EAST COAST EARTHQUAKES

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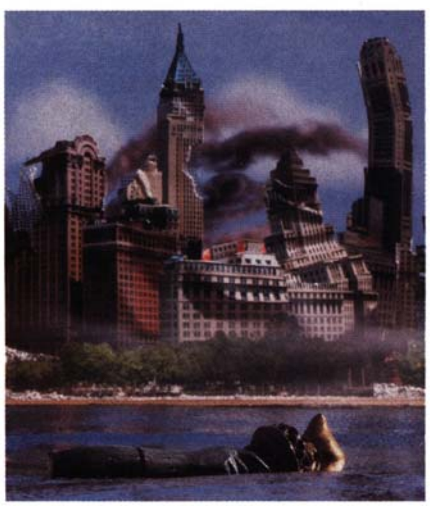
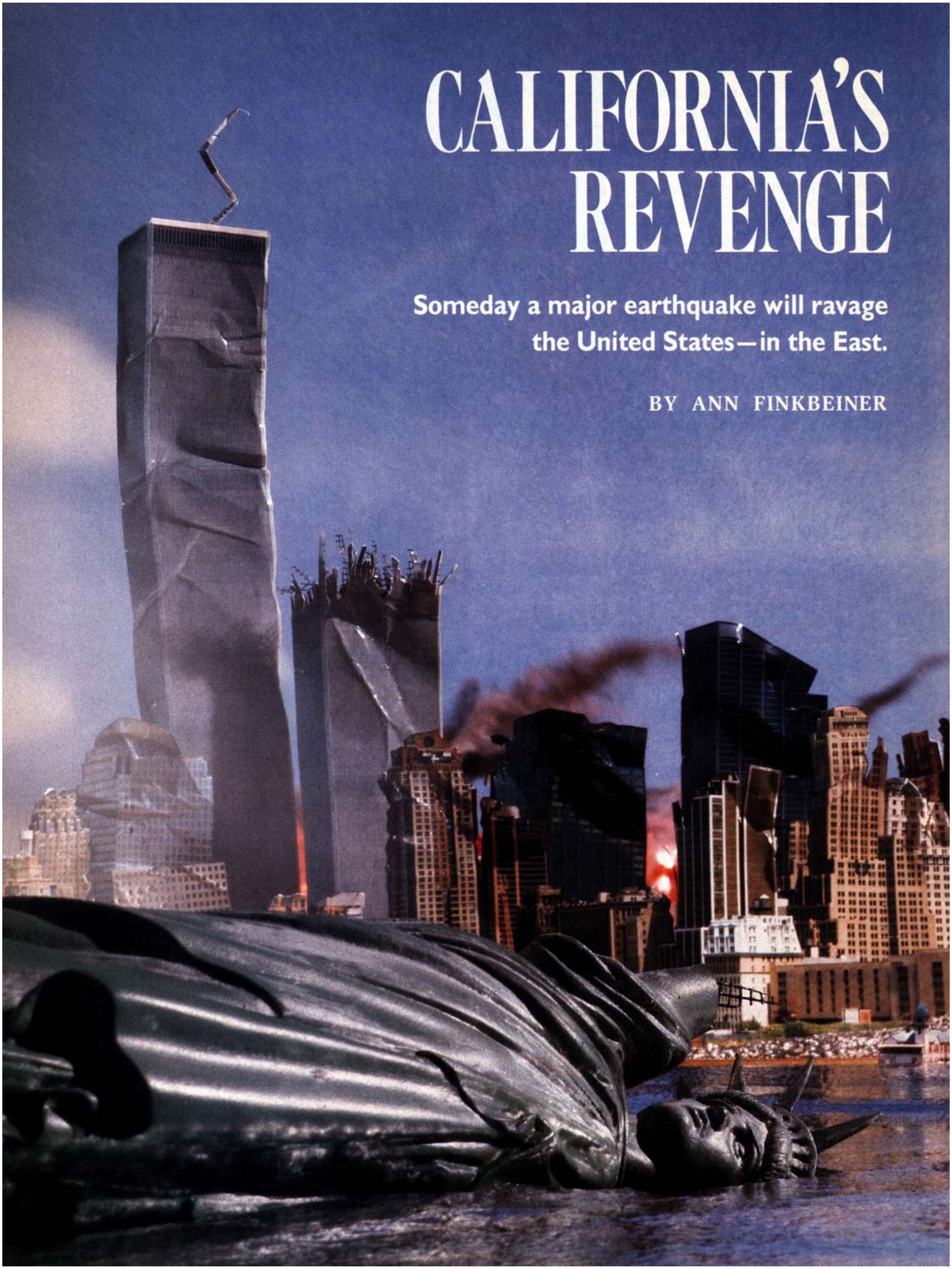


