Limitations of the short earthquake record for seismicity and seismic hazard studies

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

ABSTRACT

Attempts to study earthquake recurrence in space and time are limited by the short history of instrumental seismology compared to the long and variable recurrence time of large earthquakes. As a result, apparent concentrations and gaps in seismicity and hence seismic hazard within a seismic zone, especially where deformation rates are slow (<10 mm/yr), are likely to simply reflect the short earthquake record. Simple numerical simulations indicate that if seismicity were uniform within a tectonically similar seismic zone, such as the Atlantic coast of Canada, St. Lawrence valley, or the coast of North Africa, thousands of years of record would be needed before apparent concentrations and gaps of seismicity and hazard did not arise. Hence, treating sites of recent seismicity as more hazardous for future large earthquakes is likely to be inappropriate, and it would be preferable to regard the hazard as comparable throughout the seismic zone.

Keywords: Canada, North Africa, seismic hazard, earthquake simulation, earthquake record.

INTRODUCTION

A major theme of this volume is the difficulty in assessing seismic hazards within continental plates and formulating effective mitigation strategies. Two coupled difficulties make these far more difficult than at typical plate boundaries. Unlike the situation at plate boundaries, we have no theoretical basis for predicting deformation rates and hence seismic moment release rates within plate interiors. Hence, we can only rely on the known seismic history. However, because intraplate deformation is typically slower (<1 mm/yr) than at most plate boundaries (Dixon et al., 1996; Newman et al., 1999; Calais et al., 2005; Bada et al., this volume, chapter 16; Camelbeeck et al., this volume, chapter 14; Leonard et al., this volume, chapter 17), the recurrence times for large earthquakes in individual parts of the seismic zone are longer. As a result, the historic and instrumental seismic record may often give an inaccurate view of the long-term seismicity.

This situation gives rise to a common feature of many seismic hazard maps that predict the maximum shaking expected for given probabilities within specified intervals, namely "bull's-eyes" of high predicted hazard within a tectonically similar seismic zone. For example, bull's-eyes (Fig. 1) appear in the predicted hazard due to intraplate earthquakes along the passive margin of Atlantic Canada and the St. Lawrence valley fault system. However, because the earthquakes are thought to result from reactivation of fossil structures primarily by stresses including those due to postglacial rebound (Stein et al., 1979, 1989; Mazzotti et al., 2005), there is no reason to expect parts of these structures to be more hazardous than others. This situation can also arise at slowly deforming plate boundaries. Hence, although the rate of

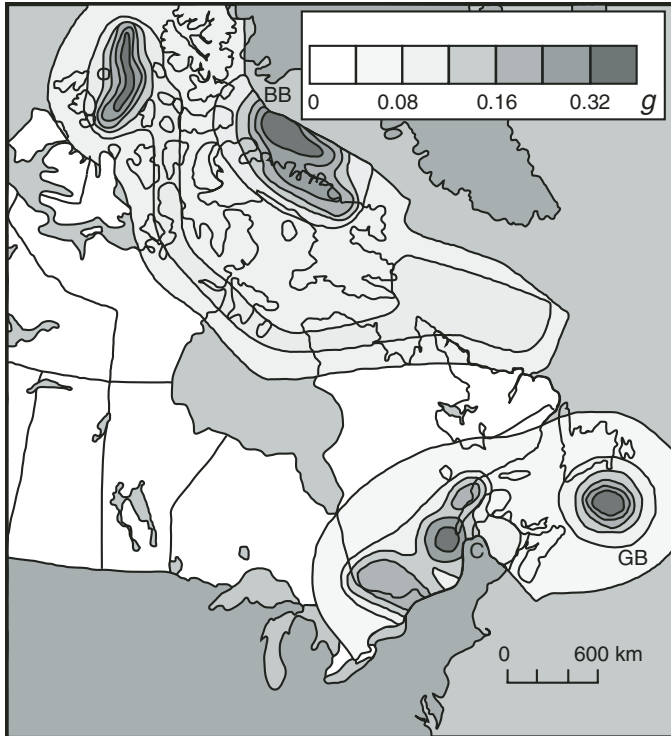[†]Corresponding author e-mail: seth@earth.northwestern.edu.

Figure 1. Seismic hazard map of Canada derived in 1985 showing peak ground acceleration expected at 2% probability in 50 yr (Geological Survey of Canada, 1985). This map, based primarily on the recorded and historic seismicity, shows bull's-eyes of high predicted hazard in Baffin Bay (BB), on the Grand Banks (GB), and in the Charlevoix (C) area. More recent maps, also including geological data, reduce the effect of the bull's-eyes and predict more diffuse hazard.

convergence between the Eurasian and Nubian (west African) plates varies smoothly along the coast of North Africa (Argus et al., 1989), the predicted hazard from the resulting earthquakes shows distinct bull's-eyes (Fig. 2).

The bull's-eyes arise because the predicted hazard in these maps depends on the earthquake history. The Canadian coastal maps reflect the 1929 M7.3 Grand Banks and 1933 M7.4 Baffin Bay earthquakes (Stein et al., 1979, 1989; Hasegawa and Kanamori, 1987; Bent, 1995, 2002), the St. Lawrence map reflects five M6 earthquakes in the Charlevoix area since 1663 (Bent, 1992; Schulte and Mooney, 2005), and the most impressive North Africa map results from the October 1980 M_s 7.3 El Asnam earthquake (Nabelek, 1985).

