The Next Big One
By Joel Achenbach**,** *National Geographic*, April 2006

The Hayward Fault, a long and lethal crack in the Earth, slices along the base of the Berkeley Hills and directly through the University of California. It passes under a theater and a couple of dormitories—no problem, they're just freshman dorms—and kinks the concrete steps outside California Memorial Stadium. You can straddle the fault, one leg up the steps, one leg down.

Then the fault runs underneath the stadium. One map shows it splitting the goal posts in the north end zone. It races downfield, barrels through the south end zone, and keeps going, careening down the street toward Oakland.

Back in the 1920s, when architects drew up plans for a grand football stadium at California's flagship university, they refused to let a geologic imperfection stand in their way. Earthquake science was still young, but the architects apparently realized that the Hayward is a fault, where two pieces of crust move past each other. So the architects gamely built the stadium in two halves, shaped sort of like a coffee bean, with a line, the fault, essentially splitting the structure. Each half of the stadium could move independently, riding the shifting crust without breaking a sweat.

Scientists now know that the Hayward creeps—it inches along steadily, although millimeters along would be more accurate. At the rim of the stadium, a Berkeley professor named Richard Allen shows me the result of 80 years of creep: a four-inch jog in the concrete, inelegantly bandaged with a rusty metal plate. We're both a little amused. What hubris to build a stadium on a fault!

But Allen points out the central problem: Faults don't just creep. They also "break." They "rupture." The creep happens in plain sight, but the breaking, the rupturing, the lurching—the earthquaking—will hit you blindside.

Allen teaches Berkeley's oldest course on earthquakes. He calls it Earthquakes in Your Backyard. The name couldn't be more appropriate, because the Hayward is a particularly dangerous fault. It hasn't spawned a major earthquake since 1868. Sometime soon, it could go.

Much of the stadium is built on soft ground, the kind that amplifies seismic waves. "In an earthquake," says Allen, "the entire field may liquefy." The players wouldn't sink into a jiggling vat of goo. They'd just get knocked off their pins—tackled by a temblor.

But of course no one on that field is worried about an earthquake. It's a hot summer day a few weeks before the start of the season. The players are worried about making the team. They're worried about beating Stanford.

You see right there a fundamental problem with earthquakes: They refuse to operate on human standard time. They're on their own peculiar schedule. Earthquake faults have a nasty way of combining patience with impulsiveness. Wait, wait, wait—lurch.

It's been a hundred years since the last big one in California, the 1906 San Francisco earthquake, which helped give birth to modern earthquake science. A century later, we have a highly successful theory, called plate tectonics, that explains why 1906-type earthquakes happen—along with why continents drift, mountains rise, and volcanoes line the Pacific Rim. Plate tectonics may be one of the signature triumphs of the human mind, geology's answer to biology's theory of evolution. And yet scientists still can't say when an earthquake will happen. They can't even come close.

Some of the simplest questions about earthquakes remain hard to answer. Why do they start? What makes them stop? Does a fault tend to slip a little—telegraphing its malign intent—before it breaks catastrophically? Why do some small quakes grow into bigger quakes, while others stay small?

And there's the broader question: Are there clear patterns, rules, and regularities in earthquakes, or are they inherently random and chaotic? Maybe, as Berkeley seismologist Robert Nadeau says, "A lot of the randomness is just lack of knowledge." But any look at a seismic map shows that faults don't follow neat and orderly lines across the landscape. There are places, such as southern California, where they look like a shattered windshield. All that cracked, unstable crust seethes with stress. When one fault lurches, it can dump stress on other faults. UCLA seismologist David Jackson, a leader of the chaos camp, says the field of earthquake science is "waking up to complexity."