Shaking up the city, p. 78

CALIFORNIA'S REVENGE

Someday a major earthquake will ravage the United States—in the East.

BY ANN FINKBEINER



The earthquake that struck near Santa Cruz on October 17, 1989, killed 62 people and was felt over 66,000 square miles. But most of San Francisco and large parts of Santa Cruz itself were unscathed. The earthquake that struck Charleston on August 31, 1886, flattened the city. Few buildings went untouched. Nearby dams burst, and the floods washed trains off their tracks. In a town of 50,000, as many as 110 people died. The quake cracked walls in Chicago, 750 miles away; it was felt over an area of 1.5 million square miles, from Massachusetts to Wisconsin to Bermuda.

Of course, as everyone knows, earthquakes are not supposed to happen in South Carolina. California is another story: even well before October's quake geologists were saying there was a good chance of an earthquake of roughly that magnitude (7 on the Richter scale, about the same as the Charleston quake) striking precisely that segment of the San Andreas Fault. Geologists even know why the San Andreas, that egregious scar on the California landscape, is so quake-prone. It marks the boundary between two of Earth's shifting, crust-bearing plates—the one that carries the Pacific Ocean and the one that carries North America. As these two giant slabs grind past each other at a few inches a year, they get stuck at certain points. Stress builds up over decades and then gets released all of a sudden. Most earthquakes happen in the heavily faulted rock at plate boundaries, and not only in California: the devastating quakes that struck the Philippines and Iran this summer are recent examples of this process.

Charleston is different. Like the rest of the East, it is nowhere near a plate boundary—the eastern edge of the North American plate is a ridge that runs down the middle of the Atlantic. For a long time it was assumed the rock under Charleston must have huge, hidden faults. But when geologists combed the area in the 1970s and early 1980s, they came up empty. There was nothing special about Charleston, they concluded, that distinguished it from the rest of the East.

"Until the early eighties, people could look at the Charleston quake as peculiar to that area," says John Armbruster of Lamont-Doherty Geological Observatory. "But now we have to admit the possibility of a large quake coming out of nowhere. The Charleston quake was a wild card. That scares the hell out of people."

What has started to scare geologists and building engineers is the growing realization that nearly all of

PHOTOGRAPH BY J. R. ROST

eastern North America—everything east of the Rockies—must be considered vulnerable to damaging earthquakes. Quakes happen less frequently in the East than in the West, but also less predictably; in most cases, as in Charleston, geologists can't even find the guilty fault. What's more, when an eastern quake does occur it is felt over a much wider area than a quake in the West—precisely because the East is not crisscrossed by fault-shattered rock, which tends to dampen the spread of shock waves.

And unlike much of the West, the more heavily populated East is not at all prepared for a major earthquake. San Franciscans were spared a grimmer disaster this past year by building codes enacted decades ago, but most people in the East live and work in buildings that are not much better equipped to resist shaking than Charleston was in 1886. Seven years ago that city, now with a metropolitan population of 500,000, commissioned a report on what a magnitude 7 quake might do these days. The estimate was more than 2,000 deaths, more than 8,000 serious injuries, and $2.4 billion in damage.

Charleston's quake was not the strongest ever to strike east of the Rocky Mountains. In December 1811 and January and February 1812 the area around the Mississippi River town of New Madrid, Missouri, was rocked by three earthquakes, the description of which is a series of superlatives.

