Code Red: Earthquake Imminent?

UNDERSTANDING EARTHQUAKE HAZARD MAPS

This house in Lincolnville, S.C., was thrown by the 1886 Charleston earthquake.

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Seth Stein

Americans have become accustomed to color-coded alert level warnings that purport to predict the risk of an imminent terrorist attack. These levels, which vary from "severe" red to "low" green, prompt fear or ridicule because it is not clear how officials set the alert level. Presumably, it reflects a mix of information of varying reliability and current U.S. politics.

The terrorism threat-level system has a geologic counterpart: colored hazard maps that predict the risk of ground shaking due to earthquakes. Around the world, insurance companies turn to these maps to set premiums, while governments use them to specify building code standards for earthquake-resistant construction. Like security warnings, earthquake hazard maps are subject to many questions and fluctuate as the data and assumptions that go into them change.

Most features on hazard maps stay the same year after year. High hazard areas along the San Andreas Fault in California, for example, have been fixtures on U.S. hazard maps for decades. We have learned enough about the fault's recent history to know that earthquakes are relatively common. Furthermore, we have enough data to feed into computer programs to model future hazards.

Hazard versus Risk

The potential danger posed by earthquakes or other natural disasters can be described in two ways: hazards or risks. "Hazard" is the intrinsic natural occurrence of earthquakes and the resulting ground motion and other effects. "Risk" is the danger a hazard poses to life and property.

Although hazard is an unavoidable geological fact, the amount of risk changes based on human actions. Areas of high hazard can have low risk because few people live there — such as Alaska's Aleutian Islands, which are seismically active but sparsely populated. And areas of modest hazard can have high risk due to large populations and poor construction. Earthquake risks can be reduced by human actions, whereas hazards cannot.

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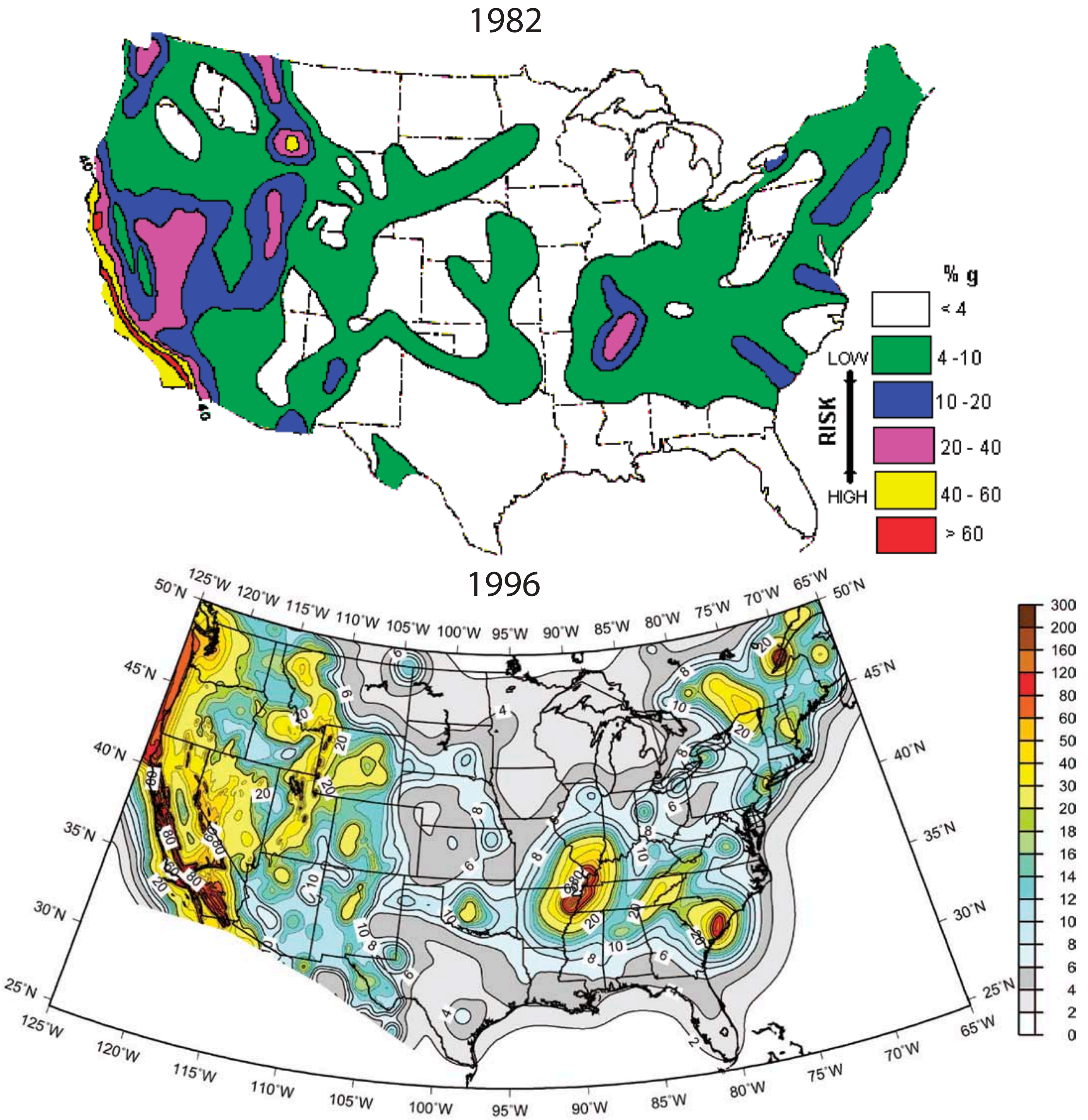