This regular versus chaotic debate isn't some esoteric academic squabble. Earthquakes kill people. They level cities. The tsunami of December 26, 2004, spawned by a giant earthquake, annihilated more than 220,000 lives. The magnitude 7.6 quake centered in Kashmir last October killed at least 73,000 people. Perhaps as many as a million would be dead or injured if a major quake felled the unreinforced high-rise structures of Tehran, Kabul, or Istanbul. One of the world's largest economies, Japan, rests nervously atop a seismically rambunctious intersection of tectonic plates. A major earthquake on one of the faults hidden underneath Los Angeles could kill ten thousand people. A tsunami could smash the Pacific Northwest. Even New York City could be rocked by a temblor.

Yet at the moment, earthquake prediction remains a matter of myth, of fabulations in which birds and snakes and fish and bunny rabbits somehow sniff out the coming calamity. What scientists can do right now is make good maps of fault zones and figure out which ones are probably due for a rupture. And they can make forecasts. A forecast might say that, over a certain number of years, there's a certain likelihood of a certain magnitude earthquake in a given spot. And that you should bolt your house to its foundation and lash the water heater to the wall.

Turning forecasts into predictions—"a magnitude 7 earthquake is expected here three days from now"—may be impossible, but scientists are doing everything they can to solve the mysteries of earthquakes. They break rocks in laboratories, studying how stone behaves under stress. They hike through ghost forests where dead trees tell of long-ago tsunamis. They make maps of precarious, balanced rocks to see where the ground has shaken in the past, and how hard. They dig trenches across faults, searching for the active trace. They have wired up fault zones with so many sensors it's as though the Earth is a patient in intensive care.

Surely, we tell ourselves—trying hard to be persuasive—there must be some way to impose order and decorum on all that slippery ground.

We've been trying ever since the Earth humbled San Francisco. In April 1906 the city was the commercial and financial powerhouse of the West, a crucible of great fortunes, a place utterly decadent by reputation, gorgeous by any definition, with some 400,000 citizens and perhaps nearly as many bars. The famed Enrico Caruso performed at the opera the night of April 17.

All that changed at 5:12 the next morning, when the bars had finally emptied. Something happened deep under the seafloor just off the Golden Gate, out near the shipping channel. Along an ancient crack in the Earth, two slabs of rock began moving in opposite directions.

An earthquake will unzipper a fault at two miles per second. This one broke north and south. In some places the slip was just 6 or 7 feet, but elsewhere the ground lurched fully 16 feet in a snap. The fault broke for 270 miles, from Shelter Cove, way up in the redwood country of northern California, all the way south to the old mission town of San Juan Bautista.

It wasn't the worst earthquake in history by a long shot, but it was sensational. Not only did it heave the ground and topple buildings, it ruptured the water mains, leaving San Franciscans helpless as their Victorian homes and bustling shopping districts and warehouses and opera burned to the ground. No one knows how many people died, but about 3,000 is the consensus.

It inspired a kind of war on earthquakes, using the weapons of science. Until the San Francisco earthquake, geologists weren't sure how earthquakes and faults were connected. Many believed that faults were the by-products of earthquakes, not their source. The great Berkeley geologist Andrew Lawson had discovered the San Andreas Fault more than a decade earlier, naming it after the San Andreas Valley—and possibly himself (Andreas equals Andrew). But he thought it was just a little sniffle of an earth crack, a trivial thing not much more than a dozen miles in length, responsible for the narrow valley that holds San Andreas Lake and Crystal Springs Reservoir on the San Francisco Peninsula.

But earthquakes are teachable moments. When the fires died down and San Francisco started to rebuild, Lawson and a team of colleagues set out to solve the mystery of the Great Earthquake. They literally walked the "mole tracks" where the fault rupture had churned across barnyards and meadows. Then they continued south for 600 miles, reading the landscape, discovering the unbroken sections of the fault. This fault just kept going and going, all the way down past Los Angeles. In 1908 the team published the fabled Lawson report, which showed this rip in the Earth in vivid photographic detail.

