The Geological Society of America
Special Paper 425
2007

Approaches to continental intraplate earthquake issues

Seth Stein†
Department of Earth and Planetary Sciences, Northwestern University, Evanston, Illinois 60208, USA

"We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard."—John F. Kennedy, 1962

ABSTRACT

The papers in this volume illustrate a number of approaches that are becoming increasingly common and offer the prospect of making significant advances in the broad related topics of the science, hazard, and policy issues of large continental intraplate earthquakes. Plate tectonics offers little direct insight into the earthquakes beyond the fact that they are consequences of slow deformation within plates and, hence, relatively rare. To alleviate these problems, we use space geodesy to define the slowly deforming interiors of plates away from their boundaries, quantify the associated deformation, and assess its possible causes. For eastern North America, by far the strongest signal is vertical motion due to ice-mass unloading following the last glaciation. Surprisingly, the expected intraplate deformation due to regional stresses from plate driving forces or local stresses are not obvious in the data. Several approaches address difficulties arising from the short history of instrumental seismology compared to the time between major earthquakes, which can bias our views of seismic hazard and earthquake recurrence by focusing attention on presently active features. Comparisons of earthquakes from different areas illustrate cases where earthquakes occur in similar tectonic environments, increasing the data available. Integration of geodetic, seismological, historical, paleoseismic, and other geologic data provides insight into earthquake recurrence and the difficult question of why the earthquakes are where they are. Although most earthquakes can be related to structural features, this explanation alone has little predictive value because continents contain many such features, of which a few are the most active. It appears that continental intraplate earthquakes are episodic, clustered, and migrate. Thus on short time scales seismicity continues on structures that are active at present, perhaps in part because many events are aftershocks of larger past events. However after periods of activity these structures may become inactive for a long time, so the locus of at least some of the seismicity migrates to other structures. Analysis of the thermo-mechanical structure of the seismic zones gives insight into their mechanics: whether there is something special about them that results in long-lived weak zones on which intraplate strain release concentrates, or as seems more likely, that they are not that unusual, so seismicity migrates. Accepting our lack of understanding of the underlying causes of

†E-mail: seth@earth.northwestern.edu.

Stein, S., 2007, Approaches to continental intraplate earthquake issues, *in* Stein, S., and Mazzotti, S., ed., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, p. 1–16, doi: 10.1130/2007.2425(01). For permission to copy, contact editing@geosociety.org.

the earthquakes, the limitations of the short instrumental record, and the possibility of migrating seismicity helps us to recognize the uncertainties in estimates of seismic hazards. Fortunately, even our limited knowledge can help society develop strategies to mitigate earthquake hazards while balancing resources applied to this goal with those applied to other needs.

Keywords: intraplate earthquakes, continental deformation, seismic hazards.

INTRODUCTION

The papers in this book represent a range of ongoing research addressing the related topics of the science, hazard, and policy issues of large continental intraplate earthquakes. As summarized in the preface, addressing these issues is more difficult than for the far more common earthquakes on plate boundaries, for two reasons. First, we lack a model like plate tectonics that gives insight into the causes, nature, and rate of the earthquakes. Second, because intraplate earthquakes are much rarer owing to the slow deformation rate, we know much less about these earthquakes and their effects.

As a result, probably none of the authors would claim to be an "expert" on intraplate earthquakes. After all, an expert should know why, where, and when such earthquakes occur, what their effects will be, and how society should address them. Because none of these issues is well understood at present, the authors are simply researchers exploring these messy issues.

These issues involve both fundamental science and societal implications. The challenge is to understand the nature and causes of these relatively rare but sometimes very destructive earthquakes and use what we learn to assess the hazard they pose and help society formulate sensible policies to address the resulting risk. In doing so, it is useful to distinguish between hazards and risks. The hazard is the intrinsic natural occurrence of earthquakes and the resulting ground motion and other effects. Although we can define it in various ways for different purposes, and our estimates of it have large uncertainties, the hazard is a natural feature. In contrast, the risk is the danger the hazard poses to life and property, and can be reduced by human actions. Hence, we seek to estimate the hazard and choose policies consistent with societal goals to reduce the resulting risk.

An underlying theme is that many of the scientific and societal issues differ significantly from those posed by the far more common earthquakes at plate boundaries. Figure 1 illustrates this point by comparing a type example of a continental intraplate seismic zone, the New Madrid seismic zone in the central United States, with southern California, part of the boundary zone between the Pacific and North American plates. New Madrid seismic zone earthquakes of a given magnitude are ~30–100 times less frequent because southern California earthquakes result from the ~46 mm/yr motion within the plate boundary zone, whereas New Madrid is within the interior of the North American plate, which is stable to better than 2 mm/yr. However, shaking from New Madrid seismic zone earthquakes is thought to be comparable to that from California earthquakes one magnitude unit larger because rock in the stable continental interior transmits seismic energy more efficiently. Because earthquakes of a given magnitude are ~10 times more frequent than those one-magnitude-unit larger, the shaking difference reduces the effect of the difference in earthquake rates by about a factor of 10. The precise net effect of these differences depends on the recurrence rate of large earthquakes and the resulting ground motion, neither of which are well known. Even so, the comparison indicates that different approaches to mitigating the seismic hazard are likely to make sense.

The hazard posed by large continental intraplate earthquakes is a small, but still significant, fraction of the threat posed by all earthquakes. Earthquakes, in turn, are just one of many challenges societies face. In the United States, on average, fewer than ten people per year are killed by earthquakes (Fig. 2), and intraplate events make up less than 10% of the total. Hence earthquakes are at the level of in-line skating or football, but far less than bicycles, for risk of loss of life (Stein and Wysession, 2003). Similarly, the approximately $5 billion average annual earthquake losses for the United States, though large, is ~2% of that due to automobile accidents. Nonetheless, large earthquakes occasionally cause many fatalities and major damage. Similarly, on a global basis, earthquakes cause an average of ~10,000 deaths per year, significant but relatively minor compared to other causes. For example, malaria causes about a million deaths per year. The challenge to societies is to thus to develop strategies that balance resources allocated to earthquake hazard mitigation with other needs.

Papers in this volume explore many of the issues in these examples. Although written by different authors addressing various geographic areas, and hence often taking different views, they illustrate approaches that are becoming increasingly common and offer the prospect of making significant advances. The goal of this introduction is to highlight some of these approaches, using North America and New Madrid as examples for comparison with some of the results and ideas presented in this volume.

DEFINING PLATE INTERIORS

Although the discovery of plate tectonics explained why the overwhelming majority of earthquakes and seismic moment release occurs on plate boundaries, it remained unclear for some time how to define plate boundaries and distinguish them from plate interiors. Although early papers defined narrow plate boundaries between idealized rigid plates, for example, treat-

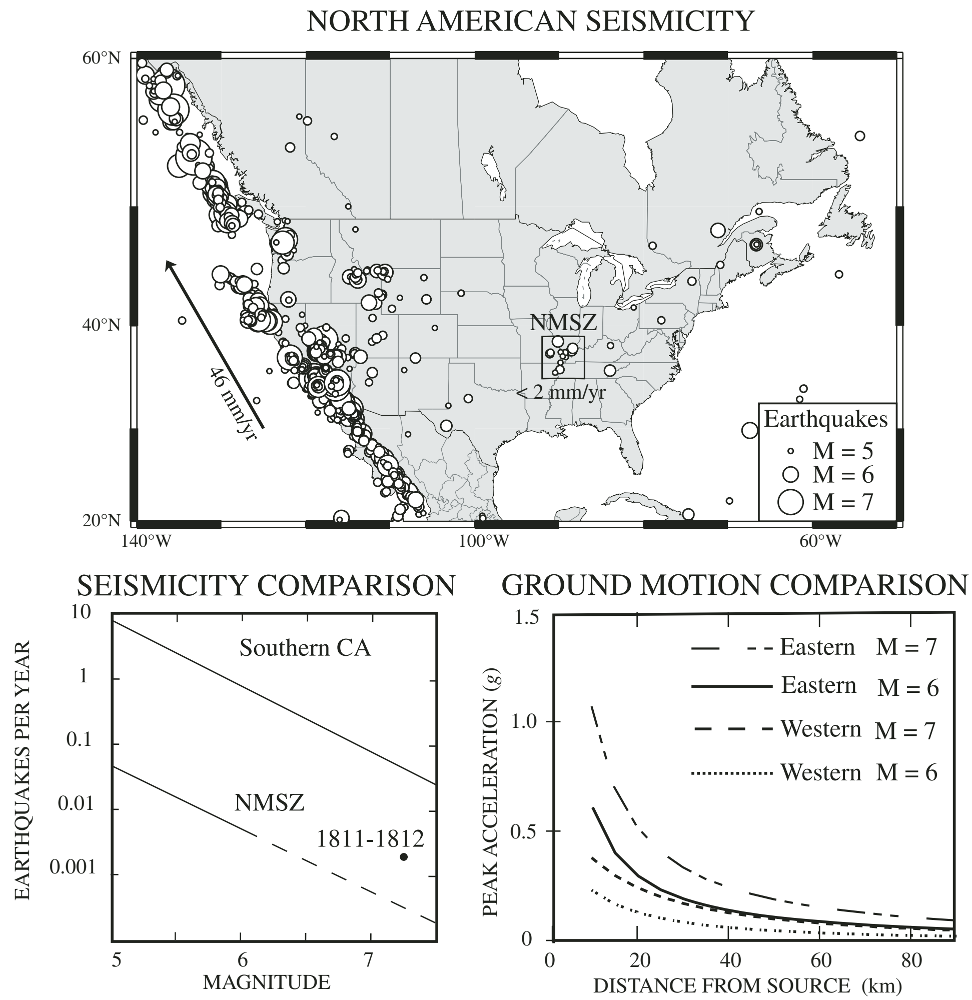

Figure 1. Top: Seismicity (M 5 or greater since 1900) of the continental portion of the North American plate and adjacent areas. Seismicity and deformation are concentrated along the Pacific–North America plate boundary zone, reflecting the relative plate motion. The stable eastern portion of the continent, approximately east of 260°, is much less active, with seismicity deformation concentrated in several zones, notably the New Madrid seismic zone. Bottom left: Comparison of the annual rates of earthquakes greater than a given magnitude for Southern California and the New Madrid seismic zone. Solid lines are computed from recorded seismicity, whereas dashed are extrapolated. Dot indicates paleoseismically inferred recurrence for the largest New Madrid seismic zone earthquakes, assuming M 7.2. Bottom right: Comparison of the predicted strong ground motion from M 7 and 6 earthquakes in the eastern and western United States (Stein et al., 2003).

ing the San Andreas fault as the boundary between the Pacific and North American plates, they recognized that not all plates were perfectly rigid. Morgan (1968, p. 1960), for example, noted that noted that "such features as the African rift system, the Cameroon trend, and the Nevada-Utah earthquake belt are most likely the type of distortion denied in the rigidity hypothesis."