The top map shows the earthquake hazard predicted for the United States by older maps, whereas the bottom map shows the prediction of the new hazard maps. Due to a new definition of the hazard, the predicted hazard in the New Madrid area in the Midwest changed from much less than in the most dangerous parts of California to the same, or even more dangerous.

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In areas where we do not know as much, however, hazard predictions can change dramatically. A prime example is the New Madrid Seismic Zone in the central United States, where a series of magnitude-7.0 or greater earthquakes occurred in 1811 and 1812 and small earthquakes continue today. Traditionally, maps showed that the hazard in the New Madrid zone was much less than in California. Now maps show that the New Madrid Seismic Zone carries the same or greater amount of hazard as California, largely because of a new definition of hazard adopted in 1996. The new definition also raised the hazard near Charleston, S.C., where a large earthquake — estimated between magnitude 6.6 and 7.3 — occurred in 1886.

Because earthquake hazard maps affect millions of people, it is important to examine how the earthquake alert levels are set and how much confidence we have in them. The best way to do this is to look at how maps change based on what mapmakers assume. There are four main assumptions: how, where, when and what.

DEFINING THE HAZARD: HOW?

The first thing to think about is how mapmakers define the hazard. Hazard is not a physical thing we measure. Instead, it is something mapmakers define and then use computer programs to try to predict. We define an earthquake hazard in a given location in terms of probabilities. The hazard is the maximum amount of shaking, typically given as a percentage of the acceleration of gravity, that a location has a certain chance of exceeding at least once in a given period. The shaking is a measure of the ground's acceleration during an earthquake because that is what damages or destroys buildings. The predicted hazard includes the effect of earthquakes anywhere close enough to a location to cause significant shaking. These probability-based models combine the effect of large earthquakes that are less likely to happen but would cause more shaking with small earthquakes that are likely to happen more frequently but would cause less shaking.

Worldwide, hazard is most commonly defined as the maximum shaking that there is a 10 percent chance of exceeding at least once in 50 years — in other words, the maximum shaking predicted to occur at least once about every 500 years. Maps based on this definition show the earthquake hazard in the New Madrid Seismic Zone is much less than the hazard in California because large earthquakes are rarer in the Midwest.

In the 1990s, however, the U.S. Geological Survey, the Federal Emergency Management Agency and earthquake engineers started using a new definition of hazard that is more affected by the less common but larger

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Hazard maps based on a new definition of "earthquake hazard" predict that Memphis, Tenn. (above), is about as dangerous as San Francisco, Calif. (below). Researchers are debating this issue and whether construction in Memphis should be subject to the same seismic standards as San Francisco.

Bottom: © iStockphoto.com/Graeme Purdy; top: © iStockphoto.com/MBCheatham

Fact and Fiction in New Madrid

This marker in Missouri commemorates the 1811 and 1812 series of earthquakes.

