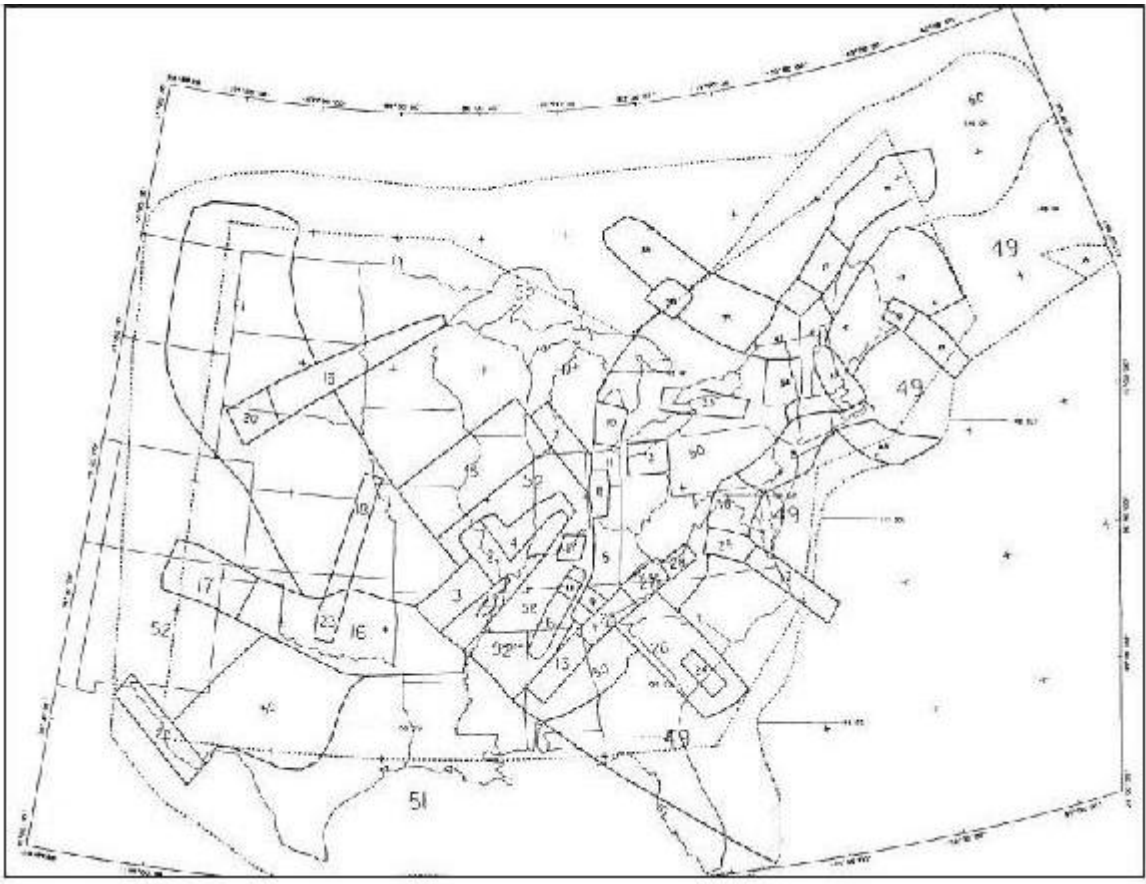
Figure 3. Source-zone map of one of the teams in the project of the Electric Power Research Institute–Seismicity Owners Group. Solid lines show primary source zones, dotted lines show secondary (background) zones. From figure 4–1 of Rondout Associates Inc. (1986).