As understanding of motions at plate boundaries and within plate interiors grew, ideas about the distribution of earthquakes and deformation away from idealized boundaries became more specific. Hence, we now would regard Morgan's three examples as illustrating three different types of slowly deforming regions. The seismically active East African rift system is now regarded as a slowly opening plate boundary between the Nubian (East African) and Somalian (West African) plates (Chu and Gordon, 1999). The Nevada and Utah earthquakes are regarded as part of the deformation associated with the broad plate boundary zone between the Pacific and North America plates (Bennett et al., 1999). In contrast, the earthquakes associated with the Cameroon volcanic line (Sykes, 1978) are considered to be within the Nubian plate.

This view came about because plate motions became better understood, both from geological plate motion models (e.g., Chase, 1972, 1978; Minster et al., 1974; Minster and Jordan, 1978; DeMets et al., 1990, 1994) and space-based geodesy

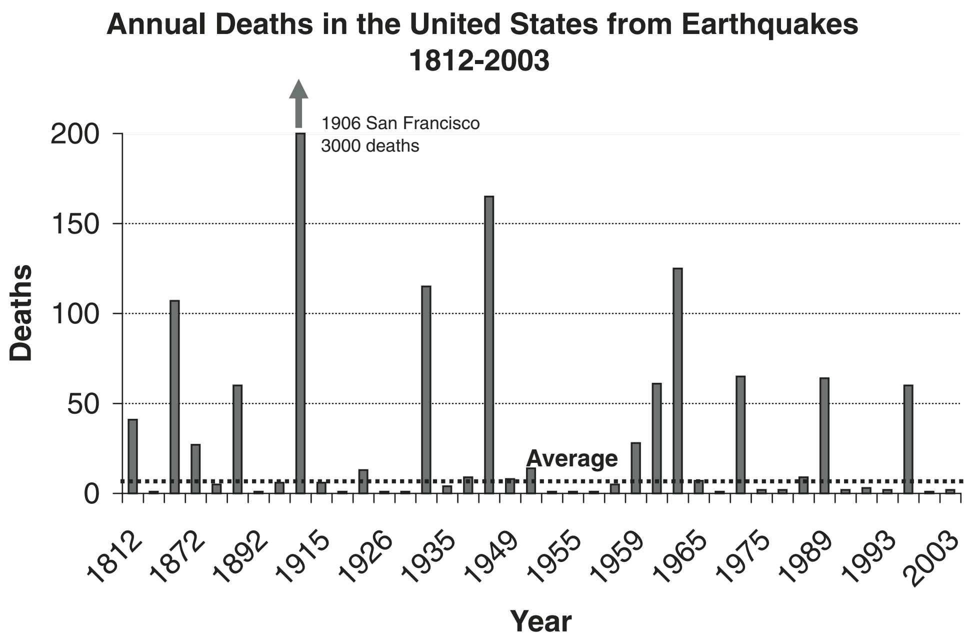

Figure 2. Earthquake deaths in the U.S. Data are from http://earthquake.usgs.gov/regional/states/us_deaths.php.

(e.g., Sella et al., 2002), which made it easier to distinguish plate boundaries from plate interiors. A key to doing so was quantification of deviations from rigid plate behavior, first by using plate motion data at plate boundaries (Stein and Gordon, 1984; DeMets et al., 1990), and later using space geodesy to measure deformation within plates. This process is illustrated by Figure 3, which shows the motions of global positioning system (GPS) sites in North America. Because the motion of a rigid plate is described by a rotation about an Euler pole, sites on the rigid North American plate should move along small circles about the pole, at rates that increase with the sine of the angular distance from the pole. This is the case in eastern North America, whereas motions in the west are quite different, showing that they are part of a broad plate boundary zone.

The deviations of GPS site velocities from those expected for a rigid plate can be used to quantify the deformation of the plate interior, which causes the intraplate earthquakes. Successive studies using increasing amounts of data from the growing number of continuous GPS sites yield increasingly precise velocities. The resulting root-mean-square (rms) misfit of site velocities to those predicted by a single Euler vector if the plate were perfectly rigid is now less than 1 mm/yr (Table 1).

The misfit is strikingly small, given that it reflects the combined effects of intraplate deformation due to tectonics and glacial isostatic adjustment, uncertainties in the positions of geodetic monuments due to the GPS techniques, and local motion of the geodetic monuments. The result seems plausible because similar values emerge from very long baseline radio interferometry studies (Argus and Gordon, 1996). Hence, sites that move faster with respect to the stable interior of the plate than a specified rate, perhaps 2–3 mm/yr, can be viewed as within the boundary zone, whereas those that move more slowly can be viewed as within the plate interior.

This process can be formalized using the GPS data to distinguish a plate boundary zone from deformation within a plate interior, just as plate motion data are tested to see whether they are statistically better fit by assuming the existence of two distinct plates (Stein and Gordon, 1984; Gordon et al., 1987). In such cases, Euler vectors can be derived and used to describe the motion of the two plates, which occurs primarily at their boundaries. Such analyses have shown that North and South America (Stein and Gordon, 1984), India and Australia (Wiens et al., 1985), and Nubia and Somalia (Chu and Gordon, 1999) should be regarded as distinct plates, often with seismicity along their boundaries, rather than single plates with distinct zones of intraplate seismicity. Conversely, application of such analysis to GPS data on opposite sides of the New Madrid seismic zone shows that treating eastern North America as two distinct blocks is not statistically justified (Dixon et al., 1996; Newman et al., 1999). As a result, the New Madrid seismic zone is regarded as a zone of deformation within the North American plate, which contains several others (Mazzotti, chapter 2; Swafford and Stein, chapter 4). Similarly, the earthquakes in the Rhine Graben of northwest Europe (Camelbeeck et al., chapter 14; Hinzen and Reamer, chapter 15) are regarded as intraplate because no significant motion across it has yet been resolved with GPS (Nocquet et al., 2005).

Hence, adequate GPS data can identify the extent of a plate boundary zone and distinguish between it and the plate

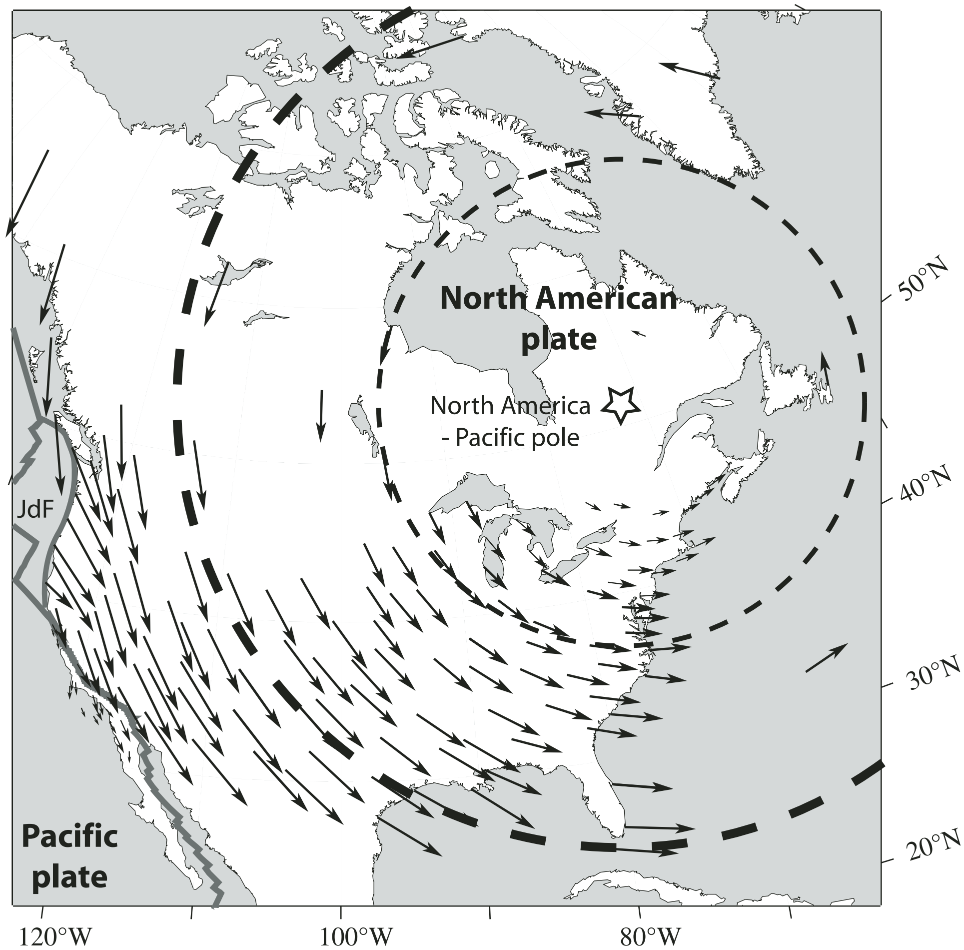

Figure 3. Global positioning system (GPS) site motions (arrows) show the difference between the interior of the North American plate and the Pacific–North America plate boundary zone. Within the plate interior, sites move in small circles about the plate rotation pole (star) at a rate increasing with distance, whereas motions in the boundary zone differ noticeably. These data show that the plate is stable to better than 2 mm/yr, it can be described by a single Euler vector, and it shows no significant motion across the New Madrid seismic zone (Stein and Sella, 2002). JdF—Juan de Fuca plate.

interior. For example, Bada et al. (chapter 16) use GPS data to map deformation in the broad Adriatic deformation region, part of the plate boundary zone between Nubia and Eurasia. However, in areas where adequate GPS data are not yet available, an earthquake can be regarded as either part of the plate boundary zone or within the plate interior. For example, the 2001 Bhuj, India (Mw 7.7), earthquake has been interpreted as a continental intraplate earthquake with analogies to the New Madrid seismic zone in the central United States (Abrams, 2001; Beavers, 2001; Bendick et al., 2001; Ellis et al., 2001). However, it occurs within the broad zone of seismicity and deformation that forms the Indian plate's diffuse western boundary with Eurasia (Fig. 4) (Stein et al., 2002; Li et al., 2002). In western U.S. terms, this location corresponds to Nevada, within the deforming plate boundary zone, where the earthquakes reflect the kinematics and dynamics of the boundary zone (Flesch et al., 2000). In contrast, the New Madrid seismicity is ~2400 km from the San Andreas fault, the nominal boundary, with no obvious relation to the Pacific–North America boundary zone (Li et al., chapter 11). This view of the Bhuj event as part of a plate boundary zone is consistent with Sarkar et al.'s (chapter 20) suggestion that the basement there shows evidence of long-term deformation.