Dustin Holmes

Almost 200 years after a series of large earthquakes shook the central United States in 1811 and 1812, we know surprisingly little about what's going on geologically where they occurred, an area known as the New Madrid Seismic Zone. We don't know why the earthquakes happened, when and why they started, if and when future large earthquakes will occur, how serious a danger they pose, or how society should confront this possible hazard. Moreover, because large earthquakes in the central United States are rare, we won't have the data to answer these questions for hundreds or thousands of years.

As a result, hype abounds. For example, a widely circulated educational video describes the 1811 and 1812 earthquakes as "the most powerful series of earthquakes ever known on Earth." Far from it. In fact, about 10 such earthquakes occur worldwide every year. And contrary to legend, the earthquakes did not ring church bells in Boston. There are no accounts that anyone in Boston felt the earthquakes.

The earthquakes were felt for long distances due to Midwest bedrock geology, but the damage was minor beyond the vicinity of New Madrid, Mo. About 160 kilometers away in Sainte Genevieve, Mo., the shocks caused no damage. A brick home that survived the quake can still be seen today, which is interesting because brick construction is especially vulnerable to earthquake shaking. In St. Louis, about 240 kilometers away, a newspaper reported, "No lives have been lost, nor have the houses sustained much injury. A few chimneys have been thrown down." Similar minor damage with "no real injury" occurred in Nashville, Tenn., Louisville, Ky., and Vincennes, Ind. No damage occurred in Fort Wayne, Ind., or Detroit, Mich. And although no church bells rang in Boston, bells did ring in Charleston, S.C.

We have historical accounts of the intensity of shaking, which can be ranked on a scale between "I" (generally not felt) to "XII" (total destruction). In the 1811 and 1812 earthquakes, New Madrid experienced violent shaking (intensity IX) whereas St. Louis, Louisville and Nashville experienced light to moderate damage, intensity VI or VII. Heavy and moderate damage occurred only within about 160 kilometers of the earthquake. Intensity maps yield estimated magnitudes of the three main shocks of about 7.2, 7.0 and 7.5, and give us ideas about what to expect if a similar earthquake were to occur again.

Small earthquakes, many of which are likely aftershocks of the 1811 and 1812 earthquakes, continue today. Earthquakes of magnitude 5 or greater occur about every 15 years. The largest in the past hundred years, a magnitude-5.5 quake in southern Illinois in 1968, caused no fatalities, with damage limited to broken windows, toppled television aerials and cracked or fallen brick and plaster.

What the future holds is unclear. Observations using GPS satellites find that the ground is moving very slowly or not at all, implying that another large 1811- and 1812-sized series of earthquakes won't occur for thousands of years or more. It's even possible that the cluster of large earthquakes in the past few thousand years is coming to an end, and it will be even longer until the next large earthquake strikes.

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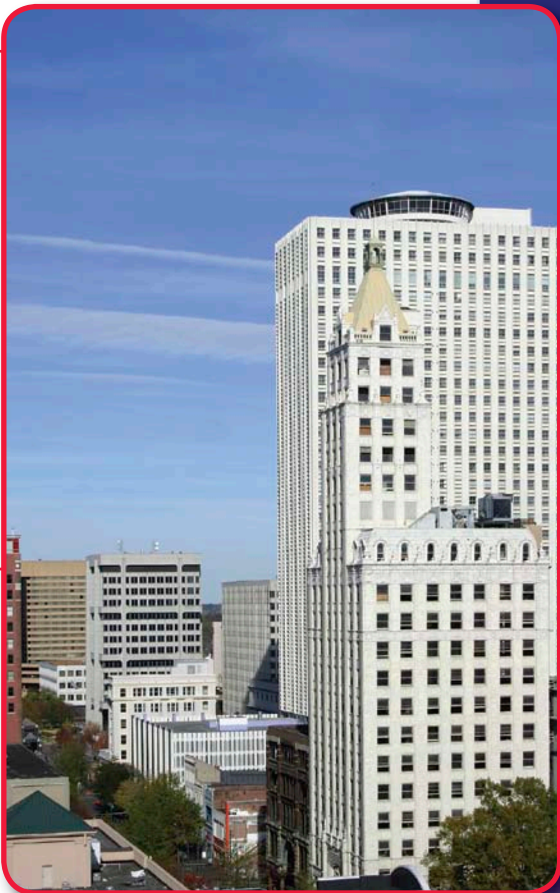

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earthquakes. The new definition — the maximum shaking that there is a 2 percent chance of exceeding at least once in 50 years, or would occur on average at least once about every 2,500 years — predicted greater earthquake hazards everywhere in the United States because it included rarer, larger earthquakes. The change was most noticeable in the central and eastern United States where big earthquakes are rare. In fact, the new map identified the New Madrid Seismic Zone as equally hazardous as many of California's faults. You can think about it as whether a building is in more danger from a flood or a meteorite impact: In 100 years, a flood is the greater risk. But in a billion years, both might have the same chance of happening at least once, even though floods will be more common. Whether the "at least once in 2,500 years" criterion makes sense — given that it's much longer than the average life of buildings — is hotly debated among geologists.