John Bradbury, a Scottish naturalist who was traveling down the Mississippi to collect plant specimens when the first quake occurred, wrote that the sound was "equal to the loudest thunder but more hollow and vibrating." Other sources reported geysers of sand and black water shooting into the air as high as trees, leaving behind craters 5 to 30 feet wide. The ground rolled in waves several feet high, knocking people down. Collapsing riverbanks changed the Mississippi's course and even created new lakes; one of them, Reelfoot Lake, now covers 18,000 acres 20 feet deep and is littered with the trunks of drowned cypress trees. "All nature," wrote Bradbury, "seemed running into chaos."

Not only were the New Madrid earthquakes strong—judging from their effects they were probably between mag-

Even geologists have neglected eastern earthquakes, partly because they're much less frequent than western ones and partly because they're harder to understand.

nitudes 8 and 9—but their reach was unparalleled. They cracked sidewalks in Charleston and collapsed scaffolding around the Capitol in Washington. They damaged well-constructed buildings over an area of 235,000 square miles, 20 times the area damaged by the San Francisco quake of 1906 (a magnitude 8.3). People felt the shaking over perhaps 4 million square miles, the largest area ever affected by any recorded quake. "If we could pick any earthquake in the forty-eight states that, if it recurred, would cause the greatest damage," says Armbruster, "it would be New Madrid."

Other eastern earthquakes, although not as spectacular, have been strong enough to cause damage. In 1929 a 7.2 quake on the coast of Newfoundland set off a large underwater landslide and triggered a tsunami that killed 27 people. The Charlevoix region, northeast of the city of Quebec along the St. Lawrence River, has had five earthquakes over the past 330 years that were magnitude 6 or greater; the most recent one, a magnitude 7 in 1925, was felt strongly as far away as New York City.

New York itself is not immune: in 1985 a magnitude 4 quake, centered just north of the city in Westchester County, woke up people throughout the area. Although it didn't do much else, it was an unsettling reminder. The fault that triggered it is one of a family of intersecting faults, some of which extend directly under Manhattan; among them are faults under 125th Street and 145th Street, as well as several under the East River. "For years now I've been beating the drum that seismicity isn't dead around New York," says geologist Charles Merguerian of Hofstra University, who has trekked into subway and water tunnels to map the city's hidden faults. "The mechanism may be different from the one in California, but it warrants concern."

All told, since the late seventeenth century eastern North America has had 16 earthquakes larger than magnitude 6 and several hundred larger than magnitude 4. (Each step up in magnitude increases an earthquake's strength by ten times, so magnitude 6 is 100 times stronger than magnitude 4.) Although Charlevoix and New Madrid are now the most seismically active areas—they feel minor tremors on a regular basis—quakes have occurred in many other parts of the East. The past century happens to have been comparatively quiet, which is why there is a lack of public concern.

Historically, even geologists have neglected eastern earthquakes, partly because they're much less frequent than western ones and partly because they're harder to understand. In a way the advent of plate-tectonic theory in the 1960s simply made them more puzzling. Once it was realized that Earth's outer shell is broken into a dozen or so plates that slide over the hot mantle, it became perfectly clear