The utility of this approach is unclear, because in these seismic zones, the deformation rate is slow, so the recurrence time for large earthquakes anywhere in the seismic zone is comparable to the length of the earthquake history. As a result, the spatial and temporal earthquake history may be adequate to show that large earthquakes occur, but is not a good representation of the long-term earthquake distribution. So the question is whether to view the hazard as highest where recent seismicity is concentrated or regard the long-term hazard as essentially uniform within regions

of similar structure. A case can be made for either model. Viewing the presently active areas as most hazardous has the advantage of simplicity, in that such areas are easily identified. These areas may reflect stress concentrations within a seismic zone and thus may be more active than other parts of the seismic zone, even if the other parts have similar structure. Moreover, even if the largest earthquakes migrate within a seismic zone, recent seismicity may still be the best indicator of activity on a hundred year time scale (Kafka, this volume, chapter 3). This is especially likely to be the case if the seismicity is dominated by the smaller aftershocks of large earthquakes (Ebel et al., 2000), as may be the case if intraplate areas have relatively long aftershock sequences owing to the slow stress loading rate (Stein and Newman, 2004).

However, this approach based on historical seismicity, traditionally used in the United States (Frankel et al., 1996) and elsewhere, may lead to an undue focus on the sites of recent earthquakes, when other areas are as or more likely to be the sites of large future earthquakes. This possibility is suggested by the fact that the largest earthquakes to date in North Africa since the El Asnam event have not occurred in regions with the highest predicted hazard (Fig. 2). Hence, a hazard map may reflect more the date when it was made than the actual hazard.

To reduce this difficulty, there is increasing interest in also using paleoseismic and geological data to predict future earthquake locations. For example, Australian paleoseismologists are considering the possibility that seismicity migrates with time, such that faults that seem aseismic from the earthquake record may be the next to generate a damaging earthquake (Clark, 2003; Leonard et al., this volume, chapter 17). Australian, Hungarian (Toth et al., 2004), and Canadian (Adams et al., 1995; Halchuk and Adams, 1999; Atkinson, this volume chapter 21) researchers are developing maps in which the hazard estimates also reflect geologic structure, and this results in maps with more diffuse hazards (Fig. 3). Although resolving this issue is a formidable task and will take extensive research over time, understanding it will make it possible to adopt the most cost-effective building codes to minimize earthquake damage.

Toward this end, we focus here on a key part of the issue. We use simple numerical simulations to assess how long an earthquake history is needed from a seismic zone in which earthquakes are uniformly distributed to avoid apparent concentrations of seismicity, and, conversely, apparent seismic gaps resulting from a short earthquake history. These simulations are thus a way of exploring the question of whether the portions of a seismic zone in which large earthquakes are known to have occurred are necessarily different from the remainder of the zone, or could simply reflect the short earthquake history.

SIMULATIONS

We chose three seismic zones where hazard maps show distinct bull's-eyes to explore the possibility that these bull's-eyes might be artifacts of the short earthquake history. One is the slowly convergent plate boundary along the coast of North Africa, and the
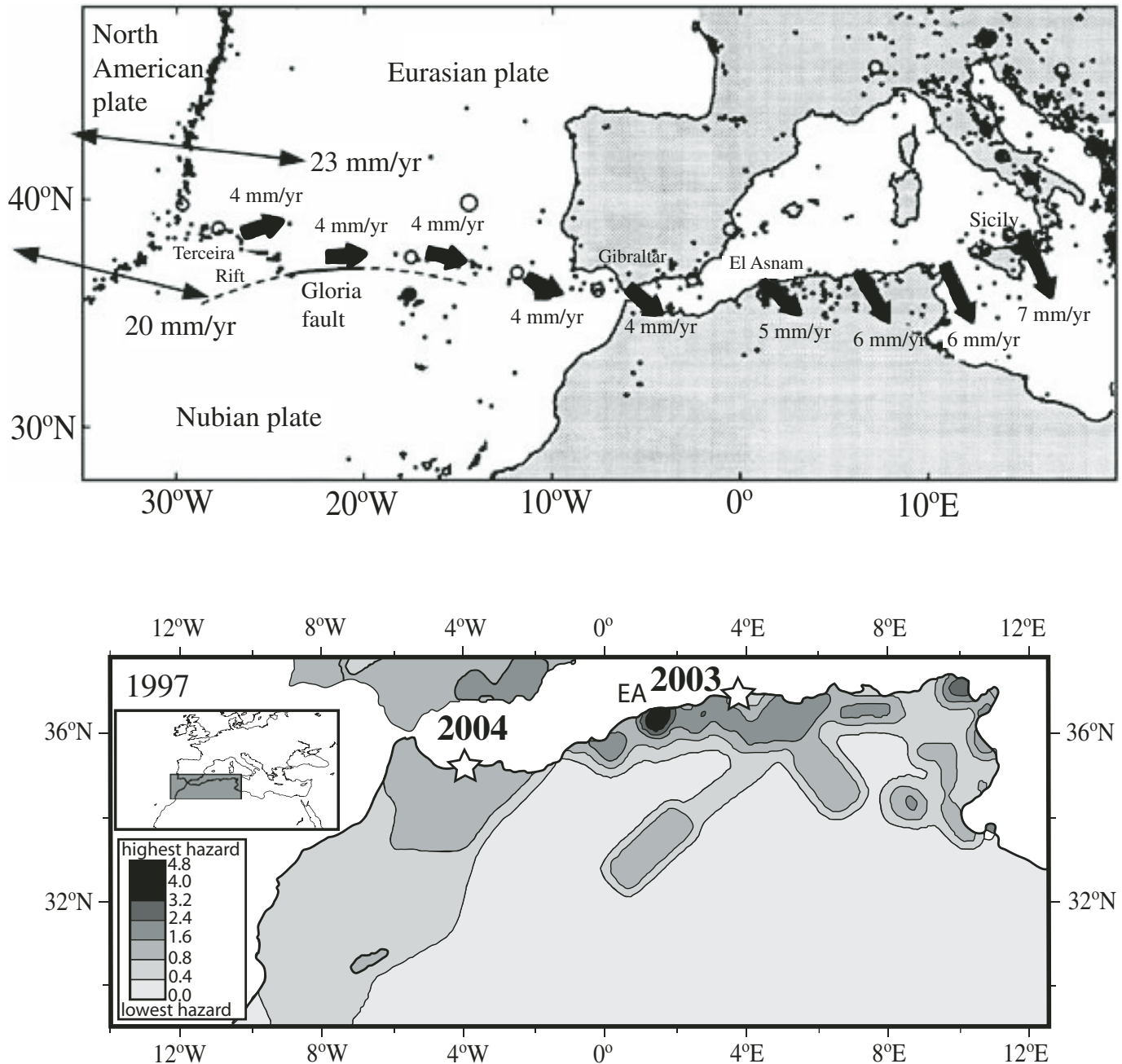
Figure 2. Top: Predicted motion of Eurasia with respect to Africa, showing convergence rate varying smoothly along the North African plate boundary (Argus et al., 1989). Bottom: Portion of Global Seismic Hazard Map (1999) for North Africa, showing peak ground acceleration in m/s^2 expected at 10% probability in 50 yr. Note prominent bull's-eye at site of the 1980 M$_s$ 7.3 El Asnam (EA) earthquake. The largest subsequent earthquakes to date, the May 2003 M$_s$ 6.8 Algeria and February 2004 M$_s$ 6.4 Morocco events (stars), did not occur in the predicted high hazard regions.

