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Challenges in assessing seismic hazard in intraplate Europe

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Abstract: Intraplate seismicity is often characterized by episodic, clustered and migrating earthquakes and extended after-shock sequences. Can these observations – primarily from North America, China and Australia – usefully be applied to seismic hazard assessment for intraplate Europe? Existing assessments are based on instrumental and historical seismicity of the past *c.* 1000 years, as well as some data for active faults. This time span probably fails to capture typical large-event recurrence intervals of the order of tens of thousands of years. Palaeoseismology helps to lengthen the observation window, but preferentially produces data in regions suspected to be seismically active. Thus the expected maximum magnitudes of future earthquakes are fairly uncertain, possibly underestimated, and earthquakes are likely to occur in unexpected locations. These issues particularly arise in considering the hazards posed by low-probability events to both heavily populated areas and critical facilities. For example, are the variations in seismicity (and thus assumed seismic hazard) along the Rhine Graben a result of short sampling or are they real? In addition to a better assessment of hazards with new data and models, it is important to recognize and communicate uncertainties in hazard estimates. The more users know about how much confidence to place in hazard maps, the more effectively the maps can be used.

A famous quotation, popularized by Niels Bohr, says that 'It is tough to make predictions, especially about the future'. Although Bohr was not discussing earthquake hazard maps, he might well have been. Earthquake hazard maps use estimates of the probability of future earthquakes and the resulting shaking to predict the maximum shaking expected with a certain probability over a given time. The resulting maps are used to develop codes for earthquake-resistant construction.

Although such maps are widely used to make policy decisions involving billions of dollars or Euros, the results are sometimes unsatisfying. The 2011 M 9.1 Tohoku earthquake and the resulting tsunami were much larger than anticipated in the Japanese national earthquake hazard map (Geller 2011). The 2008 M 7.9 Wenchuan (China) and 2010 M 7.1 Haiti earthquakes occurred on faults mapped as giving rise to low hazards (Stein *et al.* 2012). These events stimulated discussions among seismologists and earthquake engineers about practices in earthquake hazard mapping (Wang 2011; Kossobokov & Nekrasova 2012; Peresan & Panza 2012; Stirling 2012; Gulkan 2013), given that it is unknown how well hazard maps actually describe future shaking and involve complicated factors that are not well understood.

Making earthquake hazard maps is an ambitious enterprise, involving assumptions about four key questions: *where* will large earthquakes occur; *when* will large earthquakes occur; *how large* will they be; and *how strong* will the shaking be? Given the complexities of the earthquake process and our limited knowledge of it, many subjective choices are needed. As a result, maps depend heavily on their makers' preconceptions about how the Earth works. When these preconceptions prove correct, a map fares well. When they prove incorrect, a map does poorly. Hence seismic hazard maps should be viewed as having a large uncertainty.
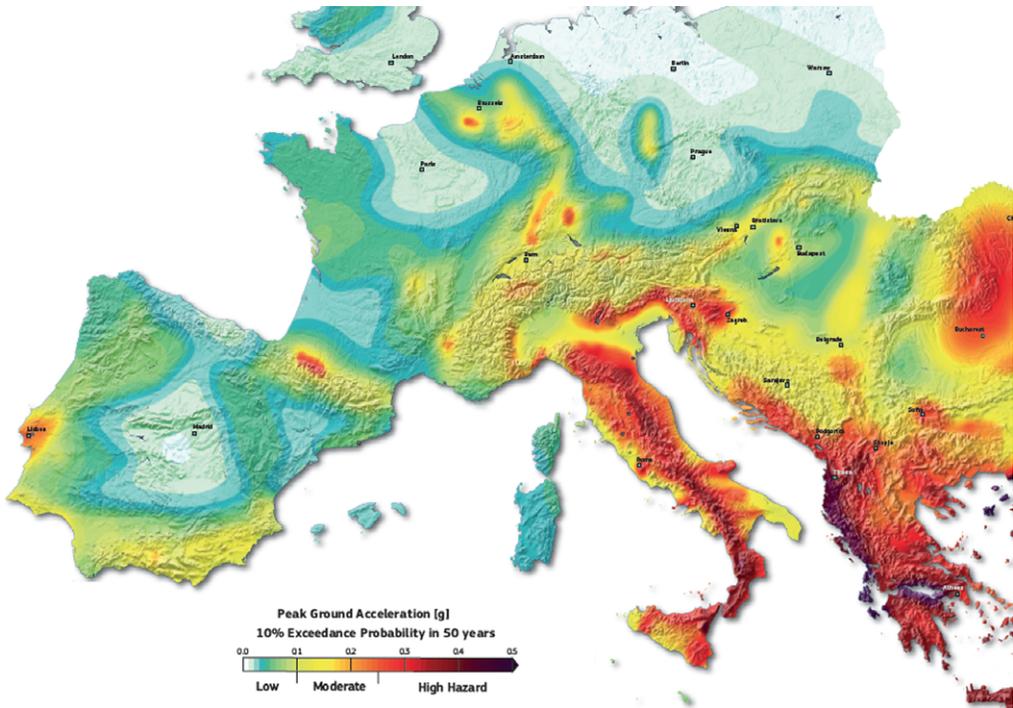
Fig. 1. Part of the 2013 SHARE earthquake hazard map (Giardini *et al.* 2013).
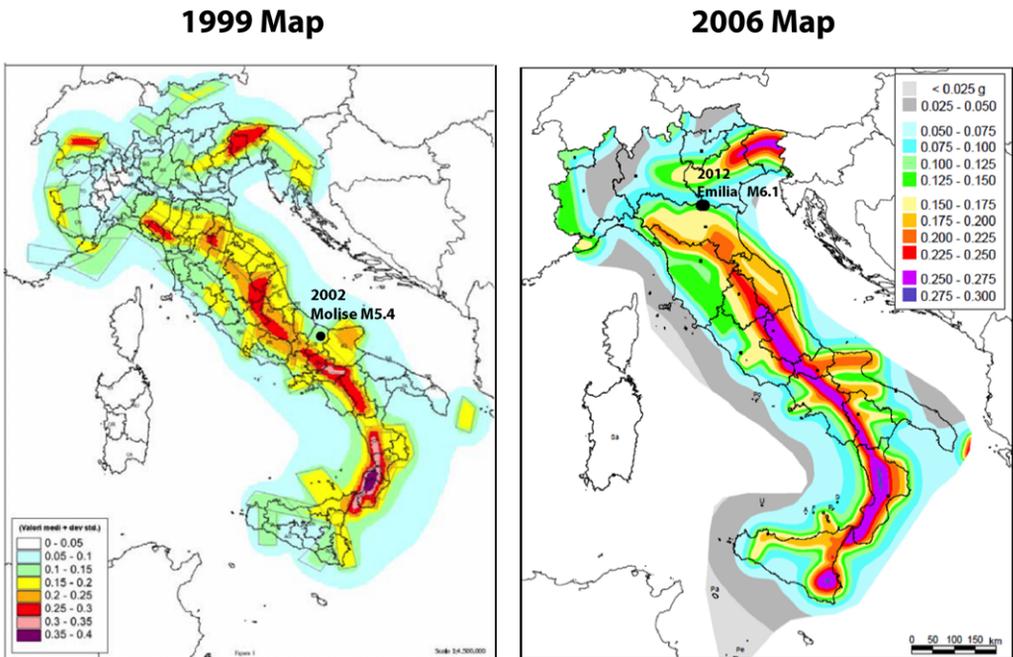