In the course of the investigation, a scientist named Harry Fielding Reid figured out why earthquakes happen. Reid studied all the reports of ground motion, of roads and fence lines offset by the fault, and came up with the key concept of "elastic rebound." The surface of the Earth isn't perfectly stiff. It bends. Land at some distance from a locked fault will slowly stretch in opposite directions, but the fault itself will remain locked, under increasing strain. Finally the fault breaks, and the land springs back violently, releasing accumulated strain. An earthquake, says Bill Ellsworth of the U.S. Geological Survey in Menlo Park, California, is "a relaxation process" —from the standpoint of the planet at least.

But science marches on—and digs deeper. At Parkfield there are still seismometers and GPS stations everywhere, and now there's even that 185-foot oil-drilling rig, a monument to what you might call testosterone science. By late summer 2005 it had punctured the fault and reached its terminal depth of two miles.

"In a sense we're testing the predictability of earthquakes," says Mark Zoback of Stanford University, part of the drilling team. Of the chaotic versus linear debate, he says, "We're the guys who are trying to find out which side is right. Not to be sanctimonious, but I think a lot of those positions are held more on belief than on data." His rig is the next best thing to sending a person down into the fault directly, although even the rig can't get instruments down to the six-mile depths where many large earthquakes start.

In Japan, government scientists say they have settled the question. Earthquakes are not random. They follow a pattern. They have detectable precursors. The government knows where Japan's big one will most likely strike. This is a country where the trains run on time, and earthquakes are supposed to do the same. "We believe that earthquake prediction is possible," says Koshun Yamaoka, a scientist at the Earthquake Research Institute of the University of Tokyo.

In fact, Japan has already named its next great earthquake: the Tokai earthquake. The government has identified and delineated by law the precise affected area—a region along the Pacific coast about a hundred miles southwest of Tokyo. After a series of small quakes in the Tokai area in the 1970s, scientists predicted that a major quake might be imminent there. The Japanese government passed a law in 1978 mandating that preparations begin for the Tokai earthquake.

Scientists have estimated a death toll of between 7,900 and 9,200 for a quake striking without warning in the wee hours. Estimated property damage: up to 310 billion dollars. At the Tokai earthquake preparedness center in Shizuoka, a map pinpoints 6,449 landslide locations. Another map shows where 58,402 houses could burn in quake-related fires. It's all remarkably enumerated. The only thing left is for the earthquake to happen.

There is, indeed, a plate boundary, called the Nankai Trough, that runs off the coast of the island of Honshu, where the Philippine plate is subducting beneath Japan. The boundary has generated massive earthquakes every 100 to 150 years. Two sections of it, side by side, broke in 1944 and 1946. But the section along Tokai hasn't generated a major quake since 1854, right about the time Commodore Perry sailed his warships into Tokyo Bay. The theory is that it's time for this part of the subduction zone to relieve its accumulated stress.

At the Earthquake Research Institute, Keiji Doi, who is in charge of public outreach, lays out the entire scenario. The land near Shizuoka is sinking toward the underwater trough at about five millimeters a year, indicating that strain is building up. "The earthquake occurrence is imminent, we believe," Doi says.

Up to this point, the Tokai tale is more a forecast than a prediction. But a precise prediction of time and place would be far more valuable for emergency planners. Thus has arisen the idea of "pre-slip," a notion that skeptics say is part science and part wishful thinking.

Naoyuki Kato, another scientist at the Earthquake Research Institute, says his laboratory experiments show that before a rock fracture gives way, it inevitably slips a little. He believes that what happens in a lab at small scale will also happen on a fault hundreds of miles long and running deep into the crust, just before the next big one.

The government has an action plan built around pre-slip. Strain meters are embedded in the ground all over the Tokai area. If one or two meters show anomalies, scientists will confer and schoolkids will go home. Three anomalies will put the country on high alert. Police, soldiers, and firefighters will race to the border of the vulnerable area. The prime minister will make a speech and say that an earthquake is imminent. Posters outlining this plan show a cartoon prime minister sitting at a desk with hands folded, looking very worried, but very much in charge.

Yet none of the experts on the Tokai earthquake describe this scenario with much conviction. Press them, and they will admit their uncertainty. Yamaoka and Kato, for example, are both bullish on pre-slip, yet they also say it may be too small to be detected.