But changing parameters for the likelihood of earthquakes has major practical implications too. The increased hazard ranking of the New Madrid Seismic Zone has caused major problems for the insurance industry, and FEMA is pressuring communities in the region, which includes parts of Arkansas, Illinois, Indiana, Kentucky and Tennessee, to adopt building codes as strong — and as expensive — as California's. Communities are grappling with how to react because it is not clear if such stricter codes make economic sense. We do not know whether the increased costs of erecting such earthquake-resistant buildings are justified by the increased benefits, or whether it would make more sense to follow less stringent standards, thus freeing up resources for other uses. For example, does it do more good to strengthen hospitals for a possible big quake, or help hospitals pay for treatment of uninsured patients? Are we better off investing in stronger schools or more teachers? Similarly, how should we balance the greater safety produced by imposing costs on businesses with the resulting reduced economic activity (firms don't build or build elsewhere), job loss (or reduced growth) and reduction in tax revenue? As economists say, there's no free lunch.

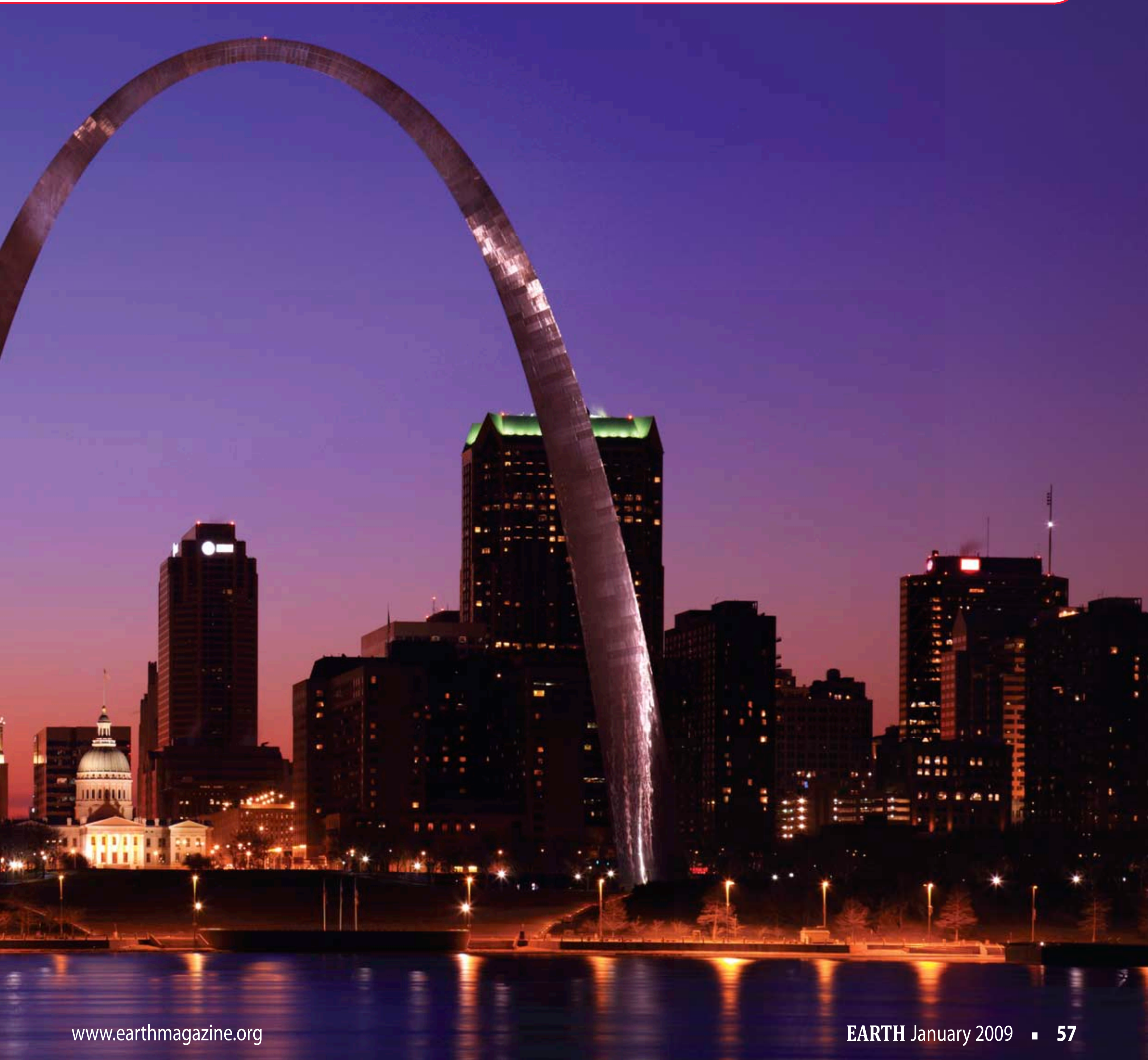
New hazard maps that show a high earthquake hazard in Memphis (left) and St. Louis (below right) are important for making seismic hazard policy for the Midwest.