TABLE 1. GLOBAL POSITIONING SYSTEM (GPS) SITES AND ROOT-MEAN-SQUARE (RMS) FITS

Study	Number of sites	Rms misfit (mm/yr)
Dixon et al. (1996)	8	1.3
Newman et al. (1999)	16	1.0
Sella et al. (2002)	64	0.86
Calais et al. (2006)	119*	0.70

Note: Sites with best-determined velocities.

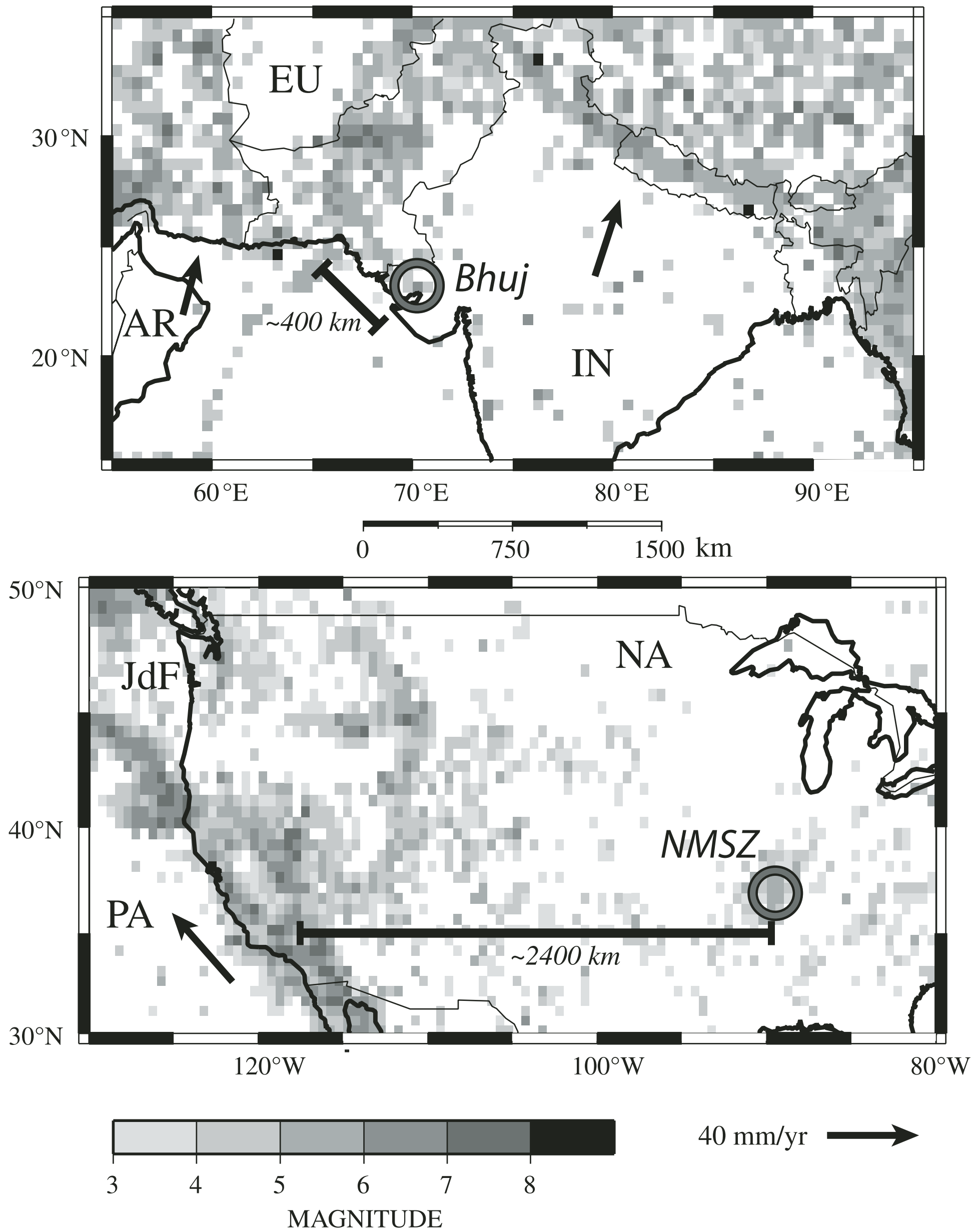

Figure 4. Earthquake magnitude release (1900–1999, depths < 100 km) for part of Indian plate and surroundings (top) and the western United States (bottom), plotted at same spatial scale. In each pixel, cumulative seismicity is estimated by summing the moment release inferred from published magnitudes and reinterpreting its sum as the magnitude of a single event; shaded as shown by the horizontal bar. The Bhuj earthquake is ~400 km from the nominal boundary (EU—Europe, IN—India, AR—Arabian plate), a distance that in U.S. terms is about halfway across the boundary zone between the Pacific (PA) and North American (NA) plates, in the central Nevada seismic belt where magnitude 7 earthquakes occur. In contrast, the New Madrid seismic zone (NMSZ) is in the plate interior, ~2400 km from the nominal boundary (Stein et al., 2002). JdF—Juan de Fuca plate.

DESCRIBING AND MODELING INTRAPLATE DEFORMATION

Space geodetic data have dramatically improved our view of intraplate deformation beyond what was previously possible with sparse earthquake, paleoseismic, and other geologic data. The results can be surprising (Sella et al., 2006; Calais et al., 2006). Figure 5 shows a vertical velocity field for eastern North America that is clearly dominated by the effects of glacial isostatic adjustment from ice-mass unloading following the last glaciation. Vertical velocities show upward rebound (~10 mm/yr) near Hudson Bay, the site of maximum ice load at the Last Glacial Maximum, that decreases to slower subsidence (1–2 mm/yr) south of the Great Lakes. Also shown is a residual horizontal velocity field derived by subtracting the best-fit rigid plate rotation model. These data show coherent deformation associated with the Cascadia subduction zone. The scattered motions in eastern North America are interpreted as showing motions directed outward from Hudson Bay and secondary ice maxima in western Canada. In addition, the motions show a pattern of southeast-directed flow in southwestern Canada that rotates clockwise to southwest-directed flow in the central-western United States. Some of the horizontal scatter is presumably a combination of local site effects (noise for these purposes) and intraplate tectonic signal, but no coherent pattern beyond the glacial isostatic adjustment signal is obvious.

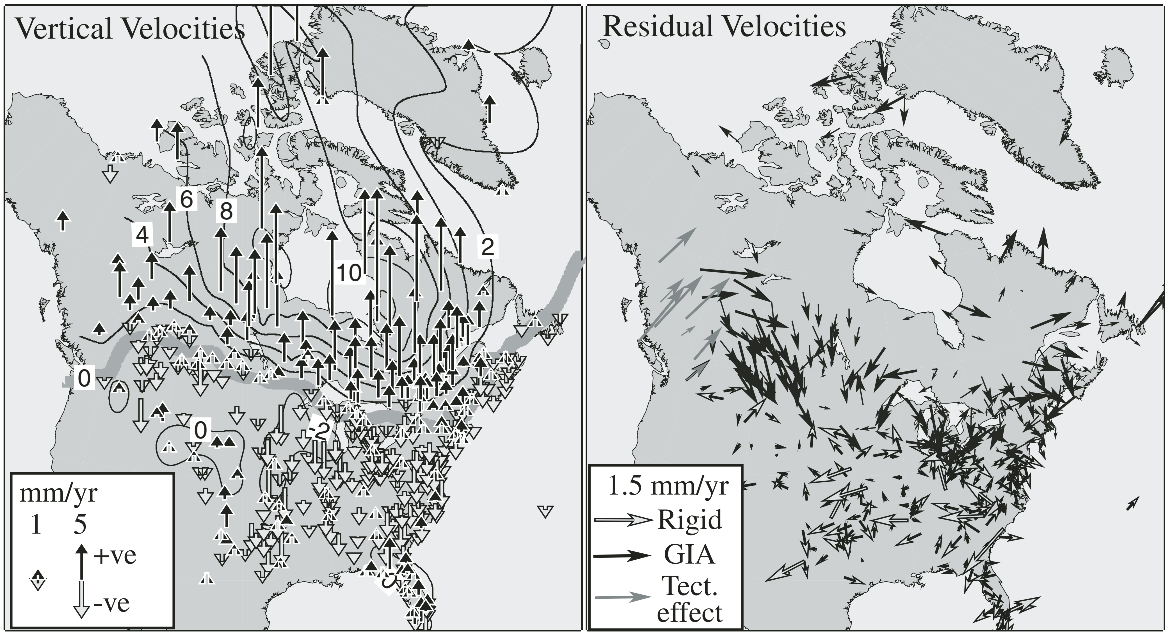

Figure 5. Left: Vertical global positioning system (GPS) site motions. Solid line shows observed “hinge line” separating uplift from subsidence. Sites west of the dashed line, in the plate boundary zone, are not shown. Right: Horizontal motion site residuals after subtracting best-fit rigid plate rotation model (after Sella et al., 2006). GIA—glacial isostatic adjustment.

Such data thus provide powerful new constraints on the intraplate deformation field and the stresses causing it. They are being used to improve models of the effects of glacial isostatic adjustment (e.g., Peltier, 2004; Wu and Mazzotti, chapter 9) via more accurate descriptions of the ice load and laterally variable mantle viscosity. The data will address the long-suspected role of glacial isostatic adjustment as a possible cause or trigger of seismicity in eastern North America and other formerly glaciated areas (e.g., Stein et al., 1979, 1989; Hasegawa and Basham, 1989; Mazzotti and Adams, 2005). Previously, assessing the significance of this effect has proven difficult because the predicted velocities and hence strains vary significantly among glacial isostatic adjustment models, which until recently could not be well constrained. Hence, James and Bent (1994) and Wu and Johnston (2000) found that glacial isostatic adjustment may be significant for seismicity in the St. Lawrence valley but not the more distant New Madrid zone, whereas Grollimund and Zoback (2001) favored glacial isostatic adjustment as the cause of New Madrid seismicity.

Surprisingly, the data show no clear evidence for the platewide compression inferred from stress data and interpreted as a consequence of platewide stresses (e.g., Zoback and Zoback, 1989). Moreover, as will discussed shortly, there is no clear evidence of strain accumulation across the New Madrid zone. Hence the data provide strong upper bounds on both platewide and local deformation.

The increasingly high-quality intraplate velocity fields are now providing data that can be combined with earthquake mechanisms and other data to improve our understanding of intraplate deformation. They can be used to test numerical models of deformation, such as those shown by by Liu et al. (chapter 19) and Wu and Mazzotti (chapter 9). The approach has provided new insights in plate boundary zones, where rates are higher (e.g., Flesch et al., 2000; Liu et al., 2000, 2002). It will become increasing useful within plate interiors for understanding the stresses that cause earthquakes and the rheology of the plate interior, assessing what fraction of the deformation occurs seismically, and providing information on the location and recurrence time of future earthquakes.