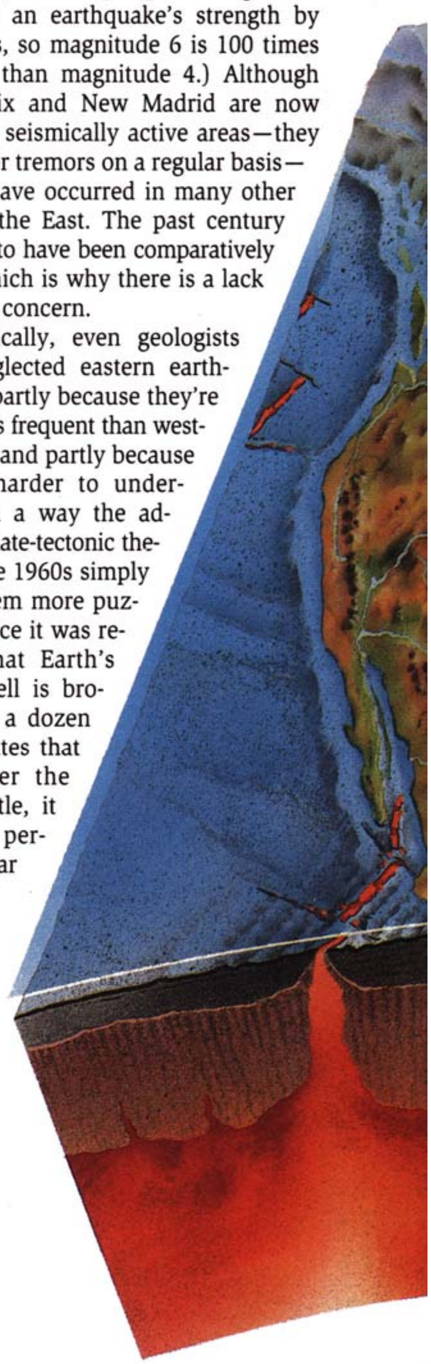
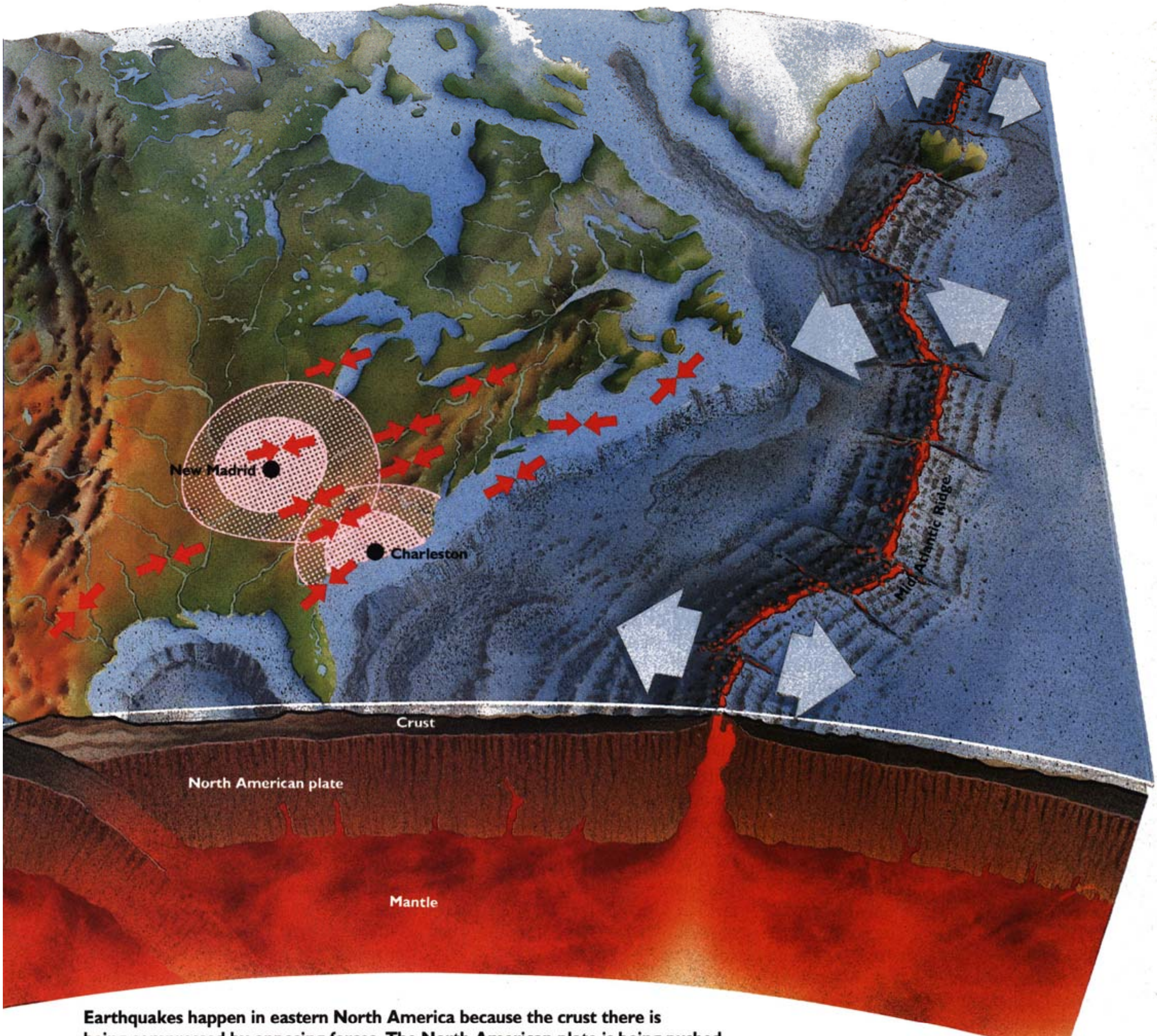