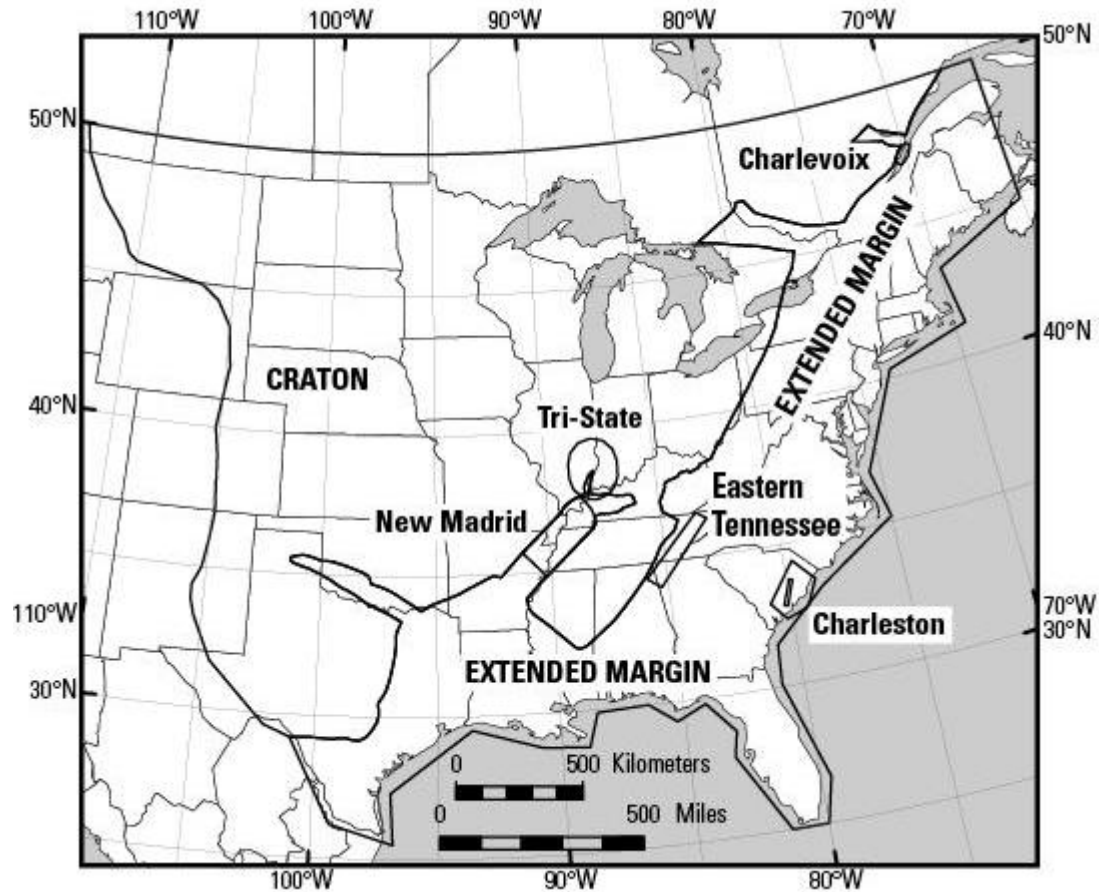
Figure 4. Source-zone map of eastern part of 2008 USGS national seismic-hazard maps. There are two sources at Charleston, for a total of eight throughout the map area. Names of two background zones are capitalized. Six other zones were defined to accommodate different values of a, b, or Mmax. Eastern Tennessee, Charlevoix, and Tri-State source zones take their Mmax from the Extended Margin zone. Modified from Wheeler and Frankel (2000) and Wheeler and Cramer (2002).
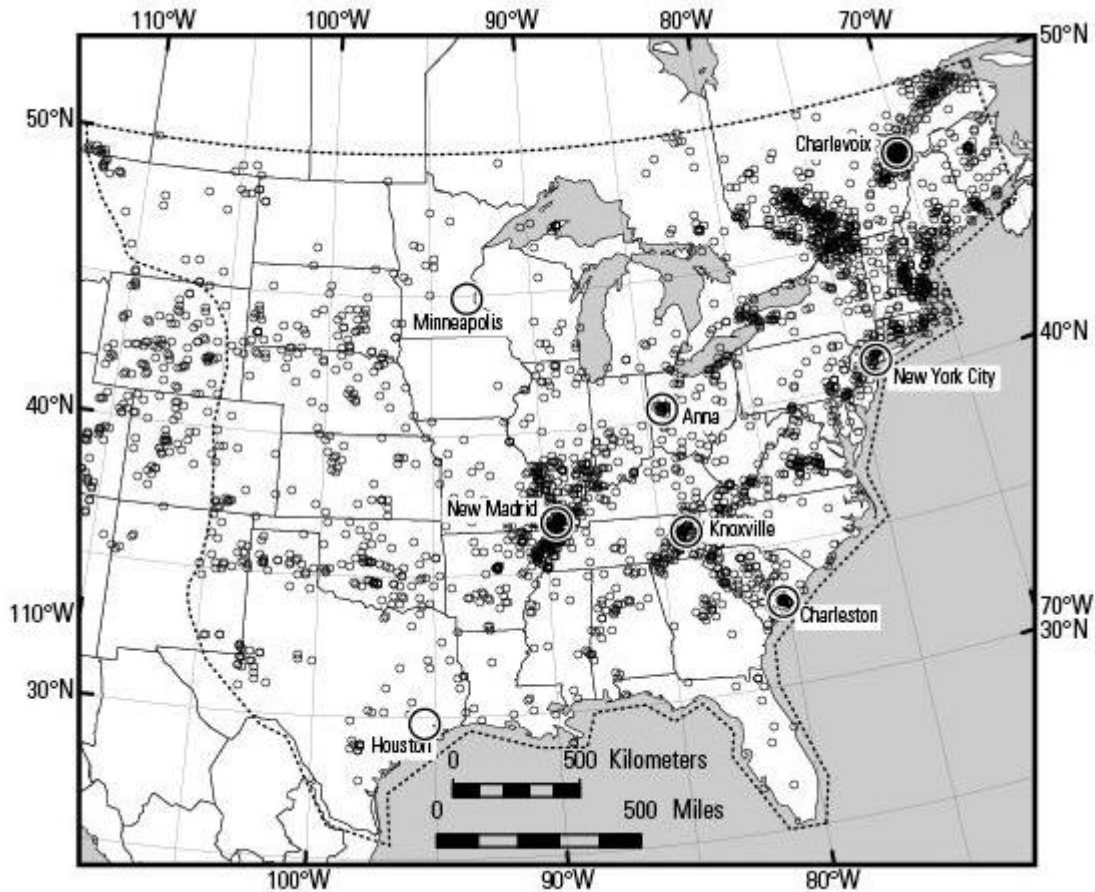
Figure 5.   Seismicity and the eight cities listed in table 4. Large open circles show cities. Small open circles show locations of earthquakes of magnitude 3.0 and