Fig. 2. Comparison of successive Italian hazard maps (Stein *et al.* 2015*a*), which forecast some earthquake locations well and others poorly. The 1999 map was updated to reflect the 2002 Molise earthquake and the 2006 map will probably be updated after the 2012 Emilia earthquake. Reproduced with permission of the Seismological Society of America.
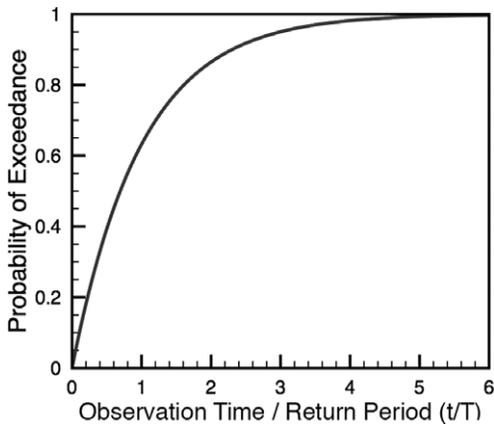
Fig. 3. Assumed probability *p* that during a *t*-year-long observation period, shaking at a site will exceed a value that is expected on average once in a *T*-year return period (Stein *et al.* 2015*a*). Reproduced with permission of the Seismological Society of America.

This paper is an overview of some of the challenges in assessing earthquake hazards in intraplate Europe. Consideration of the recent SHARE European seismic hazard map illustrates the challenges involved. In the portion of the map shown here (Fig. 1), the highest hazard is predicted in the circum-Adriatic region. The high hazard reflects plate motions: Nubia (west Africa) subducts beneath the Calabrian and Hellenic arcs. Adria rotates counterclockwise relative to Eurasia, diverging along the Appenines and converging north of the Po plain and along the Dinarides, the east coast of the Adriatic Sea. These plate motions are known from space geodetic data (Calais *et al.* 2002; Stein & Sella 2005; Weber *et al.* 2009) and abundant

earthquake focal mechanisms (Anderson & Jackson 1987); they give rise to sufficiently high seismicity to give a good availability of earthquake records. As a result, the locations of future earthquakes, the rates of earthquake recurrence and the expected ground shaking can be inferred with reasonable, although not total, success.

However, even in the most active area, assessing hazard is difficult, as illustrated by a comparison of successive Italian hazard maps (Fig. 2). Often, the Earth does not behave as expected. Many earthquakes, for example the 2009 L'Aquila earthquake, occur in areas mapped as high hazard. Others, however, occur in areas mapped as having low hazard. The 1999 map was updated to reflect the 2002 Molise earthquake and the 2006 map will probably be updated after the 2012 Emilia earthquake.

These examples illustrate the important question of what to do after a major earthquake yielding shaking larger than that anticipated in a hazard map. Hazard mappers have two choices. One is to regard the high shaking as a low-probability event allowed by a probabilistic seismic hazard map, which used estimates of the probability of future earthquakes and the resulting shaking to predict the maximum shaking expected with a certain probability over a given time (Hanks *et al.* 2012; Frankel 2013). The probabilistic algorithm anticipates that, in a specified number of cases, shaking exceeding that mapped should occur (Cornell 1968; Field 2010).

The predicted hazard in probabilistic maps depends on the probability, or equivalently the observation period (*t*) and return period (*T*), used. The probability *p* that earthquake shaking at a site will exceed the mapped value in *t* years is assumed to be $p = 1 - \exp(-t/T)$, which is approximately t/T for $t \ll T$. This probability is small if t/T is small and increases with time (Fig. 3). For a given
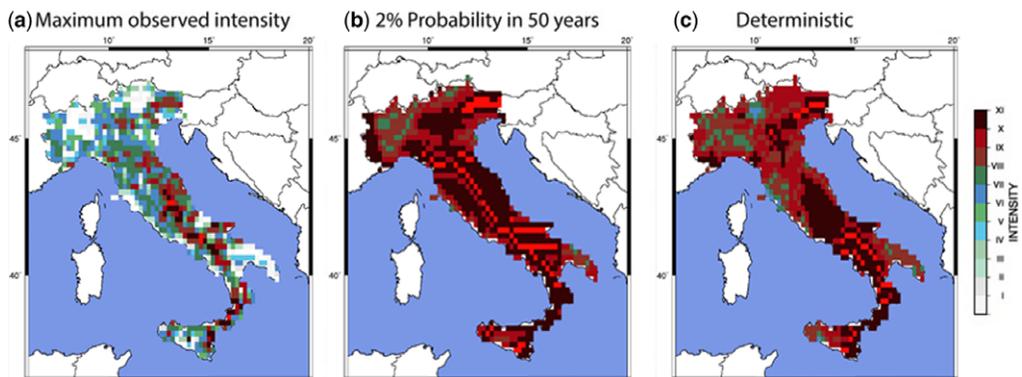