ILLUSTRATION BY IAN WORPOLE

why earthquakes occur at plate boundaries: that's where the plates rub past each other or ram into each other. The middles of the continental plates, on the other hand, are far from this jostling, and for the most part they have been coherent, unbroken rock for at least 2 billion years.

Earthquakes happen nonetheless in the middle of plates because the plates are not perfectly rigid. They are under a lot of stress, and as a result they deform, not just at their boundaries but in the center as well. Geologists can measure the long-term effects of this stress; one method involves examining oil-well boreholes to see how much and in what direction the circular hole has been squeezed out of shape. This past year Mary Lou Zoback of the U.S. Geological Survey and her husband, Mark Zoback of Stanford, assisted by many collaborators, assembled a global map of such measurements. The map shows



Earthquakes happen in eastern North America because the crust there is being compressed by opposing forces. The North American plate is being pushed toward the west-southwest by hot rock welling up from the mantle along the Mid-Atlantic Ridge, while Europe and Africa are pushed to the east-northeast. (A similar ridge in the Pacific is pushing ocean floor under Mexico.) The motion of the plate is resisted, however, by drag exerted by the underlying mantle. The resultant compressional stress (red arrows) was released in huge earthquakes at New Madrid, Missouri, in 1811 and Charleston, South Carolina, in 1886. Both quakes did serious damage over enormous areas (dark pink) and moderate damage (light pink) over still larger ones.

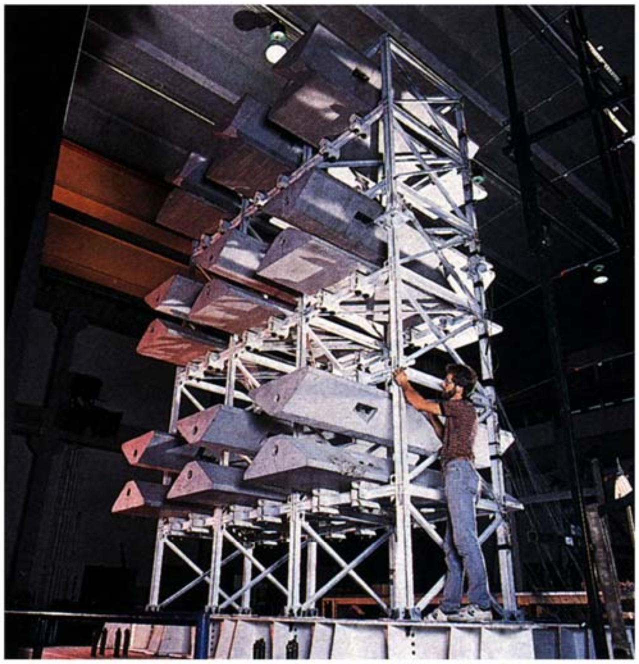
that eastern North America is being compressed along an axis that runs east-northeast to west-southwest. That, as it happens, is roughly the direction North America is moving over the mantle.