other two are intraplate seismic zones in eastern North America along the passive margin of Atlantic Canada and the St. Lawrence valley fault system. For each, we used a frequency-magnitude (b-value) relation derived from the recorded seismicity. We then computed synthetic space-time histories of earthquakes with $M \geq 7$ or 6 (for the St. Lawrence) assuming a Gaussian distribu-

tion of recurrence times with standard deviation equal to 0.35 times the mean recurrence time. We assigned each earthquake a location along the seismic zone (treated as one dimensional) using a uniform random number generator. The results are shown as synthetic seismicity maps, with events plotted as 30- or 6- (for the St. Lawrence) km-diameter circles that approximate the fault area.
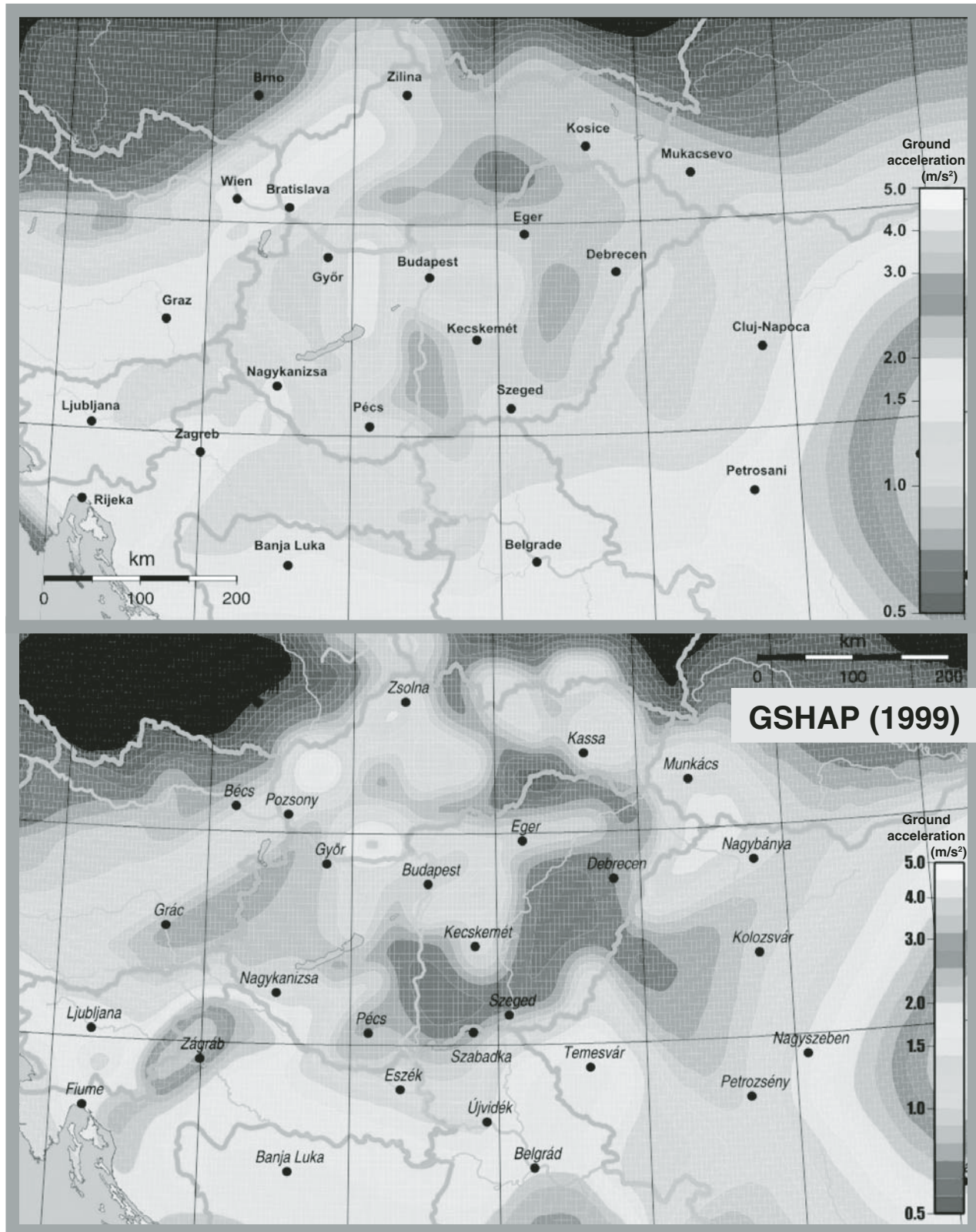
Figure 3. Alternative hazard maps for Hungary and the surrounding area, showing peak ground acceleration in m/s^2 expected at 10% probability in 50 yr. The Global Seismic Hazard Assessment Program (GSHAP) model, based only on historic and recorded seismicity (bottom), predicts more concentrated hazard near sites of earlier earthquakes, compared to a model that includes geological data (top), which predicts more diffuse hazard (Toth et al., 2004).