Fig. 4. Comparison of (**a**) historical intensity data for Italy with (**b**) probabilistic and (**c**) deterministic hazard maps, both of which over-predict the observed shaking (Stein *et al.* 2015*a*). Reproduced with permission of the Seismological Society of America.
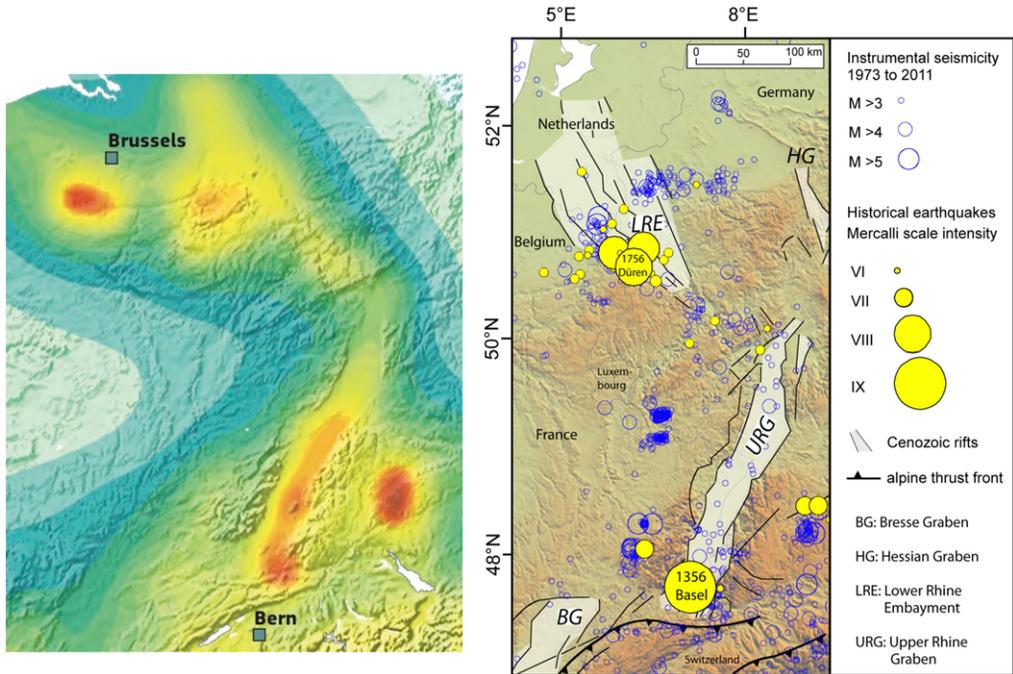
Fig. 5. Left: SHARE map section including the Upper Rhine Graben and Lower Rhine Embayment. Right: Historical seismicity of NW Europe (Kübler 2013).

return period, higher probabilities occur for longer observation periods. For example, shaking shown by a map with a 475-year return period should have about a 10% chance of being exceeded in 50 years, 41% in 250 years, 65% in 500 years and 88% in 1000 years. Thus in 50 years there should be only a 10% probability of exceeding the mapped shaking, whereas there is a 63% probability of doing so in an observation period equal to the return period. Equivalently, in 50 years the shaking at 10% of the sites on a map should exceed the mapped shaking, and it should do so at 63% of the sites in an observation period equal to the return period.

The longer the observation time compared to the return period assumed in making the map, the more information we have and the better we can evaluate the map (Beauval *et al.* 2008, 2010). For example, if, in a 50-year period, a large earthquake produced shaking exceeding that predicted by a 475-year map at 40% of the sites, this situation could imply that the map was not performing well. However, if, in the subsequent 200 years, no higher shaking occurred at the sites, the map would be performing as designed.

The usual choice, however, is to accept that higher than anticipated shaking was not simply a low-probability event consistent with the existing map, but instead provides new information (Stein *et al.* 2015*b*), and to revise the map to show increased hazard in the heavily shaken area. Whether and how much to revise a map is a complicated issue, because a new map that better describes the past may or may not better predict the future. For example, increasing the predicted hazard after an earthquake on a fault will make better predictions
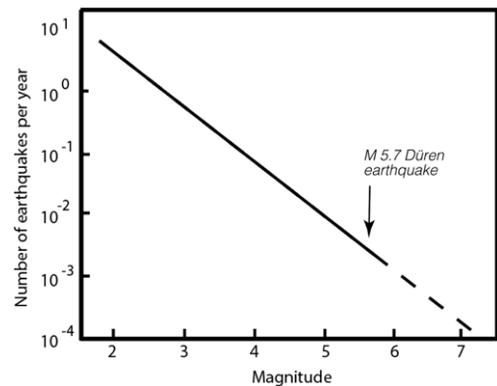