greater, with foreshocks and aftershocks removed (Mueller and others, 1997), updated through 2001 (C.S. Mueller, U.S. Geological Survey, oral commun., November 1, 2002). Earthquakes are not shown outside dotted line that represents outer borders of craton and extended-margin source zones (fig. 4), except in central western part of map area.
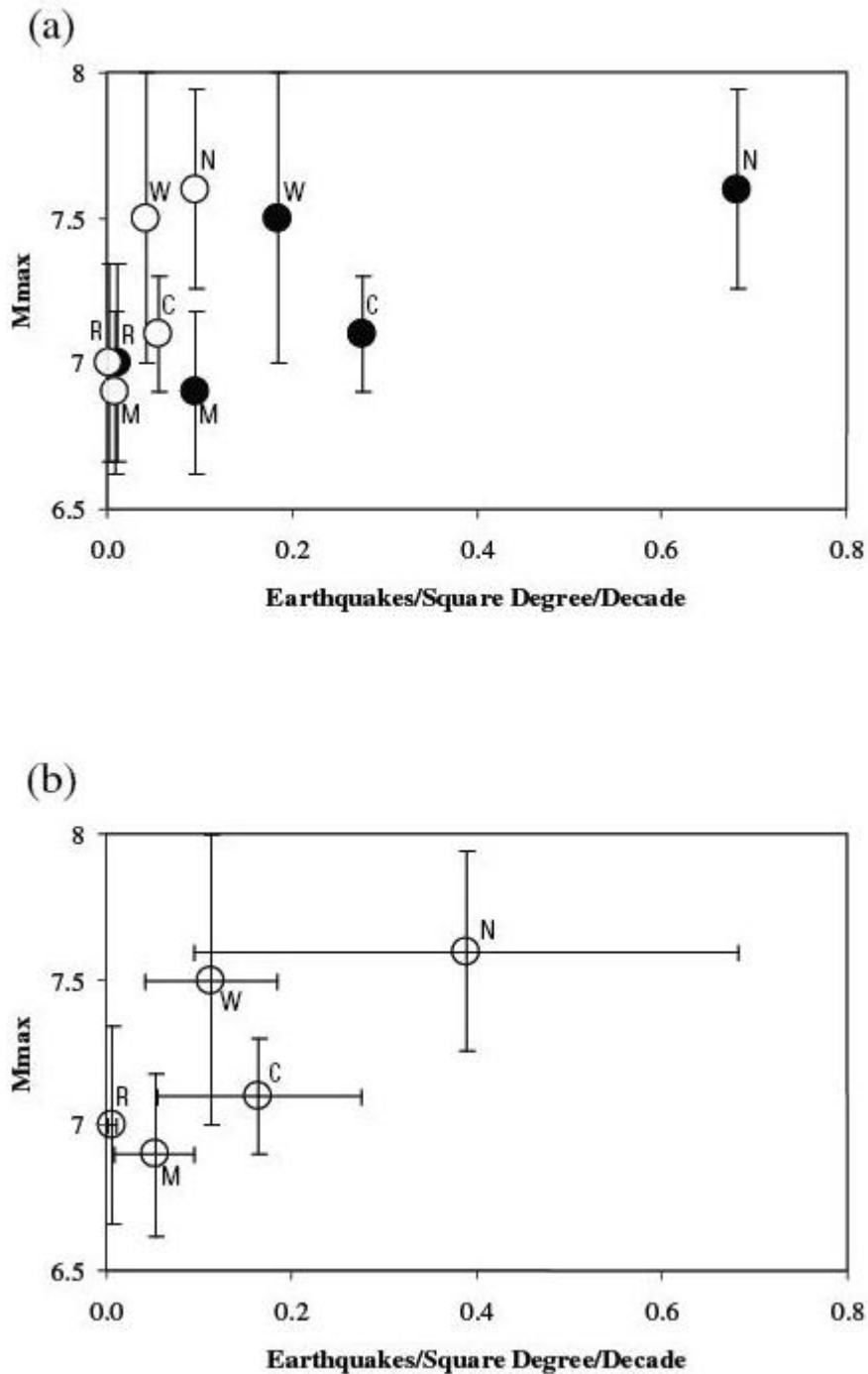
Figure 6. Seismicity rate compared to Mmax for two faults (M, Meers; R, Cheraw) and three seismic zones (N, New Madrid; C, Charleston; W, Wabash Valley). (a) Rates for magnitude at least 3.0 (closed circles) and at least 4.0 (open circles) (see text). Areas over which rates were calculated, in square degrees, are: New Madrid, 4; Charleston, 