TAKING A GLOBAL VIEW

A key to the development of plate tectonics was the formulation of a global synthesis by concentrating on similarities between different areas. The same approach is increasingly being taken in studies of continental intraplate earthquakes. Hence, papers in this book discuss earthquakes in regions outside North America, including Antarctica (Reading, chapter 18), Australia (Leonard et al., chapter 17), China (Liu et al., chapter 19), Europe (Bada et al., chapter 16; Camelbeeck et al., chapter 14; Hinzen and Reamer, chapter 15) and India (Sarkar et al, chapter 20).

Such earthquakes are increasingly viewed not only in terms of specific locations, but also in terms of their tectonic environments (e.g., Gangopadhyay and Talwani, 2003; Schulte and Mooney, 2005). For example, a significant fraction of continental intraplate seismicity occurs along passive continental margins, presumably due to reactivation of fossil structures, including those associated with postglacial rebound (Stein et al., 1979, 1989; Mazzotti et al., 2005). As a result, studies are exploring common features that may contribute to the seismicity (e.g., Mazzotti, chapter 2), such as fault geometry (Gangopadhyay and Talwani, chapter 7) and the effects of postglacial rebound (Wu and Mazzotti, chapter 9; Jacobi et al., chapter 10).

A similar global view is also increasingly being taken in addressing seismic hazards, illustrated by the recent Global Seismic Hazard Map (Giardini et al., 2000). Figure 6 compares earthquake recurrence rates among continental intraplate seismic zones discussed in this volume. On average, a magnitude 6.5 or greater earthquake is expected in Australia about every 20 yr, whereas an earthquake of this size is expected about every 350, 500, and 800 yr in the Pannonian Basin, New Madrid seismic zone, and northwestern Europe, respectively. Hence, some of these areas face similar challenges in assessing the earthquake hazard (Atkinson, chapter 21; Camelbeeck et al., chapter 14; Hinzen and Reamer, chapter 15; Leonard et al., chapter 17; Wang, chapter 24) and developing sensible mitigation strategies (Crandell, chapter 25; Lomnitz and Castanos, chapter 26; Searer et al., chapter 23).

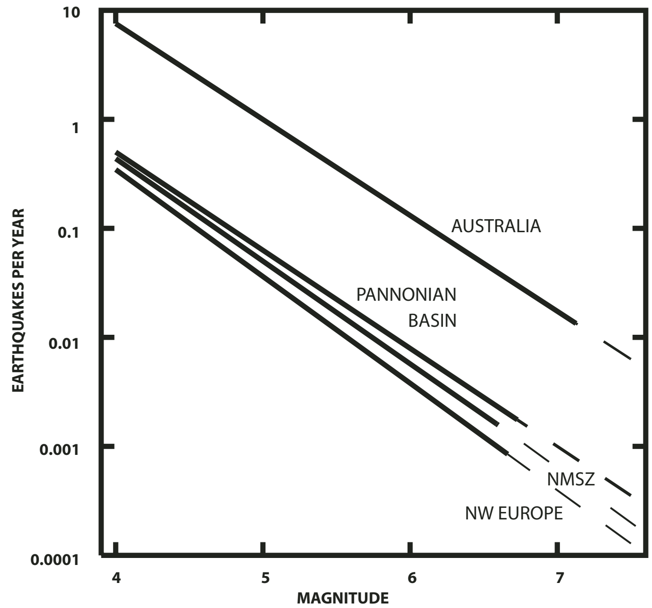

Figure 6. Comparison of the annual rates of earthquakes greater than a given magnitude for several seismic zones discussed in this volume. Solid line shows reported data; dashed line is extrapolated. Sources: New Madrid (Stein and Newman, 2004), Australia (Leonard et al., chapter 17), Pannonian Basin (Bada et al., chapter 16), northwest Europe (Camelbeeck et al., chapter 14). NMSZ—New Madrid seismic zone.

CONFRONTING THE SHORT EARTHQUAKE RECORD

A major difficulty for continental intraplate studies is the short history of instrumental seismology compared to the time between major earthquakes. As a result, inferences drawn from the earthquake history can have serious limitations and leave many questions unanswered. This problem arises even at some plate boundaries. For example, modern seismicity maps show little activity on the segment of the southern San Andreas fault on which the Mw ~7.9 1857 earthquake occurred. The segment of the Sumatra trench on which the great (Mw 9.3) December 2004 earthquake occurred was not particularly active seismically, was not considered particularly dangerous, and was not high risk on seismic gap maps. However, because intraplate deformation is typically much slower (<1 mm/yr) than at most plate boundaries, the recurrence times for large earthquakes in individual parts of the seismic zones are longer, making the recorded seismicity an even worse sample.

This situation gives rise to a number of difficulties. Almost every aspect of hazard estimation faces this challenge, because hazard estimates seek to quantify the shaking expected during periods of time (once in 500 yr in California and most other countries, once in 2500 yr in the central and eastern United States) that are much longer than the seismological record.

One issue is deciding where large earthquakes are likely. Seismic hazard maps for places like the North African coast, North America's eastern continental margin, or the St. Lawrence valley sometimes show bull's-eyes of high predicted hazard where we know from instrumental or historic records that moderate to large earthquakes have occurred. These bull's-eyes result from the assumption that the sites of recent seismicity are more likely to have future large earthquakes than other sites on the same structures. However, one could also assume that the risk is comparable in similar environments for which the short record does not show earthquakes, or higher in these locations due to stress transfer from previous earthquakes. Aspects of this issue are also explored in this book (Mazzotti, chapter 2; Kafka, chapter 3; Swafford and Stein, chapter 4; Li et al., chapter 11; Atkinson, chapter 21).

A related issue is inferences of the maximum size and recurrence interval of future earthquakes in a given area from the short earthquake history. This involves estimating the frequency-magnitude (b value) curve for an area (Okal and Sweet, chapter 5). A crucial question is how well the rate and size of the largest earthquakes can be inferred from the small earthquakes (Fig. 6), even when historical and paleoseismic data are added (Camelbeeck et al., chapter 14; Hinzen and Reamer, chapter 15; Bada et al., chapter 16; Leonard et al., chapter 17). Some insight comes from plate boundary segments with long records, which show variability in the size and recurrence time of large earthquakes. Hence, a short earthquake record from an area with long recurrence times is likely to either miss the largest earthquakes entirely or preferentially detect large earthquakes with recurrence times shorter than the average. As a result, frequency-magnitude (b value) studies are likely to either underpredict the size of the largest earthquakes or conclude that they are characteristic, i.e., more common than expected from the rate of smaller earthquakes (Fig. 7). Moreover, whether characteristic earthquakes appear can depend on the portion of a seismic zone samples (Wesnousky, 1994; Stein et al., 2005).

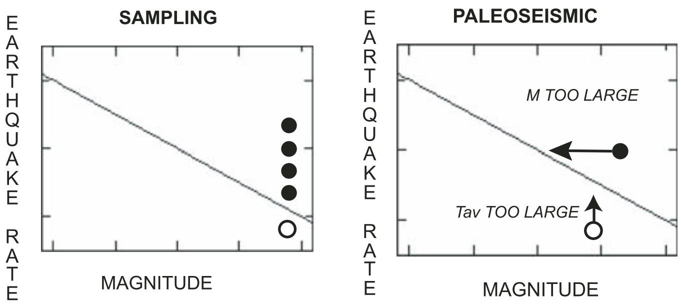

Figure 7. Possible apparent deviations from a log-linear frequency-magnitude relation due to a short earthquake record. Left: Due to sampling bias, the largest earthquakes can seem more common (characteristic, solid circles) than their long-term average recurrence interval, Tav. Alternatively, they can be missed or seem less common (uncharacteristic, open circles) than their long-term average. Right: Apparent characteristic earthquakes occur if paleoseismic data yield overestimates of magnitudes. Apparent uncharacteristic earthquakes occur if paleoseismic data yield overestimates of recurrence intervals (after Stein and Newman, 2004).

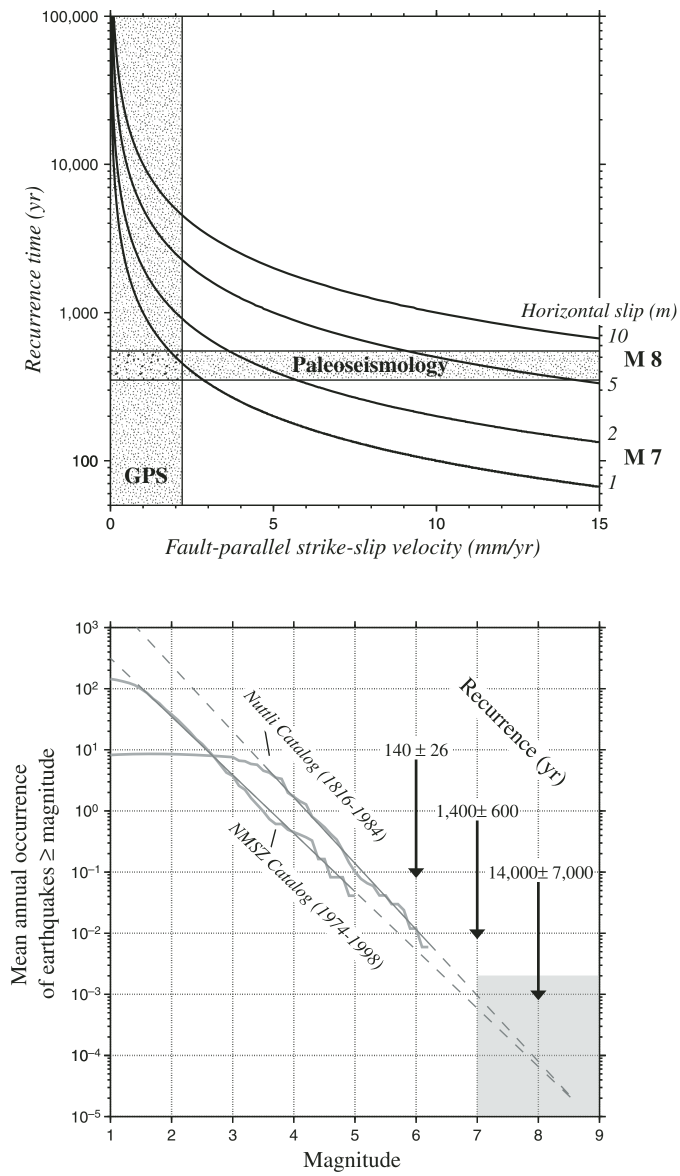

Figure 8. Top: Relation between interseismic motion observed from global positioning system (GPS) and paleoseismic estimates for the recurrence interval of large New Madrid earthquakes. The paleoseismic and geodetic data are jointly consistent with slip in 1811–1812 of ~1 m, corresponding to a magnitude 7 earthquake. Bottom: Earthquake frequency-magnitude data for the New Madrid seismic zone (NMSZ). Both the recent and historic (1816–1984) data have slopes close to one and predict recurrence intervals of ~1000 yr for magnitude 7 earthquakes and 10,000 yr for magnitude 8 earthquakes. Estimates are shown with 2 sigma uncertainties (after Newman et al., 1999).