Fig. 6. Earthquake frequency–magnitude data for the Lower Rhine Embayment (Vanneste *et al.* 2013). Reproduced with permission of the Royal Astronomical Society.
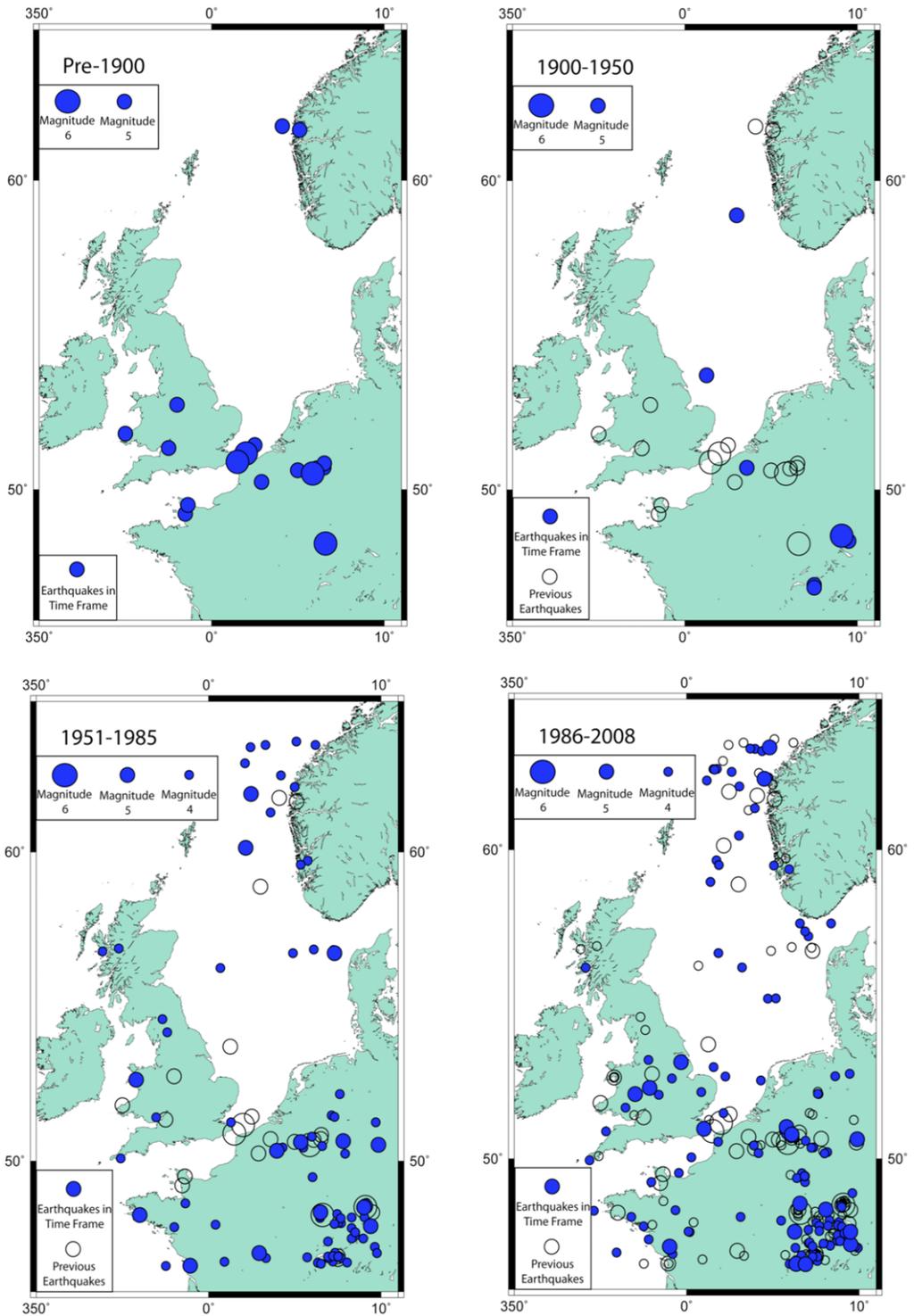
Fig. 7. Seismicity of the Lower Rhine Embayment for different periods (taken from Royal Observatory of Belgium catalogue; Kusters 2014).
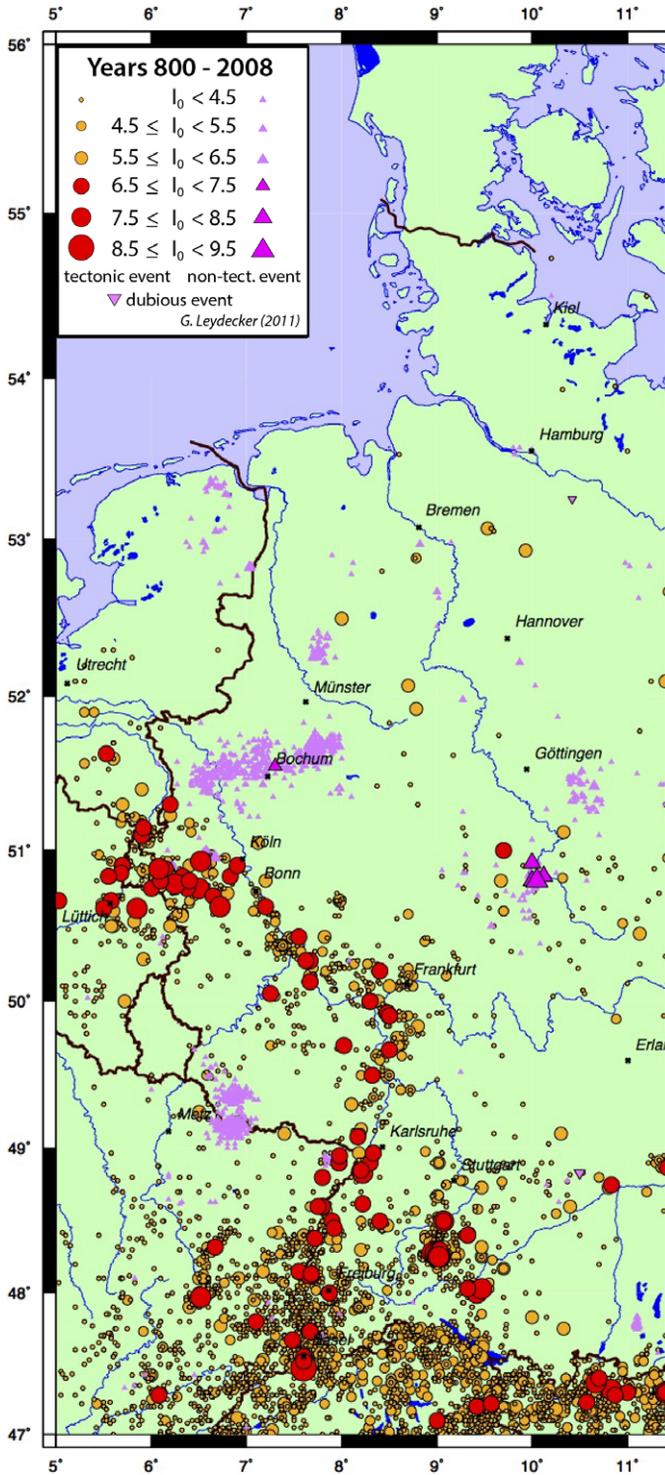
Fig. 8. Historical seismicity of the region shown by earthquakes with different epicentral intensities from 800 AD (Leydecker 2011). Reproduced with permission of Bundesanstalt für Geowissenschaften und Rohstoffe (BGR).

if the average recurrence time is short compared with the map's time window, but will over-predict future shaking if the average recurrence time is much longer than the map's time window.

Another illustration of the challenge involved is given by Figure 4, which compares historical intensity data for Italy from 217 BC to AD 2002 (Nekrasova *et al.* 2014), developed from a compilation by Gruppo di Lavoro (2004), with two seismic hazard maps. Both a probabilistic hazard map and a deterministic hazard map significantly over-predict the reported shaking. It is possible that some of the assumptions in making the hazard map were biased towards over-predictions. However, it is likely that much of the misfit results from the catalogue being biased towards too-low values. The historical catalogue is thought to be incomplete (Stucchi *et al.* 2004) and may underestimate the largest actual shaking in areas as a result of a space–time sampling bias and/or difficulties with the historically inferred intensities.

The Rhine Graben

Making earthquake hazard maps is even more challenging within plates, as illustrated by the Rhine Graben area (Fig. 5), the most active seismic zone in northwestern Europe. This area is seismically active, but much less so than the circum-Adriatic region. Earthquakes in the latter result from plate motions at rates of about 5 mm a^{-1} (Devoti *et al.* 2008), whereas deformation within NW Europe has not yet been convincingly resolved geodetically and is thus slower than about 1 mm a^{-1} (Nocquet & Calais 2004).

The zone is divided into the Upper Rhine Graben (URG), extending northeastwards along the topographic graben from the Basel area, and the Lower Rhine Embayment (LRE), trending northwestwards towards the North Sea. The largest historical earthquake in the LRE, the 1756 Düren earthquake, had a moment magnitude of *c.* 5.7 and palaeoseismic investigations have found evidence that large earthquakes with magnitudes up to 7.0 have occurred since the late Pleistocene (Camelbeeck *et al.* 2007, 2014). The largest historical earthquake in NW Europe, the 1356 earthquake with estimated moment magnitude 6.0–6.5, destroyed the city of Basel and caused damage in much of the URG (Meghraoui *et al.* 2001).