North Africa

We simulated the seismicity along the North Africa coast (Fig. 4) from Tunisia to Morocco, which results from the convergence between Eurasia and Nubia at <10 mm/yr (Argus et al., 1989; Sella et al., 2002; Fernandes et al., 2003). We used two frequency-magnitude relations derived from the Advanced National Seismic Systems (ANSS) catalog. The first, derived from 1963 to 2004 seismicity for which magnitudes are presumably well estimated, yields $a = 4.63$ and $b = 0.91$. Hence, an earthquake
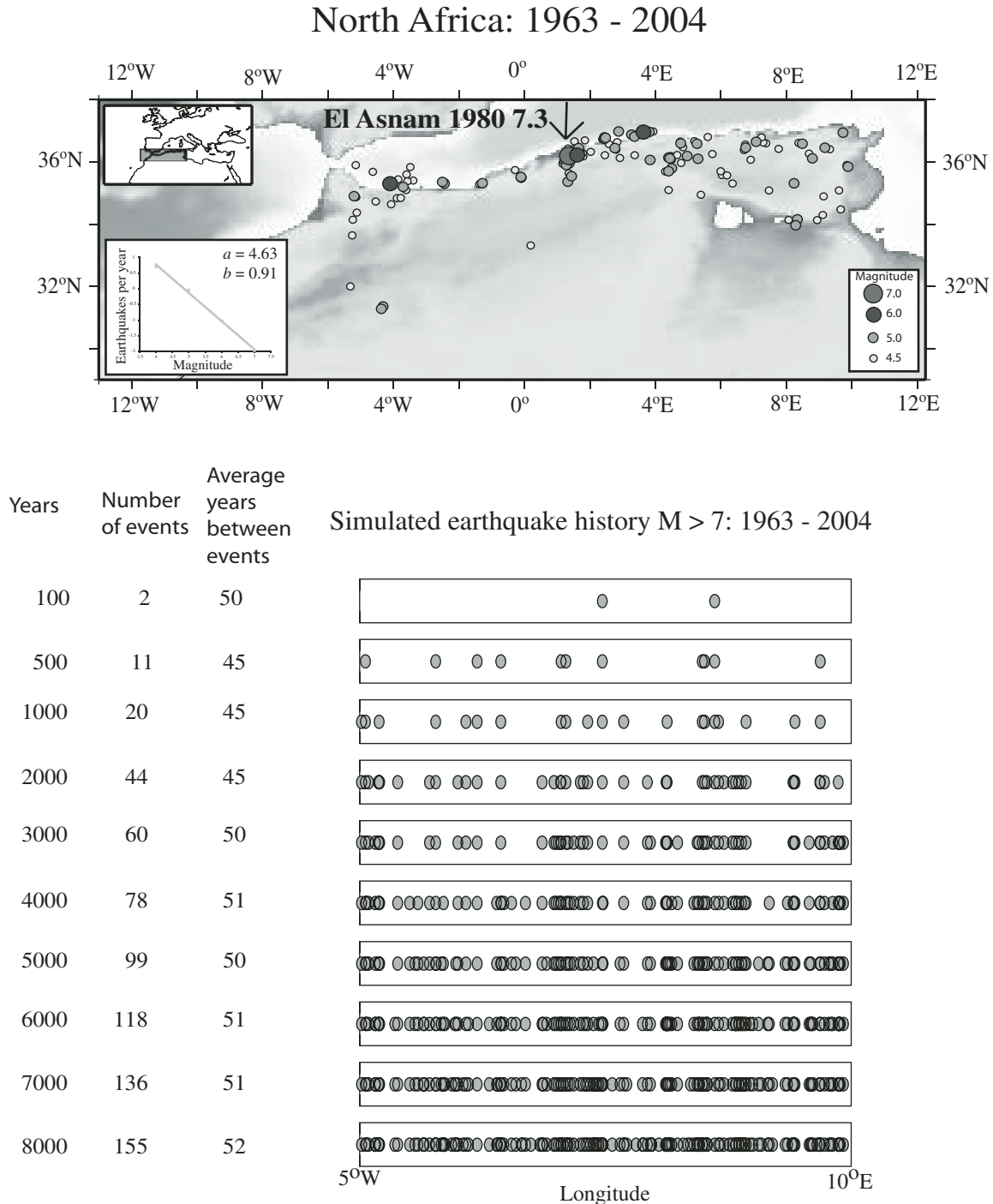

Figure 4. Seismicity along the North Africa plate boundary for 1963–2004. Simulations using a frequency-magnitude relation derived from these data predict that if seismicity is uniform in the zone, ~8000 yr of record is needed to avoid apparent concentrations and gaps.