Although additions of historical and paleoseismic data are valuable, combining these data with seismological data is tricky. Historical studies add events with known dates but with considerable uncertainty in magnitudes. For example, magnitude estimates for the 1906 San Francisco earthquake based on early seismological data have been as high as 8.3, compared to the typical current value of 7.9. The challenge is even greater for pre-instrumental data; recent results suggest low M 7 magnitudes for the largest 1811–12 New Madrid earthquakes (Hough et al., 2000), but published estimates range from low M 7 to over M 8. Paleoseismic studies have uncertainties both in the estimated dates and in recurrence times due to possibly missed events and even larger uncertainties in estimated magnitudes. For example, paleoliquefaction analysis for New Madrid seems to have overestimated the size of paleoevents, producing apparent characteristic earthquakes (Stein and Newman, 2004). Conversely, some paleoearthquakes may not yet have been identified in the nearby Wabash seismic zone, making the implied recurrence interval for large events too long and causing apparent uncharacteristic earthquakes (earthquakes less frequent than expected from the small earthquakes).

INTEGRATING GEODETIC, SEISMOLOGICAL, HISTORICAL, AND PALEOSEISMIC DATA

Geodetic data provide crucial insights into the issues raised by the short earthquake record because they measure the strain accumulating that will be released in future earthquakes. Hence, combinations of the geodetically observed deformation rate with the earthquake history give insight into the size and recurrence time of future large earthquakes.

This approach is illustrated in Figure 8 for New Madrid zone, where GPS data show less than 1–2 mm/yr of motion across the seismic zone (Newman et al., 1999; Gan and Prescott, 2001; Calais et al., 2005, 2006; Stein, 2007; Newman, 2007). Large earthquakes occurred in 1811 and 1812, and earlier such events have been inferred from the distribution of paleoliquefaction features. Wesnousky and Leffler (1992) did not find paleoliquefaction features comparable to those attributed to the 1811–1812 earthquakes and, hence, suggested that such large earthquakes are less common than implied by the instrumental and historic seismicity. In contrast, Tuttle (2001) interpreted paleoliquefaction features as showing that earthquakes comparable to or perhaps somewhat smaller than those in 1811–1812 occurred ca. 1450 ± 150 A.D. (M ≥ 6.7) and 900 ± 100 A.D. (M ≥ 6.9). Taken together, the GPS and paleoseismic data indicate that large earthquakes ~500 yr apart that release 1–2 mm/yr of interseismic motion would have magnitude ~7, consistent with the frequency-magnitude data from smaller earthquakes (Stein and Newman, 2004). Earthquakes with magnitude 8 would require motion across the seismic zone much faster than observed. These constraints are improving as the precision of the GPS site velocities increases (Calais et al., 2005, 2006).

A point worth noting is that such analyses relate the long-term seismicity to the presently observed deformation. The results can thus be biased by transient postseismic deformation. For example, if motions near the fault are dominated by transient strain after the 1811–1812 earthquakes (Rydelek and Pollitz, 1994; Rydelek, 2007), the interseismic strain accumulation rate is even smaller. Alternatively, Kenner and Segall (2000) proposed that a weak zone under the New Madrid seismic zone has recently relaxed, such that, for a few earthquake cycles, strains can be released faster than they accumulate. This hypothesis suffers from the fact that there is no evidence for such a weak zone (McKenna et al., chapter 12) and no obvious reason for why the proposed weakening occurred.

Geodetic data are being integrated similarly with seismological, historical, paleoseismic, and other geologic data in other intraplate seismic zones (Mazzotti, chapter 2; Camelbeeck et al., chapter 14; Leonard et al., chapter 17). Among the best such data at present are those presented by Bada et al. (chapter 16) for the Pannonian Basin, where the GPS shortening rate is well constrained and consistent with the seismicity. As for New Madrid, longer series of higher-quality GPS data will make this approach progressively more powerful.

This approach is also starting to shed light on the question of what fraction of the intraplate deformation is released seismically, because geodetic strain rates can be compared to those inferred from the seismic moment release. It appears that essentially all of the expected motion occurs seismically on the San Andreas fault (Stein and Hanks, 1998) and in continental interiors, as implied in Figure 8 and by the Pannonian Basin results (Bada et al., chapter 16). In contrast, trenches (Pacheco et al., 1993), oceanic transforms (Kreemer et al., 2002), and some (but not all) continental plate boundary zones (e.g., Jackson and McKenzie, 1988; Klosko et al., 2002; Pancha et al., 2006) appear to have significant aseismic motion. At present, it is unclear how well these variations are known, and whether they reflect differences in rheology and deformation, or are artifacts of the short earthquake history—this is crucial because most of the slip occurs in the infrequent largest events.

INVESTIGATING THE MECHANICS AND LONGEVITY OF SEISMIC ZONES

A fundamental question about continental intraplate earthquakes is why they are where they are. Although most earthquakes can be related to some structural feature, the explanation has limited predictive value, because continents contain many such features, of which a few are the most active. Hence, it is important to know whether over time seismicity continues on the structures that are most active at present, or is episodic and migrates between many similar structures. This issue is both of scientific importance and is crucial for assessing seismic hazards.

One approach to the question is to compare seismological, historical, paleoseismic, and other geological data. This approach increasingly finds that continental intraplate earthquakes are episodic, clustered, and migrate. Faults seem to go through cycles of activity punctuated by long periods of inactivity (Crone et al., 2003). Sarkar et al. (chapter 20) examine basement structure near the site of the Bhuj earthquake for evidence of long-term deformation. Studies for Australia (Leonard et al., chapter 17) and northwest Europe (Camelbeeck et al., chapter 14) consider the role of faults that appear to have been active in the past, although the short seismic record sometimes shows no activity on them. The idea that seismicity migrates is consistent with results for North America—these results indicate that the New Madrid zone became active recently (Schweig and Ellis, 1994, Newman et al., 1999; Holbrook et al., 2006), and they also show evidence of Holocene surface faulting that appears to be seismically inactive at present (Crone and Luza, 1990). What mechanism makes faults "turn on," "turn off," or change sense of motion remains unclear. Possible factors include stress changes due to regional tectonics (Bada et al., chapter 16; Liu et al., chapter 19), post-glacial rebound (Stein et al., 1979, 1989; Mazzotti et al., 2005; Wu and Mazzotti, chapter 9; Jacobi et al., chapter 10), and denudation (Van Arsdale et al., chapter 13).

Another approach is to explore spatial and temporal correlations in seismicity. Kafka (chapter 3) finds that portions of seismic catalogs predict later seismicity well. An interesting question is: Does the fact that seismically active areas are likely places for continued small earthquakes make future large earthquakes more likely there than in other regions that may be equally or more susceptible to strain concentrations? Part of the challenge in answering this question involves understanding the role of static (Li et al., chapter 11) and dynamic (Hough, chapter 6) stress triggers in controlling future earthquake locations. A related question is whether much of the present seismicity reflects aftershocks of large past earthquakes (Stein and Newman, 2004).

A third approach explores the thermo-mechanical structure of the seismic zones to assess whether there is something special about them that results in long-lived weak zones on which intraplate strain release concentrates. Mazzotti (chapter 2) considers various models for the relations among lithospheric strength, strain distribution, and seismicity. Gangopadhyay and Talwani (chapter 7) propose that fault geometry favors earthquake occurrence. McKenna et al. (chapter 12) use heat-flow data to infer that the New Madrid zone is not significantly hotter and weaker than its surroundings, although such weakness has been postulated. These results argue against the New Madrid seismic zone being a long-lived weak zone on which intraplate strain release concentrates, and they favor a model of migrating seismicity.

RECOGNIZING THE UNCERTAINTY IN SEISMIC HAZARD ESTIMATES

Given the limitations of our present knowledge about continental intraplate earthquakes, it is not surprising that estimates of the hazard they pose have considerable uncertainties (Atkinson, chapter 21; Wang, chapter 24). These uncertainties result from the fact that we do not understand the underlying causes of the earthquakes and have a limited earthquake history, typically without seismological records of the largest earthquakes of concern. Hence, their magnitudes and recurrence intervals are difficult to reliably infer, and the resulting ground motion must be extrapolated from smaller earthquakes (Bent and Delahaye, chapter 22).

As a result, a wide range of hazard estimates can be made. These are illustrated by comparison of maps for the New Madrid region (Fig. 9) that show the maximum predicted acceleration expected approximately once every 2500 yr for different assumptions. As shown, the areas of significant hazard (0.2 g corresponds approximately to the onset of major damage to some buildings) differ significantly. The differences are even