North America is being pushed by the ridge that runs down the middle of the Atlantic. The ridge is a spreading center: it marks the boundary along which the European and North American plates are spreading apart. As the plates spread, the hot, liquid rock of the mantle oozes up into the gap and congeals to form new ocean crust. The force of the upwelling helps push the plate away from the ridge, toward the west-southwest. But the plate doesn't glide along like an air-hockey puck. Its motion is thought to be resisted by drag exerted by the underlying mantle. The two opposite forces may well account for the compressional stress in eastern North America.

Knowing where the stress comes from, however, doesn't tell you where it is going to be released. And for a long time the geographic distribution of earthquakes in eastern North America has appeared to be more or less random. Recently, though, Arch Johnston and Lisa Kanter, two geophysicists at Memphis State University (not far from New Madrid), discovered an intriguing pattern to midplate quakes. After plotting the locations of more than 800 such quakes around the world, Johnston and Kanter found that most of them occurred in just two kinds of geologic settings.

The first can be found in the coast of continents that were once ripped apart to form a new ocean. For example, 200 million years ago the Atlantic didn't exist; Europe and North America were joined in the supercontinent Pangaea. Then Pangaea began to stretch thin along a long line—either because it was being pulled apart from its edges or because it was being pushed from below by upwelling magma. Eventually it was torn completely in two, and the rift became the Mid-Atlantic Ridge. The continental margins of North America and Europe are the old edges of the rift, now separated by an ocean. They are regions of weak, thin, and cracked crust. The Charleston quake occurred in such crust; so did a magnitude 6 quake that shook Cape Ann, near Boston, in 1755.

The other typical setting for a midplate quake, according to Johnston and Kanter, is along lines where the crust began thinning out into a midocean ridge but for some reason stopped. These failed rifts are also regions of weakened crust. A failed rift lies under the St. Lawrence River, near Charlevoix. A large failed rift called the Reelfoot Rift runs right under the Mississippi River, from southern Arkansas past New Madrid and into southern Illinois.



Engineers at the State University of New York at Buffalo test quake-dampers on a six-story model.

PHOTOGRAPH COURTESY NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH, STATE UNIVERSITY OF NEW YORK AT BUFFALO

Together continental margins and failed rifts make up only a quarter of Earth's stable continental crust, but they account for nearly half its moderate quakes (between magnitudes 4.5 and 6), 60 percent of the serious ones (between magnitudes 6 and 7), and all the ones above magnitude 7. "We didn't start out to look for this pattern," says Johnston. "It just fell out as the study progressed."

A geographic pattern to past quakes, however, is still no basis for forecasting future ones. In California, geologists can sometimes forecast the likelihood of a quake occurring at a certain place within a certain time because they have only to look at the ground to find an active fault. When an earthquake happens along the fault, the ground on one side is offset in relation to the other, and each succeeding earthquake exaggerates the offset. Ground that was once flat now has hills and valleys; roads and streams and long outcroppings of rock have jags in their paths.

"In places along the San Andreas," says Mark Zoback, "you find the other half of a rock outcrop a couple of hundred miles away." By dating each jag, geologists can estimate how often and at what intervals earthquakes recur on that fault, and thus get a rough idea of when the next one should be expected.

In the East this method generally doesn't work. For reasons no one knows, eastern faults generally do not break the surface. (The most notable exception to this rule in the United States is the Meers Fault, a wall between 9 and 15 feet high that runs for 18 miles across southwestern Oklahoma.) And no fault has generated the changes in topography—the jags and hills and valleys—that repeated earthquakes should cause. If the 1811 earthquake at New Madrid was a repeat of earlier earthquakes, says Johnston, "we ought to have a lot of topography here that we just don't have."

Within only the past two years have Johnston's colleagues Eugene Schweig and Ronald Marple discovered a subtle topographic feature near New Madrid that may be the surface expression of a deep-seated earthquake-generating fault. Called the Bootheel Lineament, it's a 50-mile-long, 30-to-60-foot-wide linear depression, filled with sand in many parts, that is nowhere more than two feet deep. Marple first noticed it on aerial and satellite images.

