LESSONS FROM JAPAN

By Katie Neith

Tectonic plates worldwide have been slipping, sliding, and shoving one another around like sumo wrestlers for eons untold. But the titans have been hitting the mat recently, starting with the magnitude 9.1 Sumatra-Andaman earthquake in December 2004, which was followed by the 8.8 Maule shaker in Chile in February 2010. The latest in this string of large earthquakes, of course, is the March 11 Tohoku event, registering at a magnitude of 9.0.

When the bouts shift to land versus infrastructure, the human race is always on the losing end. Death tolls from Japan's earthquake and the resulting tsunami are estimated to exceed 18,000 people. It will take hundreds of billions of dollars to rebuild the country, and cleanup of the heavily damaged Fukushima nuclear plant could take decades. But while the costs are unprecedented, the magnitude of these quakes is nothing new.

"It's not that recent earthquakes are any worse, it's just that our exposure is much greater," explains Mark Simons, a geophysicist at Caltech's Seismological Laboratory. He points to a series of large earthquakes that happened in the late '50s and early '60s and included the biggest one on record—Chile's 9.5-magnitude Valdivia quake in 1960.

"In the 50 years since the Chile earthquake, cities have grown tremendously, which makes the need to understand the specifics of the earthquake processes all the more important," he says.

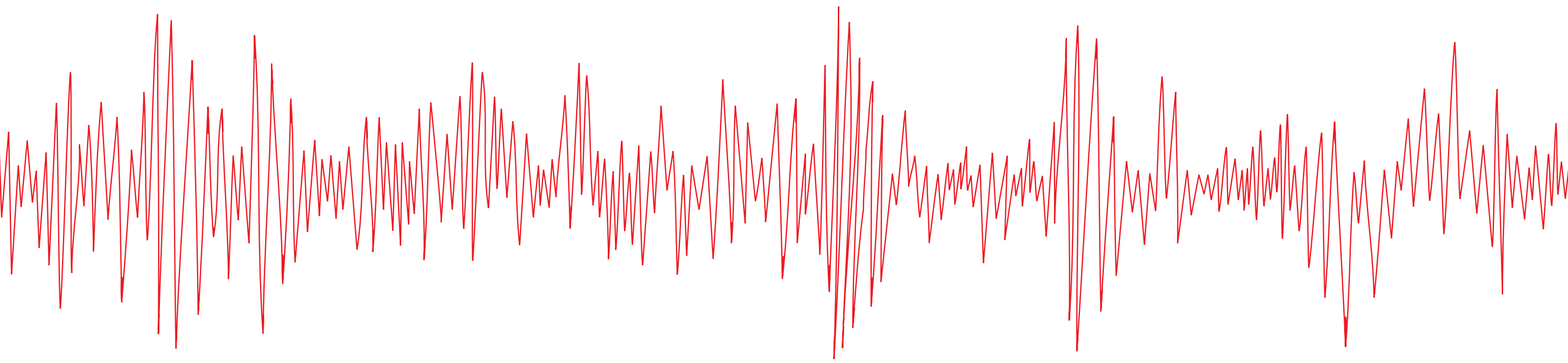
The Tohoku earthquake devastated the land and its people. But rising from the rubble like a phoenix (or *fushicho* in Japanese) is a slew of seismological data that will ultimately help save lives.

"This event is the best-recorded great earthquake ever," says Simons, the lead author of a recent paper in *Science* that presented the first large dataset from the temblor. Published online in May and in print in the June 17 issue, the study was written by 14 researchers from Caltech and JPL, and one from the University of Michigan.

The lion's share of the recordings used in the study came from GeoNet, a dense network of more than 1,200 GPS receivers that measure local ground displacements. Japan was the first nation to embrace GPS technology for nationwide tectonic monitoring, and the Geographical Survey Institute of Japan installed the GeoNet array some 15 years ago—an investment that has paid huge dividends. The paper also drew on arrays of broadband seismometers from around the world, as well as open-ocean tsunami data from buoys, to put together a detailed picture of how the earth moved that day.