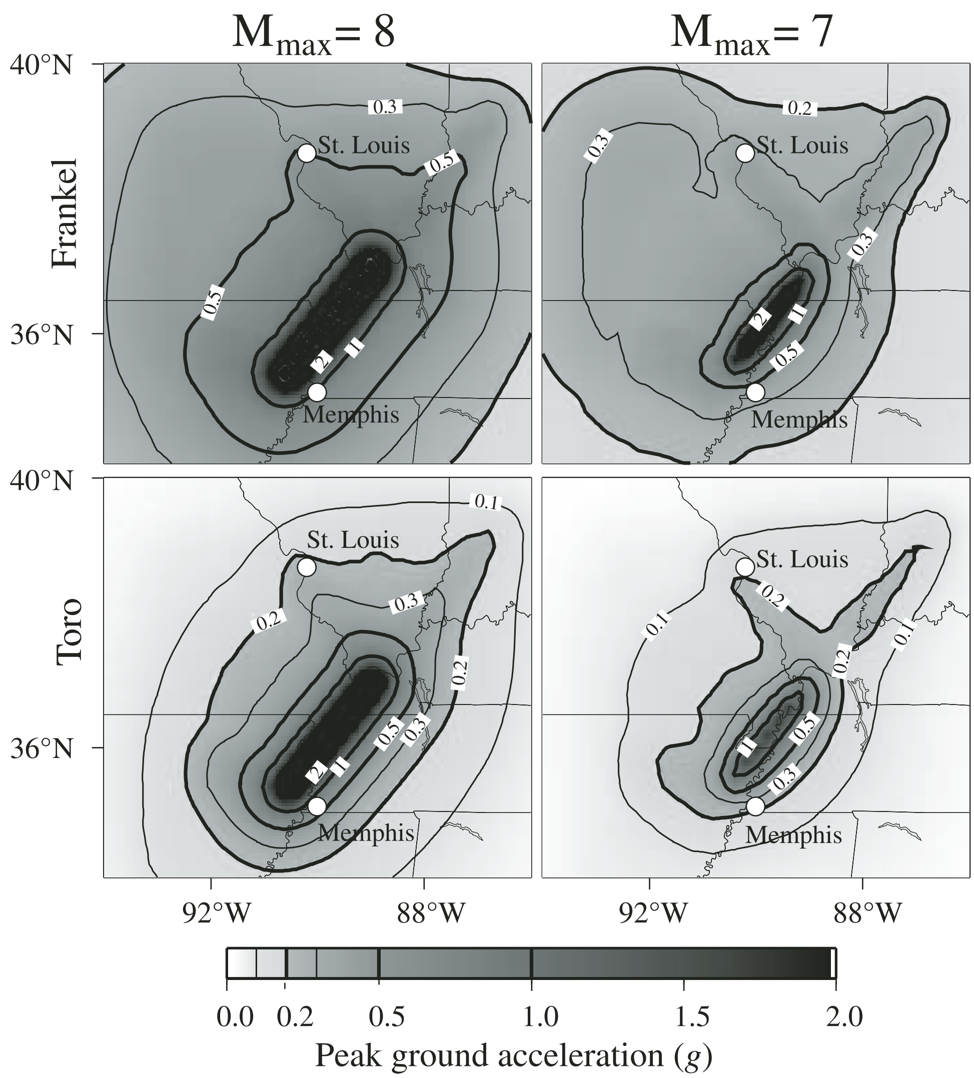

Figure 9. Comparison of the predicted seismic hazard (peak ground acceleration expected at 2% probability in 50 yr) from New Madrid seismic zone earthquakes for alternative parameter choices. Columns show the effect of varying the magnitude of the largest earthquake every 500 yr from 8 to 7, which primarily affects the predicted acceleration near the main faults. Rows show how different ground motion models affect the predicted acceleration over a larger area (after Newman et al., 2001).

greater for longer-period ground motion, which poses the threat to tall buildings. These uncertainties will remain unresolved at least until the next major earthquake.

An important additional contributor to the uncertainty, discussed earlier, is the question of whether to view the hazard as highest where recent seismicity has been concentrated or as essentially uniform within regions of similar structure. This question relates to the issue of whether locations of large future earthquakes are well predicted by the short seismic record or if instead seismicity migrates such that faults that seem aseismic from the earthquake record may be the next to generate a damaging earthquake. Depending on the assumptions made, quite different hazard estimates arise (Atkinson, chapter 21; Swafford and Stein, chapter 4). Put another way, we can assume that earthquakes are most likely in parts of a seismic zone where they have happened recently, more likely where they haven't happened recently, or equally likely throughout the zone. The predicted hazards vary: time-independent models predict the same probability of a large earthquake regardless of the time since the last one, whereas time-dependant models predict lower probabilities for the first two-thirds of the mean recurrence interval, and then higher probabilities as the earthquake is "due" (Fig. 10; Stein and Wysession, 2003; Stein et al., 2003). There is no standard choice: some California maps have been based on time-dependant probabilities, whereas the central U.S. maps (Frankel et al., 1996) are based on time-independence. In each region, these opposite assumptions chosen tend to predict higher probabilities than the alternative, due to the longer recurrence time in the central United States.

A final crucial issue is how to define the hazard. This issue is crucial in discussions of the appropriate codes to specify the earthquake resistance of buildings for intraplate areas. For example, the U.S. Federal Emergency Management Agency (FEMA) has proposed a new building code that would increase the earthquake resistance of new buildings in the New Madrid zone to levels similar to those in southern California. This proposal derives from an argument (Frankel, 2004) that the seismic hazard, defined as the maximum predicted acceleration expected at 2% probability in 50 yr, or approximately once every 2500 yr, is comparable for sites in the New Madrid zone to that for sites in California.

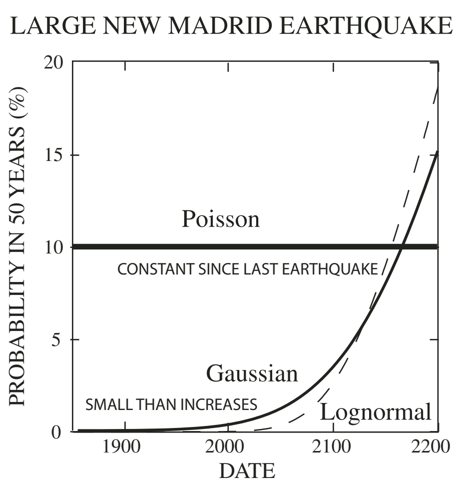

Figure 10. Predicted probabilities of a large New Madrid earthquake in the next 50 years as a function of time since the last one in 1812, for different models assuming a recurrence interval of 500 ± 100 yr. The predicted probability is much higher for the time-independent Poisson model than for the two-time-dependent models (Stein et al., 2003).

The utility of this criterion, which is much more stringent than the 500 yr one used for other natural disaster planning, is debatable. Searer et al. (chapter 23) show that the long time window makes the assumed hazard in the New Madrid seismic zone and California comparable, whereas use of a 500 yr window (as is used in California or most other countries) yields much higher hazard in California. Similarly, by taking a sufficiently long time, the hazard anywhere can be defined as comparable to California's (Stein, 2004a). This situation arises because the hazard is defined as the maximum shaking at a geographic point over a period of time rather than what would be experienced by a typical structure during its much shorter (50–100 yr) life. The difference is illustrated in Figure 11, which contrasts the fractions of the regions that might be shaken strongly enough to seriously damage some buildings. In 100 yr (upper panels), much of the California region will be shaken seriously, whereas a much smaller fraction of the New Madrid seismic zone would be. After 1000 yr (lower panels), much of the New Madrid seismic zone has been shaken once, whereas most of the California area has been shaken many times. Although the maximum shaking at a given location in the New Madrid seismic zone over thousands of years may be comparable to that in California, a building in California is much more likely to be seriously shaken during its ~50–100 yr life. Thus, over the life of a new building in Memphis, there is a reasonable probability of low to moderate shaking, but a significantly lower probability of severe shaking. Similar issues arise in other areas of intraplate seismicity.

DEVELOPING MITIGATION STRATEGIES

The final theme in this book, explored by Crandell (chapter 25), Lomnitz and Castanos (chapter 26) and Searer et al. (chapter 23) is the use of our knowledge to formulate policies that address the societal risk posed by continental intraplate earthquakes. Several approaches are used, all of which are equally applicable to mitigating the effects of other natural disasters. These include site restrictions that exclude certain structures from hazardous areas, building codes that require levels of earthquake resistance, insurance that compensates for losses and provides funds for reconstruction, and emergency preparedness for response during and after an earthquake.

Society must decide how much to accept in additional present costs in order to reduce both the direct and indirect losses in future earthquakes. This involves tradeoffs between present uses of resources and the use of those same resources for other applications that also do societal good. For example, funds

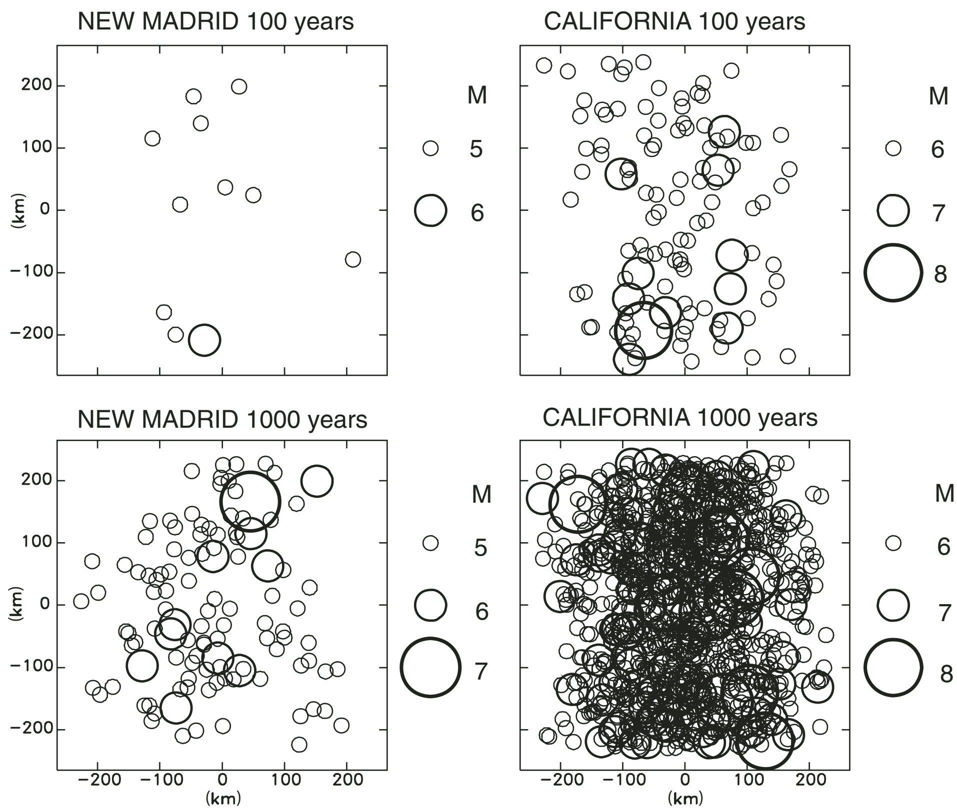

Figure 11. Schematic comparison of seismic hazard using maps for the New Madrid seismic zone and southern California on two time scales. Seismicity is assumed to be random, with California 100 times more active but New Madrid earthquakes causing strong shaking over an area equal to that for a California earthquake one-magnitude-unit larger. Areas of shaking with acceleration > 0.2g are shown by circles (Stein and Wysession, 2003).

spent strengthening schools are not available to hire teachers, and stronger hospitals may come at the expense of providing health care. Similarly, imposing costs on the private sector can cause reduced economic activity (firms don't build or build elsewhere) and impose other costs, which in turn affect society as a whole. Choosing a mitigation strategy thus requires estimations of the costs and benefits of various possible strategies. Surprisingly, these have often been proposed and even implemented without this crucial analysis. For example, the 2500 yr hazard definition for the central United States was adopted without economic analysis, making its justification questionable (Searer et al., chapter 23).