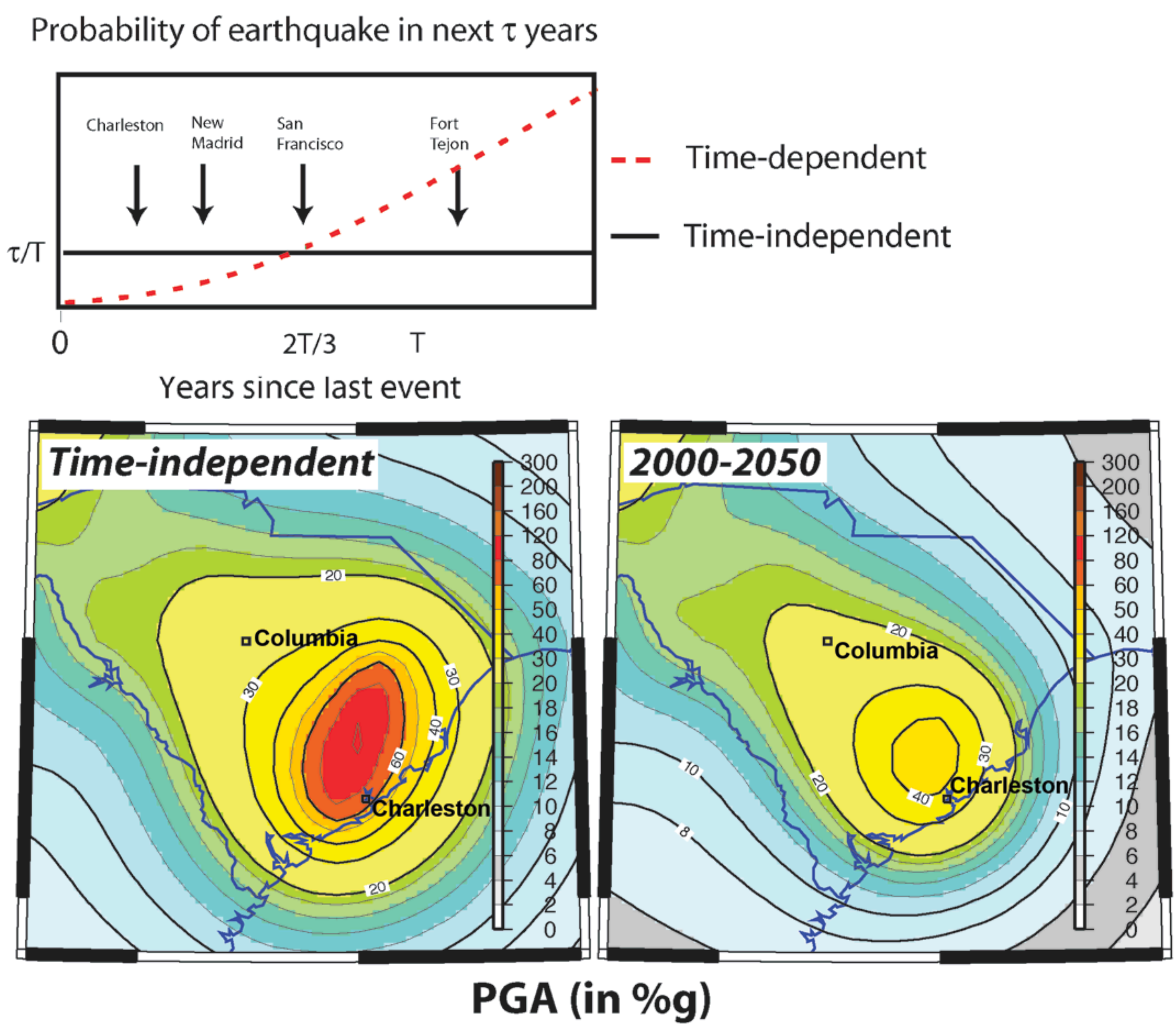
LOCATION, LOCATION, LOCATION: WHERE?