As a result, the SHARE map shows significant hazard in much of the Rhine Graben. The hazard
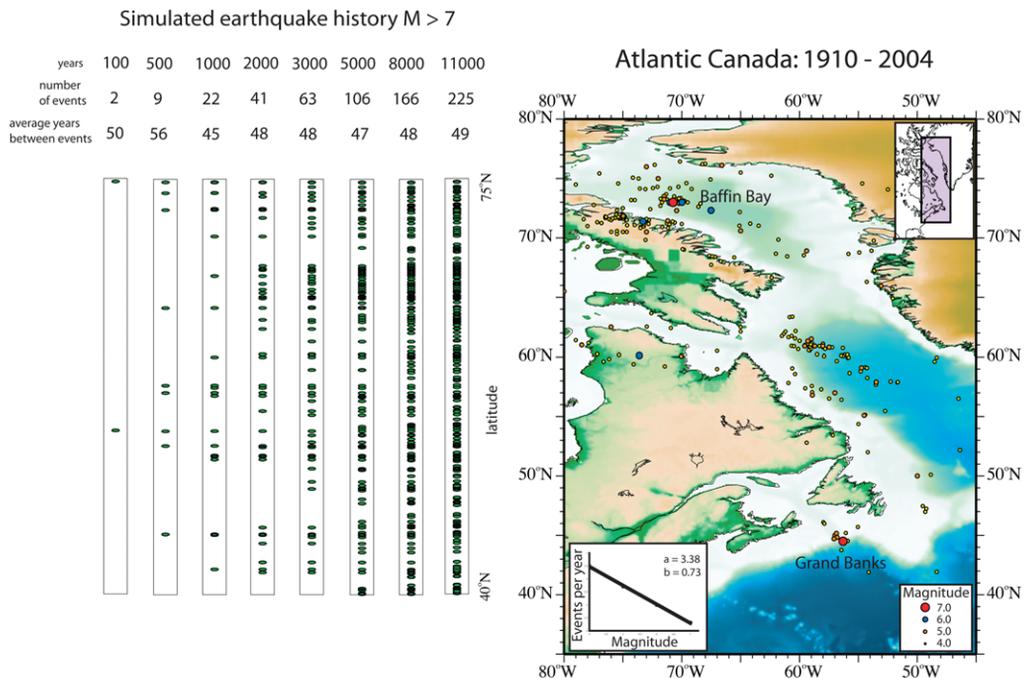

Fig. 9. Intraplate seismicity along the eastern coast of Canada. Simulations using a frequency–magnitude relation derived from these data predict that if seismicity is uniform in the zone, about 11 000 years of record is needed to avoid apparent concentrations and gaps (Swafford & Stein 2007). Reproduced with permission of Geological Society of America.

is shown as high in the southern URG, tapering off northwards, minor hazard between the URG and LRE, and then high hazard in the LRE. A natural question is whether these variations reflect real differences in earthquake hazard or biases from the fact that the earthquake history is short compared with the expected recurrence rate of the larger earthquakes.

The latter possibility is suggested by considering an earthquake catalogue compiled by the Royal Observatory of Belgium for the LRE. These data (Fig. 6) show the classic Gutenberg–Richter frequency–magnitude relation, $\log_{10} N = a - bM$, where N is the annual number of earthquakes with magnitude $\geq M$, a defines the seismicity rate and b is the slope of the line relating the rates of small and large earthquakes. The largest known earthquake in the LRE, the 1756 Düren earthquake, had a moment magnitude c. 5.7 and should occur on average about every 400 years. (A stronger earthquake with magnitude estimated as 6.3 occurred in 1692 near the city of Verviers in the Belgian Ardenne, just 30 km outside the LRE.) Extrapolating the line predicts the rate of larger earthquakes. For example, a magnitude 7.3 earthquake would occur on average about every 10 000 years, assuming such large earthquakes actually occur.

These data are for the entire LRE, so, in a few hundred years, any given portion of the area will probably not have experienced the largest earthquake that would occur over a longer time. More generally, seismicity viewed over different time intervals will appear different, with concentrations and 'gaps' in different areas (Fig. 7).

Thus the higher hazard mapped in the southern URG reflects the 1356 earthquake, but the fact that such an earthquake has not been observed in the northern URG may simply reflect the short record. Similarly, historical earthquake data going back to the year 800 AD (Fig. 8) suggests more activity in the central region between the URG and LRE than appears in Figure 5, which goes back to 1350 AD. As a result, palaeoseismic studies (e.g. Ferry *et al.* 2005) are crucial in that they extend the earthquake record beyond that available from seismological and historical data. However, palaeoseismology preferentially produces data in regions suspected to be seismically active.

Consequences of short sampling

The discussion so far illustrates one of the major challenges in assessing seismic hazard in intraplate areas – namely, that because the deformation rates are low, the earthquake record is short compared with the relatively slow rate at which the larger earthquakes occur.

Numerical simulations illustrate how short earthquake records can yield apparent concentrations of large earthquakes and seismic gaps in a region where the seismicity is uniform (Swafford & Stein 2007). The simulation in Figure 9, for the coast of eastern Canada, assumes that magnitude 7 earthquakes occur randomly along the passive continental margin at the rate with which they have occurred in the past 100 years. Approximately 8000–11 000 years of record are needed to show that the seismicity is uniform. Any shorter sample – such as that available today – would give a biased view. Hence if the seismicity and thus hazard are uniform, a hazard map produced using a too-short record will overestimate the hazard in some places and underestimate it in others. This situation yields the familiar 'bull's-eyes' or 'blobs' of high hazard mapped around the sites of large past earthquakes, which are sometimes not where subsequent large earthquakes occur (Fig. 2).

A related issue involves estimating the largest earthquake to expect. For example, for the LRE (Fig. 6), should the largest known earthquake be
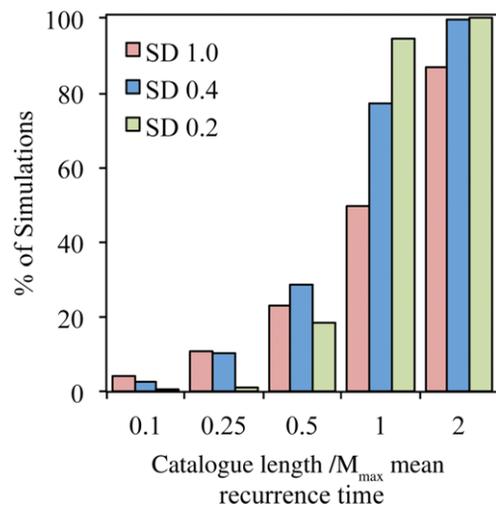