Fortunately, there is an increasing trend to explore these issues. FEMA (2001) has developed estimates of annualized earthquake losses for various cities and states in the United States that can be used for comparison with the costs of potential mitigation strategies (Stein, 2003; Crandell chapter 25; Searer et al., chapter 23). Leonard et al. (chapter 17) illustrate how the probabilistic seismic hazard estimates and their uncertainties can be used to study potential earthquake losses. An important challenge is estimating how much various mitigation strategies would reduce losses, which is the benefit that needs to be compared to their cost. A tricky aspect of this challenge is that it involves seismologists and earthquake engineers working together and appreciating each group's approach and the associated uncertainties.

Decisions on mitigation strategies involve tough choices that are ultimately economic and societal (Stein et al., 2003; Stein, 2004b, Crandell, chapter 25). Although these decisions are hard for earthquake hazard mitigation in any setting, it is especially difficult for the rarer intraplate earthquakes, the recurrence and effects of which are even less well understood. Helping to make these choices, given our imperfect knowledge, will be an increasing challenge for earth scientists in years to come as the population in earthquake-prone areas continues to grow.

ACKNOWLEDGMENTS

Much of the fun involved with puzzling over intraplate earthquakes and tectonics comes from the stimulating interchanges that this puzzling phenomena generates. I have benefited from discussions over the years with many researchers including Andrew Newman, Tim Dixon, Mian Liu, Sue Hough, John Schneider, Giovanni Sella, Stephane Mazzotti, and Eric Calais.

REFERENCES CITED

Abrams, D., 2001, Will Gujarat's problem be ours: Mid-America Earthquake Center Newsletter, April, v. 4, p. 2–3.

Argus, D.F., and Gordon, R.G., 1996, Tests of the rigid-plate hypothesis and bounds on intraplate deformation using geodetic data from very long baseline interferometry: Journal of Geophysical Research, v. 101, p. 13,555–13,572, doi: 10.1029/95JB03775.

Atkinson, G., 2007, this volume, Challenges in seismic hazard analysis for continental interiors, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(21).

Bada, G., Grenerczy, G., Toth, L., Horvath, F., Stein, S., Windhoffer, G., Fodor, L., Fejes, I., Pinter, N., and Cloetingh, S., 2007, this volume, Motion of Adria and ongoing inversion of the Pannonian Basin: Seismicity, GPS velocities and stress transfer, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(16).

Beavers, J., 2001, Kutch earthquake: What we now know: Mid-America Earthquake Center Newsletter, February, v. 4, p. 2–4.

Bendick, R., Bilham, R., Fielding, E., Gaur, V.K., Hough, S.E., Kulkarni, M.N., Martin, S., Mueller, K., and Mukul, M., 2001, The 26 January 2001 "Republic Day" earthquake, India: Seismological Research Letters, v. 72, p. 328–335.

Bennett, R.A., Davis, J.L., and Wernicke, B.P., 1999, Present-day pattern of Cordilleran deformation in the Western United States: Geology, v. 27, p. 371–374, doi: 10.1130/0091-7613(1999)027<0371:PDPOCD>2.3.CO;2.

Bent, A., and Delahaye, E., 2007, this volume, H/V at short distances for four hardrock sites in eastern Canada and implications for seismic hazard assessment, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(22).

Calais, E., Mattioli, G., DeMets, C., Nocquet, J.-M., Stein, S., Newman, A., and Rydelek, P., 2005, Tectonic strain in plate interiors?: Nature, v. 438, doi: 10.1038/nature04428.

Calais, E., Han, J., and DeMets, C., 2006, Deformation of the North American plate from a decade of continuous GPS measurements: Journal of Geophysical Research, v. 111, doi: 10.1029/2005JB004253.

Camelbeeck, T., Vanneste, K., Alexandre, P., Verbeeck, K., Petermans, T., Rosset, P., Everaerts, M., Warnant, R., and Van Camp, M., 2007, this volume, Relevance of active faulting and seismicity studies to assess long term earthquake activity in Northwest Europe, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(14).

Chase, C.G., 1972, The *n*-plate problem of plate tectonics: Geophysical Journal of the Royal Astronomical Society, v. 29, p. 117–122.

Chase, C.G., 1978, Plate kinematics: The Americas, East Africa, and the rest of the world: Earth and Planetary Science Letters, v. 37, p. 355–368, doi: 10.1016/0012-821X(78)90051-1.

Chu, D., and Gordon, R.G., 1999, Evidence for motion between Nubia and Somalia along the Southwest Indian ridge: Nature, v. 398, p. 64–67, doi: 10.1038/18014.

Crandell, J., 2007, this volume, Policy development and uncertainty in earthquake risk in the New Madrid seismic zone, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(25).

Crone, A.J., and Luza, K.V., 1990, Style and timing of Holocene surface faulting on the Meers fault, southwestern Oklahoma: Geological Society of America Bulletin, v. 102, p. 1–17, doi: 10.1130/0016-7606(1990)102<0001:SATOHS>2.3.CO;2.

Crone, A.J., De Martini, P.M., Machette, M.N., Okumura, K., and Prescott, J.R., 2003, Paleoseismicity of two historically quiescent faults in Australia: Implications for fault behavior in stable continental regions: Bulletin of the Seismological Society of America, v. 93, p. 1913–1934.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990, Current plate motions: Geophysical Journal International, v. 101, p. 425–478.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1994, Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motion: Geophysical Research Letters, v. 21, p. 2191–2194, doi: 10.1029/94GL02118.

Dixon, T.H., Mao, A., and Stein, S., 1996, How rigid is the stable interior of the North American plate?: Geophysical Research Letters, v. 23, p. 3035–3038, doi: 10.1029/96GL02820.

Ellis, M.E., Gomberg, J., and Schweig, E., 2001, Indian earthquake may serve as analog for New Madrid earthquakes: Eos (Transactions, American Geophysical Union), v. 82, p. 345–350, doi: 10.1029/01EO00211.

FEMA (Federal Emergency Management Agency), 2001, HAZUS 99 Estimated Annualized Losses for the United States: Federal Emergency Management Agency Publication 366.

Flesch, L.M., Holt, W.E., Haines, A.J., and Shen-Tu, B., 2000, Dynamics of the Pacific–North American plate boundary zone in the western United States: Science, v. 287, p. 834–836, doi: 10.1126/science.287.5454.834.

Frankel, A., 2004, How can seismic hazard in the New Madrid seismic zone be similar to that in California?: Seismological Research Letters, v. 75, p. 575–586.

Frankel, A., Mueller, C., Barnhard, T., Perkins, D., Leyendecker, E., Dickman, N., Hanson, S., and Hopper, M., 1996, National Seismic Hazard Maps Documentation: U.S. Geological Survey Open-File Report 96-532, 110 p.

Gan, W., and Prescott, W., 2001, Crustal deformation rates in central and eastern U.S. inferred from GPS: Geophysical Research Letters, v. 28, p. 3733–3736, doi: 10.1029/2001GL013266.

Gangopadhyay, A., and Talwani, P., 2003, Symptomatic features of intraplate earthquakes: Seismological Research Letters, v. 74, p. 863–883.

Gangopadhyay, A., and Talwani, P., 2007, this volume, Two-dimensional numerical modeling suggests preferred geometry of intersecting seismogenic faults, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(07).

Giardini, D., Grunthal, G., Shedlock, K.M., and Zhang, P., 2000, The GSHAP Global Seismic Hazard Map: Seismological Research Letters, v. 71, p. 679–686.

Gordon, R.G., Stein, S., DeMets, C., and Argus, D.F., 1987, Statistical tests for closure of plate motion circuits: Geophysical Research Letters, v. 14, p. 587–590.

Grollimund, B., and Zoback, M.D., 2001, Did deglaciation trigger intraplate seismicity in the New Madrid seismic zone?: Geology, v. 29, p. 175–178.

Hasegawa, H.S., and Basham, P., 1989, Spatial correlation between seismicity and postglacial rebound in eastern Canada, *in* Gregerson, S., and Basham, P., eds., Earthquakes at North Atlantic Passive Margins: Neotectonics and Postglacial Rebound: Dordrecht, Kluwer, p. 483–500.

Hinzen, K., and Reamer, S., 2007, this volume, Seismicity, seismotectonics, and seismic hazard in the northern Rhine Area, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(15).

Hough, S., 2007, this volume, Remotely triggered earthquakes following moderate mainshocks, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(06).

Hough, S., Armbruster, J.G., Seeber, L., and Hough, J.F., 2000, On the modified Mercalli intensities and magnitudes of the 1811/1812 New Madrid, central United States, earthquakes: Journal of Geophysical Research, v. 105, p. 23,839–23,864, doi: 10.1029/2000JB900110.

Jackson, J., and McKenzie, D., 1988, The relationship between plate motions and seismic moment tensors, and the rates of active deformation in the Mediterranean and Middle East: Geophysical Journal of the Royal Astronomical Society, v. 93, p. 45–73.

Jacobi, R., Lewis, C.F., Armstrong, D., and Blasco, S., 2007, this volume, Popup field in Lake Ontario south of Toronto, Canada: Indicators of late glacial and post-glacial strain, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(10).

James, T.S., and Bent, A.L., 1994, A comparison of eastern North America seismic strain-rates to glacial rebound strain-rates: Geophysical Research Letters, v. 21, p. 2127–2130, doi: 10.1029/94GL01854.

Kafka, A., 2007, this volume, Does seismicity delineate zones where future large earthquakes are likely to occur in intraplate environments?, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(03).

Kenner, S.J., and Segall, P., 2000, A mechanical model for intraplate earthquakes: Application to the New Madrid seismic zone: Science, v. 289, p. 2329–2332, doi: 10.1126/science.289.5488.2329.

Klosko, E.R., Stein, S., Hindle, D., Kley, J., Norabuena, E., Dixon, T., and Liu, M., 2002, Comparison of GPS, seismological, and geologic observations of Andean mountain building, *in* Stein, S., and Freymueller, J., eds., Plate Boundary Zones: Washington, D.C., American Geophysical Union, p. 123–133.

Kreemer, C., Haines, J., and Holt, W.E., 2002, The global moment rate distribution within plate boundary zones, *in* Stein, S., and Freymueller, J., eds., Plate Boundary Zones: Washington, D.C., American Geophysical Union, p. 173–190.

Leonard, M., Robinson, D., Allen, T., Schneider, J., Clark, D., Dhu, T., and Burbidge, D., 2007, this volume, Toward a better model for earthquake hazard in Australia, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(17).

Li, Q., Liu, M., and Yang, Y., 2002, The 01/26/2001 Bhuj earthquake: Intraplate or interplate?, *in* Stein, S., and Freymueller, J., eds., Plate Boundary Zones: Washington, D.C., American Geophysical Union, p. 255–264.

Li, Q., Liu, M., Zhang, Q., and Sandoval, E., 2007, this volume, Stress evolution and seismicity in the central-eastern USA: Insight from geodynamic modeling, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(11).