We know that some places, like the San Andreas Fault, are likely sites for earthquakes. We have long historical and geological records of shaking along various parts of the fault, so we can make sensible predictions about the patterns of earthquakes in those places. More uncertainty exists, however, where the earthquake history is too short to show any real patterns. We did not expect the December 2004 earthquake in Sumatra that caused the devastating tsunami, because we did not have a record of such earthquakes.

Therefore, we cannot make sensible hazard maps based on only the limited earthquake history. For example, along the eastern coast of Canada, older maps showed concentrated circles of high hazards only where there had been historic earthquakes. These bull's-eye patterns did not make much sense, as we only have a few hundred years of earthquake data. As such, the earthquake history alone probably does not show where, on a longer timescale, earthquakes may happen.

Looking at the geologic structures — the faults, bedrock, soils and subsurface structures where earthquakes happen — can give us better insight. Along the coast of Canada, for example, the subsurface is riddled with old faults, remnants of the breakup of the continents more than 50 million years ago. We have seen earthquakes on some of the faults and they are likely to happen on the others. New maps using this geological assumption are more sensible because they show a more uniform hazard along the coast. Increasingly, hazard maps in other areas, such as central Europe, are being changed to include the geology.





Comparison of the earthquake probabilities predicted by time-dependent and time-independent models for four different areas. Which model predicts higher hazard depends on how long it has been since the last large earthquake compared to the average time (T) between earthquakes. For example, because large earthquakes in the Charleston area occur on average 550 years apart and the last was in 1886, a time-dependent hazard map for the years 2000 to 2050 predicts much lower hazard than a time-independent map.

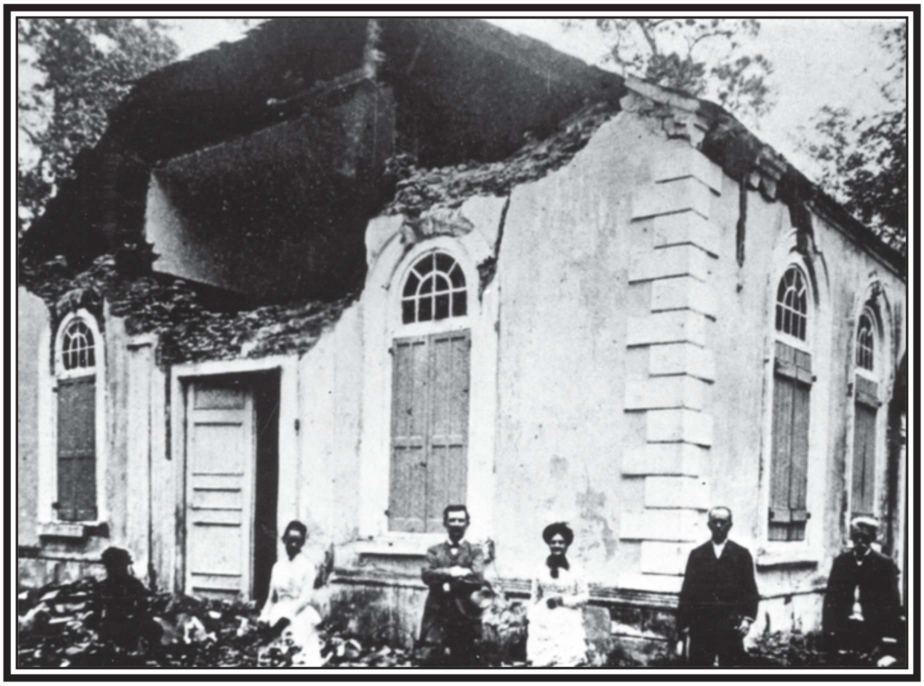
Seth Stein

TIMING IS EVERYTHING: WHEN?