Fig. 10. Numerical simulations assessing how well earthquake catalogues of different lengths recover the actual maximum magnitude M_{max} of earthquakes in an area. Catalogue lengths are given as a fraction of the mean recurrence time for earthquakes with magnitude M_{max}. Colours show results for Gaussian distributions of recurrence times with standard deviation equal to the indicated fraction of the mean. The largest earthquake observed probably reflects the length of the history used, even if larger earthquakes occur, so a catalogue shorter than an earthquake's mean recurrence time is likely to not contain an event of that size (Stein & Friedrich 2014; Merino 2014). Reproduced with permission of the Royal Astronomical Society.
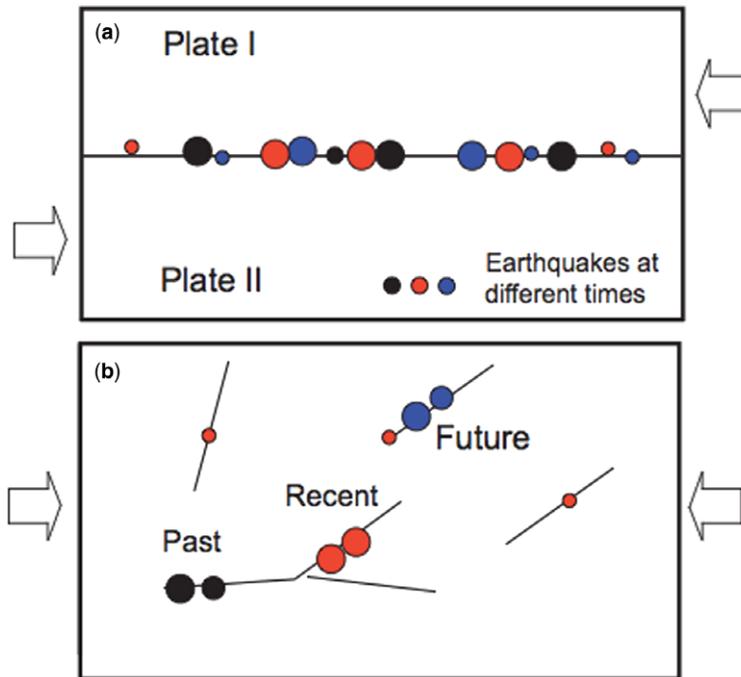
Fig. 11. Cartoon showing the difference between earthquakes (**a**) at plate boundary faults and (**b**) in mid-continents (Liu *et al.* 2011). Reproduced with permission of Geological Society of America.

regarded as the biggest that can occur in the area, or simply the largest in the past 650 years spanned by the catalogue? This question is crucial for critical facilities such as nuclear power plants that should be designed to withstand the maximum shaking expected at low annual probability or equivalently in a very long interval, e.g. 10^4–10^6 years. Numerical simulations (Fig. 10) illustrate that the larger magnitude earthquake appearing in a catalogue is likely to be that with a mean recurrence time equal to the catalogue length. Because catalogues are often short relative to the average recurrence time

of large earthquakes, earthquakes larger than anticipated often occur.

Episodic, clustered and migrating earthquakes

As discussed, the short earthquake record can bias our views of seismicity and seismic hazard even if the actual seismicity is uniform in an area, as in the simulation in Figure 9. A further complication is that, at least in some areas, the seismicity appears

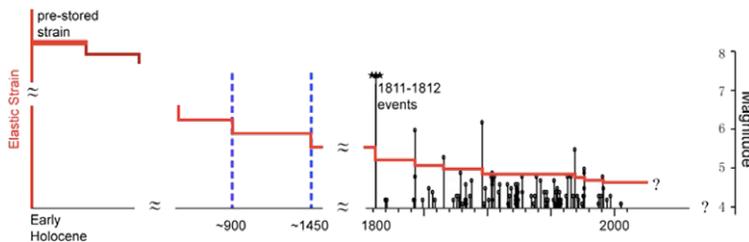**Fig. 12.** Conceptual model of a decaying New Madrid seismic zone earthquake sequence showing large earthquakes during 1811–1812 and similar events around 900 and 1450, and smaller events since 1812 (Liu *et al.* 2014). Reproduced with permission of Springer.
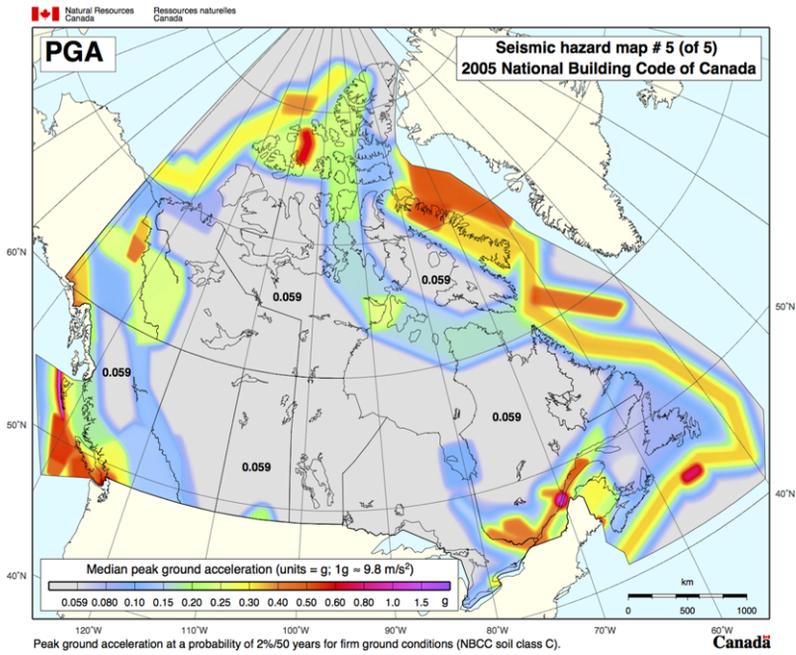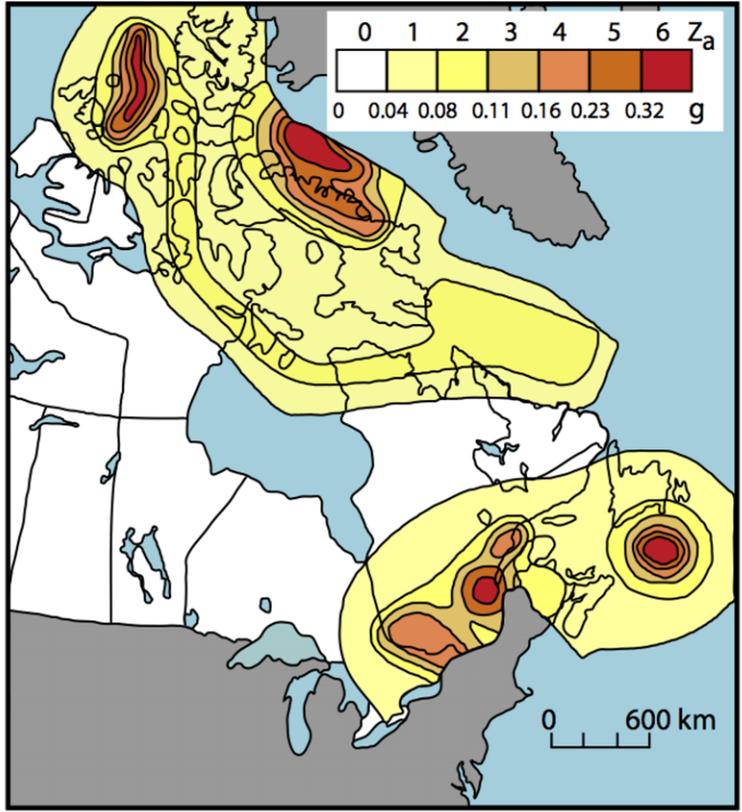
Fig. 13. Comparison of the 1985 and 2005 earthquake hazard maps of Canada (Stein *et al.* 2012). Reproduced with permission of Elsevier B. V.