Swafford and Stein

with M ≥ 7 occurs somewhere in the seismic zone about every 42 yr on average. Using this relation, apparent concentrations of large earthquakes and gaps without them appear for earthquake records up to thousands of years long. Only after 7000–8000 yr is the uniform nature of the seismicity fully apparent. This effect

is even more striking using a frequency-magnitude relation from the 1910–2004 earthquake record, which yields $a = 4.37$ and $b = 0.90$, and thus a 95 yr mean recurrence for M ≥ 7 events. The resulting simulations require 10,000–12,000 yr to show the uniform seismicity (Fig. 5).
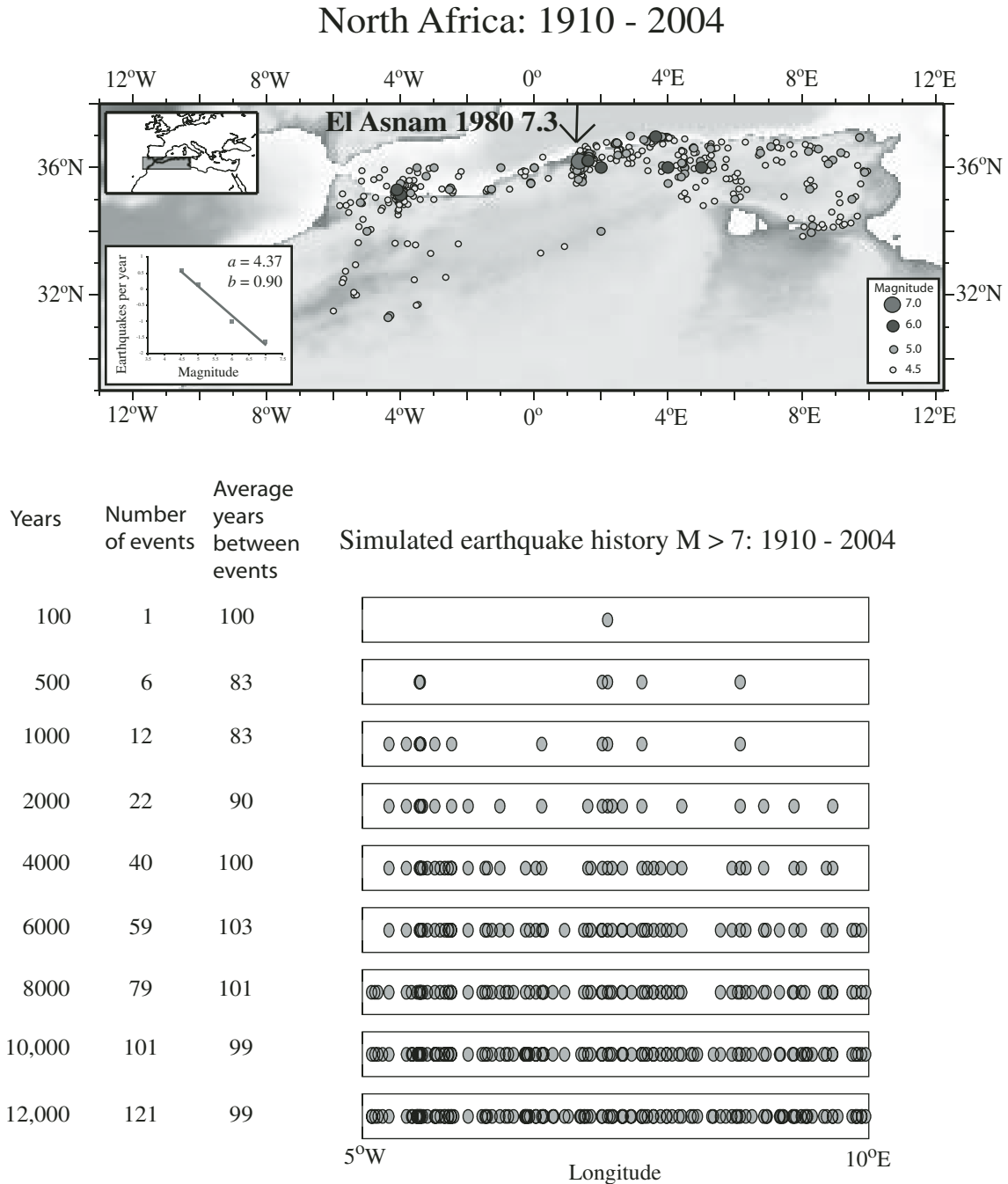

Figure 5. Seismicity along the North Africa plate boundary for 1910–2004. Simulations using a frequency-magnitude relation derived from these data predict that if seismicity is uniform in the zone, ~12,000 yr of record is needed to avoid apparent concentrations and gaps.

Atlantic Canada

The eastern coast of Canada shows the most striking example of large earthquakes along a passive continental margin, where ideal plate tectonics predict no relative motion between continental and oceanic portions of the same plate. The 1929 M7.3 Grand Banks and 1933 M7.4 Baffin Bay earthquakes are the best studied examples of this phenomenon, which also occurs on other passive margins (Stein et al., 1989; Schulte and Mooney, 2005). A frequency-magnitude relation derived for events with M ≥ 4.5 from the Geological Survey of Canada catalog from 1925 to 2003 yields $a = 3.38$ and $b = 0.73$, and thus a recurrence time of 47 yr for M ≥ 7. Simulations using this relation yield apparent concentrations of large earthquakes and gaps without them for earthquake records up to thousands of years long (Fig. 6). Approximately 8000–11,000 yr of record is needed to show that the seismicity is uniform.

St. Lawrence Valley

The St. Lawrence valley seismic zone (Fig. 7) (Mazzotti et al., 2005) is generally considered to consist of two seismic zones: the lower St. Lawrence seismic zone, defined by events with M ≤ 5, and the Charlevoix seismic zone, in which larger (M 6) events occur. Our simulations assume that large earthquakes are equally likely throughout the entire zone. A frequency-magnitude relation derived for events with M ≥ 4 from the Geological Survey of Canada catalog from 1925 to 2004 yields $a = 4.52$ and $b = 1.01$ and thus a recurrence time of ~40 yr for M ≥ 7. In the resulting simulations, 12,000–16,000 yr are needed to show the uniform seismicity.
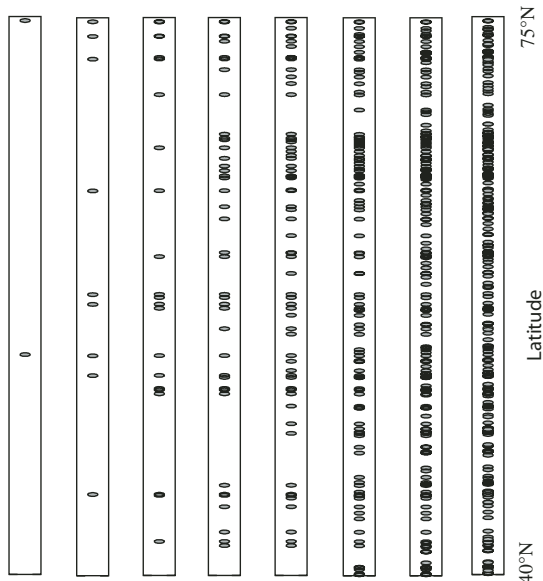
DISCUSSION