1; Wabash Valley, 10; Meers, 6; and Cheraw, 12. (b) The two rates of part (a) are averaged to characterize rate uncertainty (open circles). For each feature, rate uncertainty is taken as half the difference between the two rates in (a).
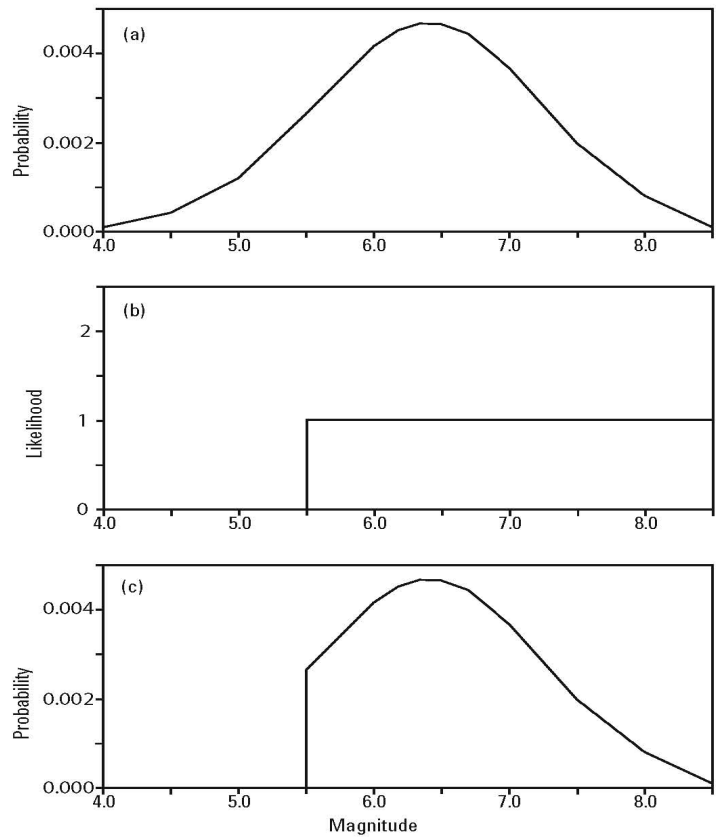
Figure 7.   Simplified graphical example of a Bayesian analysis (after Coppersmith, 1994). (a) Prior distribution developed from a histogram of the largest observed earthquake in each of several similar tectonic terranes (see text). (b) Likelihood function for Mobs = 5.5 in the area of interest. (c) Posterior distribution calculated by multiplying the prior distribution by the likelihood function, point by point along the magnitude axis.