Table 1. *Earthquake hazard uncertainties and their potential for reduction. Reproduced with permission of the Royal Astronomical Society*

Cause of uncertainty	How much can the uncertainty be reduced?
Where will large earthquakes occur?	Significantly on plate boundaries, somewhat in interiors
When will large earthquakes occur?	Little, if at all
How large will they be?	Significantly for lower bound (palaeoseismology), not for upper bound (short sample)
How strong will the shaking be?	Significantly in seismically active areas, less so in less active areas

to vary in space and time beyond that expected from the short record. These two effects have similar consequences for hazard assessment and are hard to separate.

Figure 11 illustrates how, in this view, earthquakes in mid-continents and those at plate boundaries behave very differently in space and time as a result of the geometry of the faults and the rate at which they are loaded. Faults at plate boundaries are loaded at constant rates by steady relative plate motion. Consequently, earthquakes concentrate along the plate boundary faults and show quasi-periodic occurrences, although the actual temporal patterns are often complicated. The apparent 'gaps' that appear will be filled in over time.

However, in mid-continents, the tectonic loading is shared by a complex system of interacting faults spread over a large region, such that a large earthquake on one fault could increase the loading rates on remote faults in the system. Because the low tectonic loading rate is shared by many faults in mid-continents, individual faults may remain dormant for a long time and then become active for a short period. The resulting earthquakes are therefore episodic and spatially migrating (Li *et al.* 2009; Stein *et al.* 2009).

These effects can be seen in many areas, including Australia (Leonard *et al.* 2007, 2014). A prime example is a 2000-year record from North China, which shows the migration of large earthquakes between fault systems spread over a large region, such that no large earthquake ruptures the same fault segment twice (Liu *et al.* 2011). Such behaviour may also occur in Europe. In particular, it has been suggested that the LRE (Fig. 7) may also show this effect, in addition to that of short sampling (Camelbeeck *et al.* 2007).

In such intraplate situations, we cannot use plate motion data to predict where strain will accumulate. Geodetic data can show strain accumulating. However, how to interpret faults on which little or no strain is accumulating is unclear, because faults may release strain that accumulated over very long periods of time. An example is the current seismicity in the New Madrid seismic zone in the central

USA, which appears to be after-shocks of a cluster of magnitude *c.* 7.0 events in 1811–1812 (Stein & Liu 2009). These large events and similar events in the past millennium release strain much faster than the global positioning system shows strain accumulating today (Calais & Stein 2009; Craig & Calais 2014), suggesting that they result from recent fault activation that releases pre-stored strain energy in the crust. This process would differ from standard elastic rebound in that the strain released in an earthquake is not only accumulated since the last earthquake. If so, this earthquake sequence is similar to after-shocks in that the rates of energy release should decay with time and the sequence of earthquakes will eventually end (Fig. 12). Estimation of the duration of large earthquakes from this transient release of energy shows that, within the uncertainties of model parameters, it is plausible that the New Madrid seismic zone's large earthquakes are now ending (Liu *et al.* 2014).

Because of both short sampling and migrating earthquakes, forecasting where large earthquakes will happen is like the carnival game 'whack-a-mole'. You will not hit the mole by waiting for it to come up where it went down, because it will pop up somewhere else. Thus the common practice of treating continental earthquakes as steady-state seismicity based on a short record can overestimate the hazard in presently active areas and underestimate it elsewhere.

This issue is illustrated by comparing Geological Survey of Canada hazard maps made in 1985 and 2005 (Fig. 13). The older map shows concentrated high hazard bull's-eyes along the east coast at the sites of the 1929 M 7.3 Grand Banks and 1933 M 7.4 Baffin Bay earthquakes, assuming there is something especially hazardous about these locations. The alternative is to assume that similar earthquakes can occur anywhere along the margin (Fig. 9), presumably on the faults remaining from the continental rifting. The 2005 map makes this assumption and thus shows a 'ribbon' of high hazard along the coast, while still retaining the bull's-eyes.

Long after-shock sequences

An additional complication for earthquake hazard assessment within continents is that after-shock sequences often last much longer in mid-continents, where tectonic loading is slow, than at rapidly loaded plate boundaries (Stein & Liu 2009). Durations of hundreds of years can occur, such as the current seismicity in the New Madrid seismic zone. This effect is important for hazard assessment. For
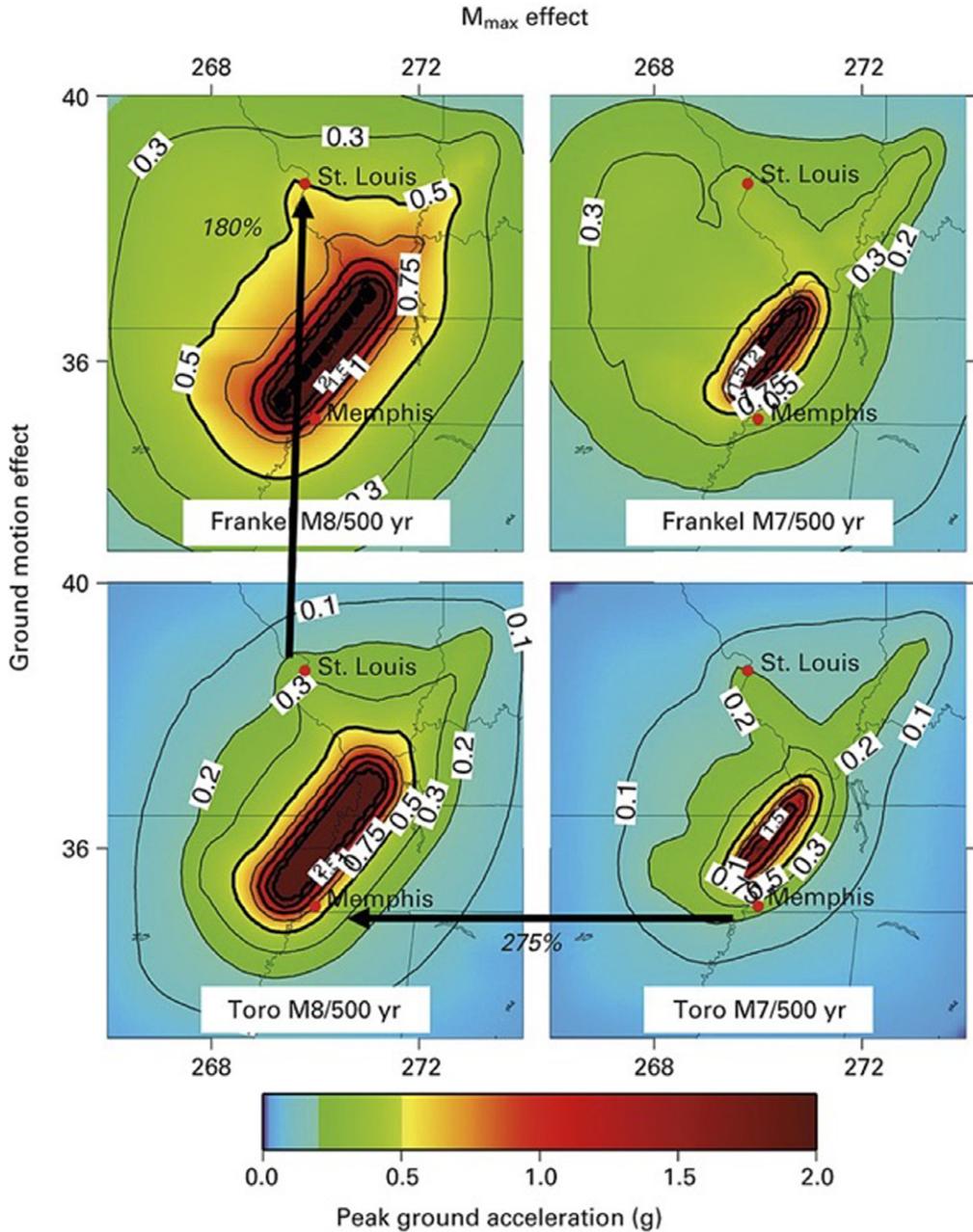