The simulations illustrate that if seismicity were uniformly distributed within a seismic zone, apparent concentrations of seismicity and seismic gaps would appear in earthquake records shorter than the time needed for large earthquakes to occur throughout the zone. For the zones used in the simulations, which are deforming more slowly than ~10 mm/yr, the time needed for the uniformity to become clear is thousands of years. Hence, it is plausible that many of the concentrations and gaps seen in real data are artifacts of the short sampling intervals.

Naturally, the simulations simplify real—and poorly understood—aspects of earthquake recurrence. They do not include all
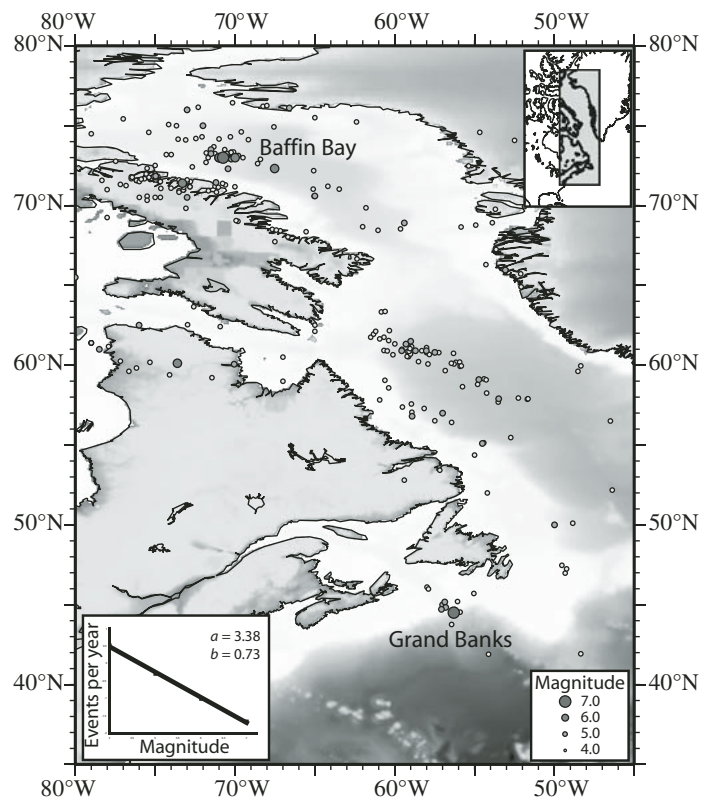

Figure 6. Intraplate seismicity along the eastern coast of Canada. Simulations using a frequency-magnitude relation derived from these data predict that if seismicity is uniform in the zone, ~11,000 yr of record is needed to avoid apparent concentrations and gaps.