It's not clear why faults in the East don't generate more visible topography. Perhaps they move back and forth, so offsets in any one direction don't accumulate. Or perhaps, as Armbruster suggests, the crust is so thick and strong that faults can't move too much, and "if an earthquake moves a fault once, the next earthquake will have to go somewhere else."

"It's a tough question for midplate earthquakes," says Johnston, "maybe *the* question. We not only don't have a good handle on the repeat time of major quakes, we don't even know whether they repeat at all."

To get around this problem, Mark Zoback and his colleague Paul Segall are trying to develop a new approach to prediction that does not require geologists to study faults. The Global Positioning System, a network of radio-emitting satellites that the Department of Defense is deploying as a navigation aid, also makes it possible to measure minute deformations of the crust—the deformations move the radio receivers—as they happen, inch by inch.

In principle the system should make it possible to measure directly which areas of the crust are being squeezed together rapidly and are thus accumulating dangerous levels of stress. Zoback and Segall plan to test the idea around Charleston and New Madrid, on the assumption that those areas are still feeling a strong squeeze. Then they'll look for similar rates of stress accumulation elsewhere in the East in hopes of identifying other quake-prone areas.

But this sort of prediction, if it ever works, is still in the future. For now the only approach to predicting earthquakes in the East is statistical: researchers look

"If you look where quakes have occurred recently, you may be looking in the wrong places. Maybe the next big one will occur in the place that's been quietest."

at the number and magnitude of earthquakes a given area has had in the recent past and then extrapolate into the future. New Madrid, for example, has been estimated to have earthquakes of magnitude 4 every year or two, magnitude 5 every 10 to 20 years, magnitude 6 every 70 to 100 years, and magnitude 8 every 500 to 1,000 years.

Using the same method, Armbruster and Klaus Jacob of Lamont-Doherty have estimated that New York City should have a magnitude 5 earthquake every 100 years and a magnitude 6 every several hundred to 1,000 years. But even the researchers themselves don't put much stock in their estimate. "It's the best we've got," says Armbruster, "but that doesn't say much for it."

One obvious flaw in the statistical approach to prediction is that it ignores the quiet places, the ones that don't even have little earthquakes at the moment—the wild cards, as Armbruster calls them. Charleston, for example, was seismically quiet for years before 1886. (In looking through the local newspapers for the 80 years before the disaster, Armbruster found no reports of tremors. "Would I have known to get out of town?" he asks. "I wouldn't.") It has been quiet again for the past century. The Boston area was quite active throughout the eighteenth and nineteenth centuries but is now much quieter. The Meers Fault in Oklahoma, which had a magnitude 7 or 8 quake 1,200 years ago, was quiet for millions of years before that and has been quiet since.

In the East, it seems, quiet periods can mean anything: a lull after the previous earthquake or the quiet before the storm of the next one or a truly earthquake-free zone. "It's impossible to say whether quiet periods are ominous or not," says Zoback. "The real enigma of eastern earthquakes is that faults turn on, produce earthquakes rapidly, then turn off and are quiescent for hundreds of thousands or millions of years. That's scary." Says Armbruster: "I kind of like the view that if you look where quakes have occurred recently, you may be looking in all the wrong places. Maybe the next big one will occur in the place that's been quietest for the longest period."

One thing that is certain is that a big one anywhere in the East will be felt over an enormous area. For an earthquake of a given strength in California, an earthquake of the same strength in the East will reach an area 100 times larger. In the West seismic waves bounce around in the shattered, faulted rock and die out before they get far. But in the comparatively solid rock of the East, where faults are much fewer and smaller, the waves move easily over long distances. A large quake under Boston, for instance, would hit New York hard, too, not to mention all the smaller cities in between.

It makes sense, then, to try to esti-

A strong earthquake can force up geysers of water-saturated sand. This resultant crater, or "sand blow," was photographed shortly after the 1886 Charleston quake.