Liu, M., Zhu, Y., Stein, S., Yang, Y., and Engeln, J., 2000, Crustal shortening in the Andes: Why do GPS rates differ from geological rates: Geophysical Research Letters, v. 27, p. 3005–3008, doi: 10.1029/2000GL008532.

Liu, M., Yang, Y., Stein, S., and Klosko, E., 2002, Crustal shortening and extension in the Andes from a viscoelastic model, *in* Stein, S., and Freymueller, J., eds., Plate Boundary Zones: Washington, D.C., American Geophysical Union, p. 325–339.

Liu, M., Yang, Y., Shen, Z., Wang, S., Wang, M., and Wan, Y., 2007, this volume, Active tectonics and intracontinental earthquakes in China: The kinematics and geodynamics, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(19).

Lomnitz, C., and Castanos, H., 2007, this volume, Disasters and maximum entropy production, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(26).

Mazzotti, S., 2007, this volume, Geodynamic models for North America intraplate earthquakes, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(02).

Mazzotti, S., and Adams, J., 2005, Rates and uncertainties on seismic moment and deformation in eastern Canada: Journal of Geophysical Research, v. 110, doi: 10.1029/2004JB003510.

Mazzotti, S., James, T., Henton, J., and Adams, J., 2005, GPS crustal strain, postglacial rebound, and seismic hazard in eastern North America: The Saint Lawrence valley example: Journal of Geophysical Research, v. 110, doi: 10.1029/2004JB003590.

McKenna, J., Stein, S., and Stein, C.A., 2007, this volume, Is the New Madrid seismic zone hotter and weaker than its surroundings?, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(12).

Minster, J.B., and Jordan, T.H., 1978, Present-day plate motions: Journal of Geophysical Research, v. 83, p. 5331–5354.

Minster, J.B., Jordan, T.H., Molnar, P., and Haines, E., 1974, Numerical modeling of instantaneous plate tectonics: Geophysical Journal of the Royal Astronomical Society, v. 36, p. 541–576.

Morgan, W.J., 1968, Rises, trenches, great faults, and crustal blocks: Journal of Geophysical Research, v. 73, p. 1959–1982.

Newman, A., Stein, S., Weber, J., Engeln, J., Mao, A., and Dixon, T., 1999, Slow deformation and lower seismic hazard at the New Madrid seismic zone: Science, v. 284, p. 619–621, doi: 10.1126/science.284.5414.619.

Newman, A., Stein, S., Schneider, J., and Mendez, A., 2001, Uncertainties in seismic hazard maps for the New Madrid seismic zone: Seismological Research Letters, v. 72, p. 653–667.

Nocquet, J.M., Calais, E., and Parsons, B., 2005, Geodetic constraints on glacial isostatic adjustment in Europe: Geophysical Research Letters, v. 32, doi: 10.1029/2004GL022174.

Okal, E., and Sweet, J., 2007, this volume, Frequency-size distributions for intraplate seismicity, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(05).

Pacheco, J., Sykes, L.R., and Scholz, C.H., 1993, Nature of seismic coupling along simple plate boundaries of the subduction type: Journal of Geophysical Research, v. 98, p. 14,133–14,159.

Pancha, A., Anderson, J., and Kreemer, C., 2006, Comparison of seismic and geodetic scalar moment rates across the Basin and Range Province: Bulletin of the Seismological Society of America, v. 96, p. 11–32, doi: 10.1785/0120040166.

Peltier, W.R., 2004, Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model: Annual Review of Earth and Planetary Sciences, v. 32, p. 111–149, doi: 10.1146/annurev.earth.32.082503.144359.

Reading, A., 2007, this volume, The seismicity of the Antarctic plate, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(18).

Rydelek, P.A., and Pollitz, F.F., 1994, Fossil strain from the 1811–1812 New Madrid earthquakes: Geophysical Research Letters, v. 21, p. 2303–2306, doi: 10.1029/94GL02057.

Rydelek, P.A., 2007, New Madrid strain and postseismic transients: Eos (Transactions, American Geophysical Union), v. 88, p. 60–61.

Sarkar, D., Sain, K., Reddy, P.R., Catchings, R.D., and Mooney, W.D., 2007, this volume, Seismic reflection images of the crust beneath the 2001 M = 7.7 Kutch (Bhuj) epicentral region, western India, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(20).

Schulte, S.M., and Mooney, W.D., 2005, An updated global earthquake catalogue for stable continental regions: Reassessing the correlation with ancient rifts: Geophysical Journal International, v. 161, p. 707–721, doi: 10.1111/j.1365-246X.2005.02554.x.

Schweig, E.S., and Ellis, M.A., 1994, Reconciling short recurrence intervals with minor deformation in the New Madrid seismic zone: Science, v. 264, p. 1308–1311, doi: 10.1126/science.264.5163.1308.

Searer, G., 2007, this volume, Does it make sense from engineering and economic perspectives to design for a 2475-year earthquake?, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(23).

Sella, G.F., Dixon, T.H., and Mao, A., 2002, REVEL: A model for recent plate velocities from space geodesy: Journal of Geophysical Research, v. 107, no. B4, doi: 10.1029/2000JB000033.

Sella, G.F., Stein, S., Dixon, T., Craymer, M., James, T., Mazzotti, S., and Dokka, R., 2006, Observations of glacial isostatic adjustment in stable North America with GPS: Geophysical Research Letters, v. 34, doi: 10.1029/2006GL02708.

Stein, R.S., and Hanks, T.C., 1998, M > 6 earthquakes in Southern California during the twentieth century: No evidence for a seismicity or moment deficit: Bulletin of the Seismological Society of America, v. 88, p. 635–652.

Stein, S., 2004a, Comment on "How can seismic hazard in the New Madrid seismic zone be similar to that in California?" by A. Frankel: Seismological Research Letters, v. 75, p. 362–363.

Stein, S., 2004b, No free lunch: Seismological Research Letters, v. 75, p. 555–556.

Stein, S., 2007, New Madrid GPS: Much ado about nothing?: Eos (Transactions, American Geophysical Union), v. 88, p. 58–60.

Stein, S., and Gordon, R.G., 1984, Statistical tests of additional plate boundaries from plate motion inversions: Earth and Planetary Science Letters, v. 69, p. 401–412, doi: 10.1016/0012-821X(84)90198-5.

Stein, S., and Newman, A., 2004, Characteristic and uncharacteristic earthquakes as possible artifacts: Applications to the New Madrid and Wabash seismic zones: Seismological Research Letters, v. 75, p. 170–184.

Stein, S., and Sella, G.F., 2002, Plate boundary zones: Concept and approaches, *in* Stein, S., and Freymueller, J., eds., Plate Boundary Zones: Washington, D.C., American Geophysical Union, p. 1–26.

Stein, S., and Wysession, M., 2003, Introduction to Seismology, Earthquakes, and Earth Structure: Oxford, Blackwell, 498 p.

Stein, S., Sleep, N.H., Geller, R.J., Wang, S.C., and Kroeger, G.C., 1979, Earthquakes along the passive margin of eastern Canada: Geophysical Research Letters, v. 6, p. 537–540.

Stein, S., Cloetingh, S., Sleep, N., and Wortel, R., 1989, Passive margin earthquakes, stresses, and rheology, *in* Gregerson, S., and Basham, P., eds., Earthquakes at North Atlantic Passive Margins: Neotectonics and Postglacial Rebound: Dordrecht, Kluwer, p. 231–260.

Stein, S., Sella, G.F., and Okal, E.A., 2002, The January 26, 2001, Bhuj earthquake and the diffuse western boundary of the Indian plate, *in* Stein, S., and Freymueller, J., eds., Plate Boundary Zones: Washington, D.C., American Geophysical Union, p. 243–254.

Stein, S., Newman, A., and Tomasello, J., 2003, Should Memphis build for California's earthquakes?: Eos (Transactions, American Geophysical Union), v. 84, p. 177, 184–185.

Stein, S., Friedrich, A., and Newman, A., 2005, Dependence of possible characteristic earthquakes on spatial sampling: illustration for the Wasatch seismic zone, Utah: Seismological Research Letters, v. 76, p. 432–436.

Swafford, L., and Stein, S., 2007, this volume, Limitations of the short earthquake record for seismicity and seismic hazard studies, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(04).

Sykes, L.R., 1978, Intraplate seismicity, reactivation of pre-existing zones of weakness, alkaline magmatism, and other tectonism postdating continental fragmentation: Reviews of Geophysics and Space Physics, v. 16, p. 621–688.

Tuttle, M.P., 2001, The use of liquefaction features in paleoseismology: Lessons learned in the New Madrid seismic zone, central U.S.: Journal of Seismology, v. 5, p. 361–380, doi: 10.1023/A:1011423525258.

Van Arsdale, R., Bresnahan, R., McCallister, N., and Waldron, B., 2007, this volume, The upland complex of the central Mississippi River valley: Its origin, denudation, and possible role in reactivation of the New Madrid seismic zone, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(13).

Wang, Z., 2007, this volume, Seismic hazard and risk assessment in the intraplate environment: The New Madrid seismic zone of the central United States, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(24).

Wesnousky, S.G., 1994, The Gutenberg-Richter or characteristic earthquake distribution, which is it?: Bulletin of the Seismological Society of America, v. 84, p. 1940–1959.

Wesnousky, S.G., and Leffler, L.M., 1992, The repeat time of the 1811 and 1812 New Madrid earthquakes: A geological perspective: Bulletin of the Seismological Society of America, v. 82, p. 1756–1785.

Wiens, D.A., DeMets, C., Gordon, R.G., Stein, S., Argus, D., Engeln, J.F., Lundgren, P., Quible, D., Stein, C., Weinstein, S., and Woods, D.F., 1985, A diffuse plate boundary model for Indian Ocean tectonics: Geophysical Research Letters, v. 12, p. 429–432.

Wu, P., and Johnston, P., 2000, Can deglaciation trigger earthquakes in North America?: Geophysical Research Letters, v. 27, p. 1323–1326, doi: 10.1029/1999GL011070.

Wu, P., and Mazzotti, S., 2007, this volume, Effects of a lithospheric weak zone on postglacial seismotectonics in eastern Canada and northeastern USA, *in* Stein, S., and Mazzotti, S., eds., Continental Intraplate Earthquakes: Science, Hazard, and Policy Issues: Geological Society of America Special Paper 425, doi: 10.1130/2007.2425(09).

Zoback, M.L., and Zoback, M.D., 1989, Tectonic stress field of the continental United States, *in* Pakiser, L.C., and Mooney, W.D., eds., Geophysical Framework of the Continental United States: Geological Society of America Memoir 172, p. 523–539.

Manuscript Accepted by the Society 29 November 2006