St. Lawrence Valley: 1925 - 2004

Simulated earthquake history M > 6: 1925 - 2004

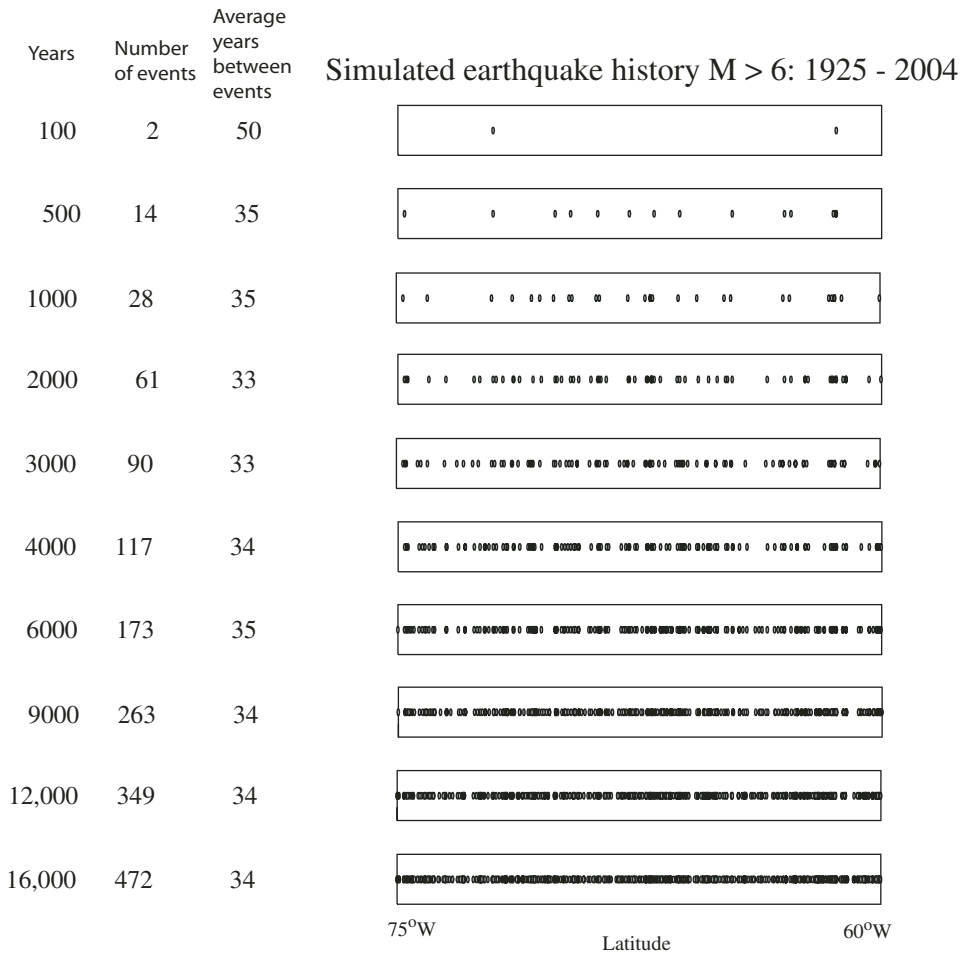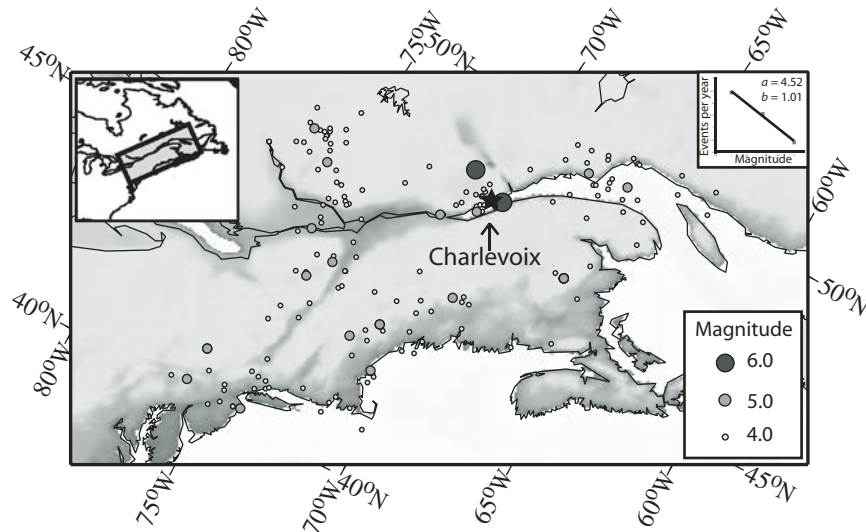| Years	Number of events	Average years between events
100	2	50
500	14	35
1000	28	35
2000	61	33
3000	90	33
4000	117	34
6000	173	35
9000	263	34
12,000	349	34
16,000	472	34

Figure 7. Intraplate seismicity in the St. Lawrence valley. Simulations using a frequency-magnitude relation derived from these data predict that if seismicity is uniform in the zone, ~16,000 yr of record is needed to avoid apparent concentrations and gaps.

possible time- and space-dependant probability effects, including stress transfer, in which stress changes due to earthquakes affect the location of future events (Stein, 1999). Similarly, all earthquakes were assumed to have the same magnitude. Although more complicated simulations are possible, it is tricky to decide which effects to include. At a plate boundary like North Africa, the known convergence rate and direction permit more sophisticated models (Lin and Stein, 2004). Even so, it appears that the size and geometry of large thrust earthquakes are highly variable along a section of a trench (Ando, 1975; Stein et al., 1986; Cisternas et al., 2005), and it is unclear how to relate moment release rate (seismic slip) to plate motion. How to model intraplate areas, where even the fundamental tectonics are unclear, is even more challenging, although models have been made for specific areas such as the New Madrid seismic zone (Mueller et al., 2004; Li et al., this volume, chapter 11). Thus, we used simulations representing the simplest possible behavior, and we believe that the basic results are likely to be robust.

The fact that simulations assuming uniform deformation rates within seismic zones yield bull's-eyes and gaps does not prove that such patterns observed in earthquake records necessarily reflect short sampling. It is also possible that within a tectonically similar seismic zone, local structures or long-lived stress and strain concentrations (Gangopadhyay and Talwani, 2003, and this volume) make some parts more active than others. Of the cases we examined, the Charlevoix concentration looks the most like the latter case. The simulations show that from seismicity data alone—in particular without geodetic data—the two possibilities are hard to distinguish.

Even so, we feel that the results have interesting implications. They bear out the effect that many features of space-time patterns of seismicity may in part reflect short sampling times. For example, modern seismicity maps show essentially no seismicity on the southern segment of the San Andreas where the large 1857 earthquake occurred. Similarly, prior to the great 2004 earthquake, the portion of the Sumatra trench on which it occurred did not appear very active and was not considered particularly dangerous. In both cases, the absence of large earthquakes from the seismological record reflects their long recurrence time. As a result, inferences from the short earthquake history would be misleading. For example, the Sumatra example and data from other trenches suggest that a previously inferred effect—that large trench earthquakes occur only when young lithosphere subducts rapidly—may largely reflect the short earthquake history sampled (Stein and Okal, 2007). Similarly, it seems likely that some cases in which large earthquakes are more frequent (characteristic) or less frequent (uncharacteristic) than expected from the rate of smaller ones may also be a time sampling effect (Stein and Newman, 2004).

The simulations also argue against the practice of treating sites of recent seismicity as more hazardous for future large earthquakes, and in favor of the more recent trend of treating hazard as uniform within a tectonic zone. As noted, the simulations show that apparent concentrations of seismicity are quite plausibly sampling artifacts where the earthquake history is short compared to the recurrence time of large earthquakes. In our view, there is no reason to believe these sites are more likely to have future large earthquakes than other sites on the same structures, assuming that they deform at similar rates. Hazard estimates using the seismicity are thus likely to overestimate hazards where earthquakes happen to have occurred recently, and underestimate it elsewhere within the seismic zone, where earthquakes happen to have not occurred. In fact, stress transfer arguments imply that large earthquakes at the other sites may be more likely (e.g., Li et al., this volume, chapter 11). Hence, we favor models that treat hazard as uniform within a tectonic zone. For example, we would regard the seismic hazard as similar all along the eastern Canadian passive margin (Stein et al., 1989; Adams and Basham, 1989), rather than highest near the sites of the Baffin Bay and Grand Banks earthquakes.