Robert Geller, an American geophysicist who works half a mile away at the University of Tokyo's school of science, is less circumspect. Geller has been in Japan for decades and has made "bashing earthquake prediction," as he puts it, a passionate hobby. He calls the prediction program "faith-based science." Pre-slip, he adds, "has never been verified to exist for actual earthquakes."

Geller's skepticism is not just a case of American outspokenness. Hideki Shimamura, an earthquake scientist at Musashino Gakuin University near Tokyo, is almost as blunt. "There may be pre-slip, but I rather doubt it," he says, adding that few researchers are willing to question the focus on Tokai lest they lose funding. The situation has potentially lethal consequences, he says: Prior to the Kobe earthquake in 1995, which killed 6,400 people, few people or public officials in Kobe had any inkling that they were vulnerable. Earthquakes were mainly someone else's problem—far to the east, in Tokai. "They didn't prepare," Shimamura says.

Since the Kobe quake, Japan has vowed to improve its readiness for a big jolt. Many of the bullet trains now brake at the first seismic tremor. Construction plans are supposed to get closer scrutiny, particularly in Tokyo, which sits on or near several dangerous faults. But the country has been shaken in recent months by a scandal: As officials looked the other way, crooked builders put up scores of structures that were far too fragile to withstand earthquakes. Their occupants were lucky that the scandal broke before the inevitable next earthquake.

Near Tokyo's sumo stadium is the Tokyo Restoration Memorial Hall, commemorating disasters that have struck the city. A dapper gentleman named Nobuo Yanai, 82 years old, visits every year to honor nine family members lost in the great Kanto earthquake of 1923. They died not in the quake itself but in a fire that raced through a field that had become a temporary home for 40,000 people—a huge throng suddenly immolated.

"They went up. Rose up in the sky. You may see the paintings over there"—and there, indeed, were paintings that showed the firestorm lifting people to the heavens. "My great-grandmother went up in the sky and disappeared."

People still die in stunning numbers when the ground beneath their feet begins to shake. Almost always it's not the earthquake that kills them, but rather their collapsing homes, offices, stores, and schools. An earthquake that might kill dozens or hundreds in California or Japan can kill tens of thousands in Latin America and Central and South Asia, where many buildings are little more than unreinforced masonry piles. There's a seismic gap between rich and poor.

Last October a magnitude 7.6 earthquake rocked northern Pakistan and Kashmir, the mountainous region claimed by both Pakistan and India. Within minutes, tens of thousands of people were dead, and countless others died later of injuries and exposure. Many were crushed when apartment buildings that had little or no steel in the concrete pillars simply pancaked. Had the quake been centered in nearby Rawalpindi, a city of 1.8 million, the casualties could have been in the hundreds of thousands.

Geophysicist Brian Tucker, head of a nonprofit organization called GeoHazards International, has been traveling the planet to lobby local officials to build sturdier housing projects, schools, and highways. He's seen cities where impoverished citizens expand their dwellings vertically, piling one brick floor on top of another, waiting for gravity to pull it all down.

In Kathmandu, a city crammed with brick-pile high-rises, an official once told Tucker, "We don't have earthquakes anymore." Surrounding the city are the Himalaya, pushed toward the stratosphere by tectonic forces. Tucker told the official, "Look out the window. That's Mount Everest. As long as you can see that, you're going to have earthquakes."

Mexico City is another catastrophe in waiting. Much of the city is built on soft mud, the remnants of a lake drained by the Spanish. In 1985 more than 9,500 people died when a subduction zone off the western coast of Mexico ruptured, sending seismic waves rolling hundreds of miles into the capital. Building codes have improved since then but only apply to new construction. And the population has boomed. Nearly 20 million people now live in a metropolis ringed by active volcanoes, testimony like the Himalaya to the tectonic forces that can level cities.