After assuming where earthquakes will occur, mappers have to assume when they will happen. Traditionally, hazard maps assume that the probability of a large earthquake on a fault is constant with time; in other words, following a large quake, a future earthquake is equally likely to happen 10 days, 10 years or 100 years later. With this time-independent model, an earthquake is never overdue. Alternatively, scientists can use a time-dependent model, where the probability of a large earthquake is small shortly after one happens, and then increases with time. A time-dependent model assumes that an area has a lower probability of an earthquake — and thus a lesser hazard — if less than about two-thirds of the assumed average time between earthquakes has passed. However, if a large earthquake has not occurred by this two-thirds time, the time-dependent model will predict higher probabilities and thus a greater hazard than the lower hazard that the time-independent model predicts.

Time-dependent models for the New Madrid and Charleston seismic zones, for example, predict significantly lesser hazards than the time-independent model because both are early in their seismic cycles. At New Madrid, it has been nearly 200 years since the large earthquakes in 1812, which is about 40 percent of the assumed 500-year earthquake recurrence interval. The large earthquake near Charleston occurred more than 120 years ago, so the area is only 22 percent into its assumed 550-year recurrence interval. In contrast, time-dependent models predict a greater hazard on the southern portion of the San Andreas Fault, because it has been

The Goose Creek Church in Charleston was damaged in the 1886 quake.



U.S. Geological Survey Photographic Library

152 years since it last ruptured in the Fort Tejon earthquake, which is longer than the assumed 132-year average recurrence.

There is a further complication at New Madrid, because GPS measurements do not show the ground motion we would expect if energy were being stored before an upcoming earthquake. The fault system may be shutting down for a while, in which case the hazard would be much less than either time-independent or time-dependent models predict.

SIZE MATTERS: WHAT?

Mapmakers must assume what will happen when earthquakes occur — an assumption that involves much uncertainty. This involves two questions: how large the earthquakes will be and how much shaking they will produce. Each question affects the predicted hazard. Seismologists base the size estimates on what they know and assume about historical quakes and the geology of the area, including the fault type. Though harder to estimate, we base the predicted shaking on what we know about what happened in past earthquakes and assumptions about how well the rock transmits seismic waves. Whatever model seismologists use for the ground shaking affects the predicted hazard all over the area, because shaking results both from the largest earthquakes and from smaller earthquakes off the main faults.

For the New Madrid area, for example, the largest future earthquakes are assumed to be like those that happened in 1811 and 1812 — somewhere between magnitude 7 and 8. Because they occurred before the seismometer was invented, no one knows their exact magnitudes. Additionally, because we do not have any seismograms from large earthquakes in this area, it is unclear how to model the shaking that large earthquakes would produce. That is not the case in California, where we have good seismic records showing how big previous earthquakes were and how much shaking they caused.

IMPLICATIONS

As these examples show, different assumptions result in quite different hazard maps. Because what to assume is often unclear, the resulting hazard estimates are likewise uncertain. This is especially true where earthquakes are rare, such as the middle of tectonic plates like North America — far from the edges where plates collide, grind past each other, or slip over or under one another. So when we use a hazard map, it is good to remember that this is just one of a large number of different and equally likely maps geologists could make.

In fact, that is what meteorologists do. Weather forecasts, for example, often show a range of predictions for the paths of hurricanes or snowstorms. Similarly, in assessing the possible effects of global warming, the Intergovernmental Panel on Climate Change reports compared a wide range of different models. The range of forecasts is used to show the range of uncertainty.

How useful are earthquake hazard maps? It's hard to say. We won't really be able to tell for hundreds or thousands of years, when we have enough data to see how good their predictions were. At this point, the method of predicting probabilities of shaking just described seems to be the best approach anyone has come up with, because it can be used to assess what levels of earthquake-resistant construction make sense in a particular earthquake zone. Specific predictions about New Madrid, Charleston, California or anywhere else probably vary in certainty. Where the data are good, the predictions are probably good. Where the data are poor, the predictions may be poor. Our best bet is to look at any given map, ask whether its predictions make sense, and act accordingly. As the old adage says, statistics like these should be used the way a drunk uses a lamppost — for support rather than illumination.

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