ACKNOWLEDGMENTS

REFERENCES CITED

Adams, J., and Basham, P., 1989, Seismicity and seismotectonics of Canada's eastern margin and craton, *in* Gregerson, S., and Basham, P., eds., Earthquakes at North Atlantic Passive Margins: Neotectonics and Postglacial Rebound: Dordrecht, Kluwer, p. 355–370.

Adams, J., Basham, P.W., and Halchuk, S., 1995, Northeastern North America earthquake potential—New challenges for seismic hazard mapping, *in* Eastern Canada and National and General Programs (Est du Canada et Programmes Nationaux et Generaux): Geological Survey of Canada, Current Research, v. 1995-D, p. 91–99.

Ando, M., 1975, Source mechanisms and tectonic significance of historical earthquakes along the Nankai Trough, Japan: Tectonophysics, v. 27, p. 119–140, doi: 10.1016/0040-1951(75)90102-X.

Argus, D.F., Gordon, R.G., DeMets, C., and Stein, S., 1989, Closure of the Africa–Eurasia–North America plate motion circuit and tectonics of the Gloria fault: Journal of Geophysical Research, v. 94, p. 5585–5602.

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).

Bent, A., 1992, A re-examination of the 1925 Charlevoix, Quebec, earthquake: Bulletin of the Seismological Society of America, v. 82, p. 2097–2113.

Bent, A., 1995, A complex double-couple source mechanism for the M_s7.2 1929 Grand Banks earthquake: Bulletin of the Seismological Society of America, v. 85, p. 1003–1020.

Bent, A., 2002, The 1933 Ms = 7.3 Baffin Bay earthquake: strike-slip faulting along the northeastern Canadian passive margin: Geophysical Journal International, v. 150, p. 724–736, doi: 10.1046/j.1365-246X.2002.01722.x.

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.

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).

Cisternas, M., Atwater, B.F., Torrejon, F., Sawai, Y., Machuca, G., Lagos, M., Eipert, A., Youlton, C., Salgado, I., Kamataki, T., Shishikura, M., Rajendran, C.P., Malik, J.K., Riza, Y., and Husni, M., 2005, Predecessors of the giant 1960 Chile earthquake: Nature, v. 437, p. 404–407, doi: 10.1038/nature03943.

Clark, D., 2003, Earthquakes move on but not without a trace: Ausgeo News, v. 70, p. 30–32.

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.

Ebel, J.E., Bonjer, K.P., and Oncescu, M.C., 2000, Paleoseismicity: Seismicity evidence for past large earthquakes: Seismological Research Letters, v. 71, p. 283–294.

Fernandes, R., Ambrosius, B., Noomen, R., Bastos, L., Wortel, M., Spakman, W., and Govers, R., 2003, The relative motion between Africa and Eurasia as derived from ITRF2000 and GPS: Geophysical Research Letters, v. 30, no. 16, doi: 10.1029/2003GL017089.

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.

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

Global Seismic Hazard Map, 1999, Global Seismic Hazard Map: http://www.seismo.ethz.ch/gshap (November 2004).

Halchuk, S., and Adams, J., 1999, Crossing the border: Assessing the difference between new Canadian and American seismic hazard maps: Proceedings of the 8th Canadian Conference of Earthquake Engineering, p. 77–82.

Hasegawa, H.S., and Kanamori, H., 1987, Source mechanism of the magnitude 7.2 Grand Banks earthquake of November 1929; double couple or submarine landslide?: Bulletin of the Seismological Society of America, v. 77, p. 1984–2004.

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).

Leonard, M., Robinson, D., Allen, T., Schneider, J., Clark, D., Dhu, T., and Burbidge, D., 2007, this volume, Towards 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., Zhang, Q., and Sandoval, E., 2007, this volume, Stress evolution and seismicity in the central-eastern USA: Insights 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).

Lin, J., and Stein, R., 2004, Stress triggering in thrust and subduction earthquakes and stress interaction between the southern San Andreas and nearby thrust and strike-slip faults: Journal of Geophysical Research, v. 109, doi: 10.1029/2003JB002607.

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.

Mueller, K., Hough, S.E., and Bilham, R., 2004, Analyzing the 1811–1812 New Madrid earthquakes with recent instrumentally recorded aftershocks: Nature, v. 429, p. 284–288, doi: 10.1038/nature02557.

Nabelek, J., 1985, Geometry and mechanism of faulting of the 1980 El Asnam, Algeria, earthquake from inversion of teleseismic body waves and comparison with field observations: Journal of Geophysical Research, v. 90, p. 12,713–12,728.

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.

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.

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. B04, doi: 10.1029/2000JB000033.

Stein, R., 1999, The role of stress transfer in earthquake occurrence: Nature, v. 402, p. 605–609, doi: 10.1038/45144.

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 Okal, E.A., 2007, Ultralong period seismic study of the December 2004 Indian Ocean earthquake and implications for regional tectonics and the subduction process: Bulletin of the Seismological Society of America, v. 97, no. 1A, p. S279–S295.

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., Engeln, J.F., DeMets, C., Gordon, R.G., Woods, D., Lundgren, P., Argus, D., Stein, C., and Wiens, D.A., 1986, The Nazca–South America convergence rate and the recurrence of the great 1960 Chilean earthquake: Geophysical Research Letters, v. 13, p. 713–716.

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.

Toth, L., Gyori, E., Monus, P., and Zsiros, T., 2004, Seismicity and seismic hazard in the Pannonian Basin, *in* Proceedings of the NATO Adria Research Workshop: The Adria Microplate: Dordrecht, Springer, p. 231–260.