Calamity has been part of the city's cultural fabric for centuries. Underneath a church in the center of town, Cinna Lomnitz, an earthquake specialist from the University of Mexico, led me down a hidden stairwell to the remains of an Aztec pyramid, sagging on the soft lake bed. An ancient relief carved into the stone shows four suns surrounding a central sun. According to Aztec legend, each sun represents a period of earthly existence, and each is eventually destroyed.

"The fifth sun is the last one," Lomnitz said. "And it will end in earthquake."

Kerry Sieh believes science can help break the cycle of calamity. Sieh, a Caltech earthquake geologist, is convinced there's a way to read the messages in the rocks, to heed the warnings encoded in their trembling. He knows firsthand how much could be gained if we could pinpoint the most dangerous faults and know when they are due to rupture.

At 6:16 p.m. on Christmas 2004, Sieh was at his computer at home when he received an emailed bulletin about a seismic event at 3.3 degrees north latitude and 95.8 degrees east longitude, near Sumatra. For Sieh, earthquake bulletins are routine—quakes happen every day, all over the world. But a number jumped out at him: 8.5. That was the initial estimated magnitude of the quake, which had happened just over an hour earlier. An 8.5 is enormous.

Soon came the aftershocks, scores of them in the next few hours. Gradually the data began to harden around the obvious fact: This was a great quake, upwards of magnitude 9. News reports said a tsunami had killed perhaps several thousand people in Sri Lanka. And then those numbers began to climb too.

The Sumatran earthquake was not a total geologic surprise. Two weeks earlier Sieh had given a talk about his research on the great undersea fault paralleling the coast of Sumatra, where one plate is subducting beneath another. He had warned that the section of the fault he was studying, well south of the part that actually ruptured, could break at any time and trigger tsunamis.

It had happened before, in the late 1300s, around 1600, and in 1797 and 1833—dates Sieh had determined by studying old coral heads along the islands off the west coast of Sumatra. When the Earth shifted in major quakes, the coral heads were lifted out of the water, leaving a gap in their growth layers. But the last really large earthquake had happened long before anyone now alive in Sumatra had been born.

Sieh and his team had distributed posters in some villages of southern Sumatra, warning of catastrophic tsunamis. But Sieh's colleague Catharine Stebbins found that the novelty of the posters and the American scientific expedition seemed to outshine the posters' message. "It was like a circus came to town." And no one thought the northern part of the fault would go first.

Late Christmas Day, as the news about the disastrous tsunami came over the wire, Sieh feared for his friends in Sumatra, and he had an ominous thought: There would be another huge quake. By releasing stress on one segment of the fault, this earthquake had increased stress on the next segment to the south.

Three months later, on March 28, 2005, that segment broke in a magnitude 8.7 quake—smaller than the first but still one of the ten biggest on record. Another tsunami followed, but this time collapsing buildings and falling debris were the big killers, taking more than 1,000 lives.

In his Caltech office, Sieh showed me a map of the Sumatran plate boundary, detailing the GPS stations he had placed along the fault before the March quake. They had all moved, yanked to and fro and up and down. One directly over the March rupture had jumped 10 feet up and 14 feet to the southwest. The pattern of movements indicates that strain is still building. "If another great earthquake happens in the next year," he said, "my guess is that there'll be another couple hundred thousand dead."

He has heard the refrain that earthquakes are chaotic and unpredictable. That's not what he sees on the map of the plate boundary. He sees a fault breaking incrementally from north to south. "Obviously this is not chaos. This is linear."

Sieh pointed to the area that he thinks is next in line. That's where he and his colleagues will spend the coming years, listening to the fault, tracking the Earth's movements, taking the measure of shaky ground.

"I would like to predict this earthquake," he said.

Study guide for this article:

Approximately how many people were killed by the tsunami in 2004?

Compare and contrast the concepts of *forecasting* and *predicting* earthquakes.

Describe the goals of GeoHazards International.

Kerry Sieh had warned, just two weeks before the Sumatra earthquake, the area was likely to have a quake and tsunami. So, why were people not more prepared for the event?