PHOTOGRAPHS COURTESY J. K. HILLERS, U.S. GEOLOGICAL SURVEY mate the odds of a large earthquake taking place anywhere in the East rather than just in specific locations. Such estimates are tentative at best. But earlier this year, addressing an audience of insurance executives, Jacob hazarded his best guess: there is a 61 percent chance, he said, that a magnitude 6 quake will take place somewhere east of the Rockies in the next 20 years; and there is a 10 percent chance of a magnitude 7 quake—roughly equivalent to the one that leveled Charleston.

Like eastern North America, Newcastle, Australia, lies in the middle of a plate, and in December it was struck by a 5.5 quake. Magnitude 5.5 is only a moderate earthquake. But this one killed 12 people, injured 200, and caused $1.5 billion in damage. Much of the damage was due to the failure of unreinforced masonry. Buildings that have metal skeletons or are made of wood tend to flex during an earthquake, but unreinforced masonry—bricks and mortar, concrete, cinder block—snaps like chalk or simply disintegrates. In New York City, half the one-, two-, and three-story buildings are unreinforced masonry; around 70 percent of the four-, five-, and six-story buildings are. That is typical of the East.

In fact, most buildings in the East are built not only with the wrong material but with the wrong design to withstand earthquakes. They are designed to hold up against the force of gravity, to take what engineers call a vertical load; and for this, roofs, floors, and foundations need not be tightly connected to walls. Earthquakes, however, exert a lateral load: they push a building from side to side. Skyscrapers of 20 stories or more usually have steel skeletons designed to withstand the lateral loads of wind, so they are somewhat protected against earthquakes too. But most other eastern buildings are not, and in an earthquake their verticals and horizontals simply separate. The floors above are deposited on the floors below. Engineers call it pancaking.

Several other eastern cities besides Charleston have commissioned studies estimating what would happen if the largest historic quake for that area were to recur today. In the six cities that have grown up around New Madrid, according to the worst-case scenario, nearly 5,000 people would die, many of them schoolchildren herded together in buildings of unreinforced masonry. The total damage in those six cities alone would be $52 billion. (A magnitude 8 quake in New Madrid, of course, would damage a much wider area.) A recurrence of the 1755 Cape Ann earthquake, magnitude 6 or so, would cause 360 deaths in the Boston area, 12,000 injuries, and perhaps $6 billion in damages. New York City's worst likely earthquake is also thought to be a magnitude 6; the number of deaths has not been estimated, but the damage to buildings has been put at $8 billion from shaking alone—that is, not counting the destruction wreaked by fires springing from ruptured gas lines.

In the long run, the way to avoid such disasters is to change the way buildings are built. Engineers know how to keep buildings from falling during most quakes. Even during the extremely damaging earthquakes in San Fernando in 1971 and in Mexico City in 1985, modern buildings with seismic designs stayed up and protected their occupants. A few states and cities in the East—including Massachusetts, Connecticut, Charleston, and Memphis—have already adopted codes requiring varying degrees of earthquake protection. Most have not.

Moreover, building codes would apply only to new construction. To guard against disaster in the short run, one would have to retrofit old buildings—strengthening them by anchoring the walls to the foundation, running rods across them to hold them together, and generally beefing up all the connections. Indeed, the Historic Charleston Foundation, which looks after the country's oldest historic district, is considering retrofitting its buildings against both earthquakes and—since Charleston seems prone to natural disasters—hurricanes. But in general the idea of governments requiring all buildings to be retrofitted is probably unthinkable—at least until a major disaster strikes.

And one almost certainly will strike, although geologists can't say where or when. "We've had two major earthquakes since the beginning of the 1800s," says Armbruster. "We haven't had a major one in this century yet, so maybe history will average and we'll have a major quake every hundred years. If you're considering any one site, maybe you're not worried. But if you're considering the East as a whole, then you're worried." ❑

Ann Finkbeiner is writing a book on caring for people with AIDS.

Few buildings in Charleston survived the 1886 quake undamaged.

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