Fig. 14. Comparison of different hazard maps (2% probability in 50 years) for the New Madrid seismic zone (Newman *et al.* 2001).

example, recent seismicity in the Tangshan region in North China has prompted concern about a repetition of the 1976 M 7.8 earthquake that destroyed this heavily populated city and killed more than 242 000 people. Although more than 30 years have passed and a new city has been built on the ruins, the memory of devastation is still fresh. Are these recent earthquakes precursors of a new period of active seismicity? Or are they the aftershocks of the great Tangshan earthquake? Analysis of the earthquake sequence, combined with data from other areas worldwide, indicates that these are probably after-shocks (Liu *et al.* 2014).

The possibility of long after-shock sequences suggests that some recent seismicity may be after-shocks of large past earthquakes. For example, Ebel *et al.* (2000) suggested that some of the ongoing URG earthquakes may be after-shocks of the 1356 Basel earthquake. Hence could some of the seismicity in areas such as the Vienna Basin (Hinsch & Decker 2003) be after-shocks of still-unrecognized large past earthquakes?

Hazard map uncertainty

For the reasons discussed here, some key parameters in the models used to produce earthquake hazard maps are poorly known, unknown or unknowable

(Table 1). Although maps may be improved by estimating some parameters better, the fact that others cannot be much better estimated at present (if ever) limits how good maps can be (Stein *et al.* 2012; Stein & Stein 2013*a*; Stein & Friedrich 2014). Hence, in addition to trying to better assess hazards with new data and models, it is important to recognize and communicate the uncertainties involved.

Some of the uncertainties can be visualized by comparing the differences between maps made using different plausible assumptions about key parameters. Figure 14 illustrates the effects of assuming different ground motion prediction equations (columns) and maximum magnitudes (rows) of the main New Madrid fault source.

As shown in Figure 15, the predictions of the maps in Figure 14 for the hazard at St Louis and Memphis vary by a factor of more than three. At Memphis, close to the main faults, the primary effect is that of magnitude, with the two M 8 models predicting the highest hazard. At St Louis, the ground motion model has the largest effect, so the Frankel model predicts higher hazard than that of Toro *et al.* (1997). Additional uncertainty results from the fact that we can regard the recurrence of large earthquakes as a time-independent process, so a future earthquake is equally likely immediately after the past earthquake and much later, or as a
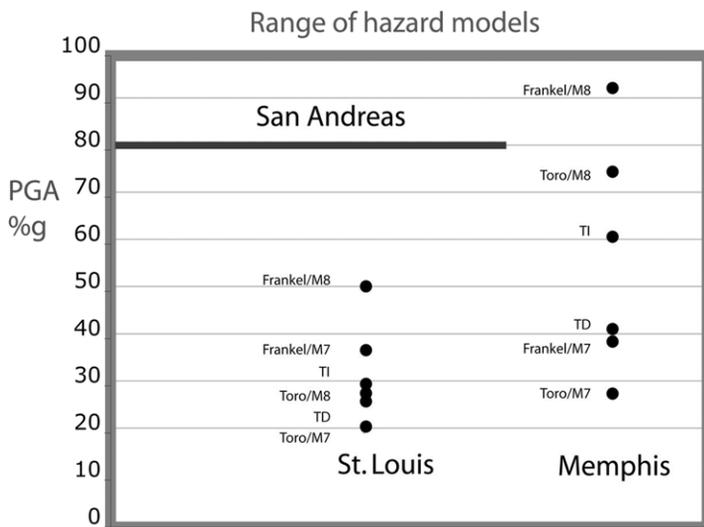

Fig. 15. Comparison of the hazard, described as peak ground acceleration (PGA) as a percentage of the acceleration of gravity expected with 2% risk in 50 yr, at St Louis and Memphis predicted by various hazard maps of the New Madrid zone, including those shown in Figure 14. For example, Frankel/M8 indicates the Frankel *et al.* (1996) ground motion model with a maximum magnitude of 8, and TI and TD indicate the difference between the time-independent and time-dependent models for a specific combination of maximum magnitude and ground motion model (Stein *et al.* 2012). Reproduced with permission of Elsevier B. V.

time-dependent process in which the probability is small shortly after the past earthquake and then increases with time (Hebden & Stein 2009). Most models show hazard well below that predicted for California. The predictions for a maximum magnitude of 7 are similar to those in which the large earthquake sequence has ended (e.g. Fig. 12) and the hazard reflects continuing after-shocks (Stein 2010).

Similar approaches are used to present uncertainties for analogous forecasts with significant economic and policy implications (Stein *et al.* 2015*a*). Meteorologists in the USA have adopted a goal of 'routinely providing the nation with comprehensive, skillful, reliable, sharp, and useful information about the uncertainty of hydrometeorological forecasts' (Hirschberg *et al.* 2011). Although seismologists have a tougher challenge and a longer way to go, we should try to do the same.

Assessing and communicating their uncertainties would make hazard maps more useful. At present, most users have no way to tell which predictions of these maps are likely to be reasonably well constrained, and which are not. Having this information would help users make better decisions about mitigation strategies. Natural hazard forecasts do not have to be perfect – or even that good – to be useful in making policies (Stein & Stein 2013*b*, 2014; Field 2015). However, the more users know about how much confidence to place in hazard maps, the more effectively the maps can be used.

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