THE STRESS OF PREDICTING STRAIN

The earthquake's punch came from a surprisingly compact region, says Simons. A megathrust quake such as this one occurs when one tectonic plate is being jammed underneath its neighbor in a region called a subduction zone—in this case, where the Pacific Plate dips below Japan. Since the energy released during a quake is proportional to the area of the fault that moves,

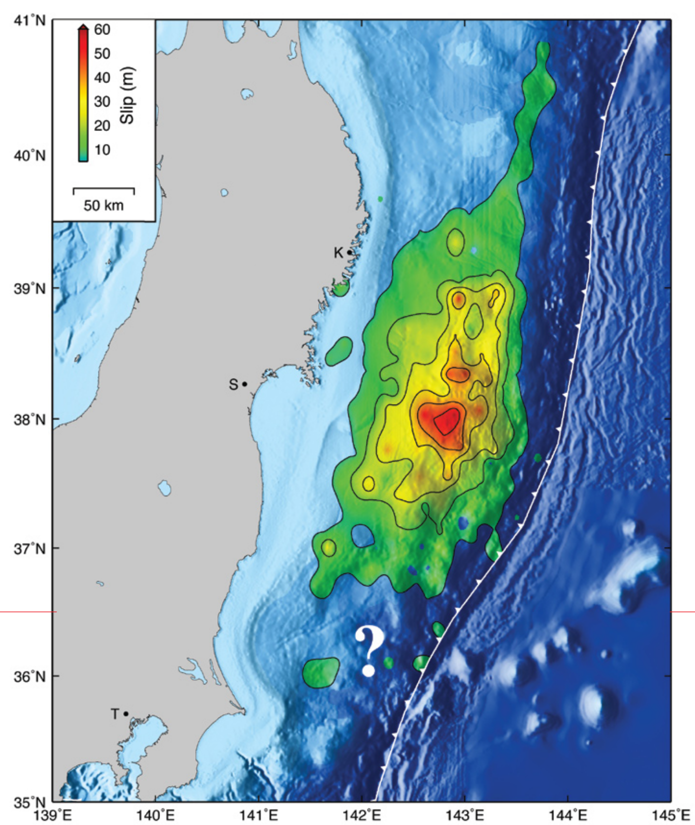


scientists expected to see a rupture zone of at least 500 kilometers. Instead, the significant slip was confined to a region about half that length—some 250 kilometers, or roughly the distance between Los Angeles and Bakersfield.

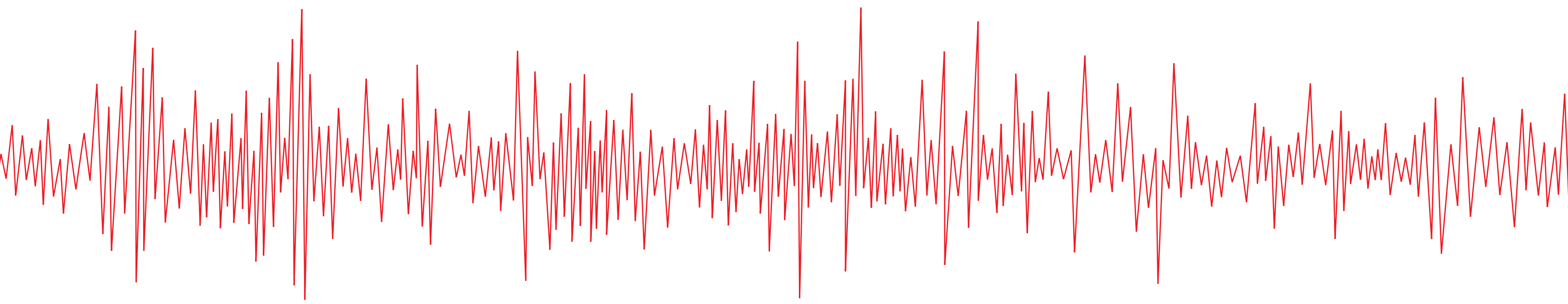
Furthermore, the area where the fault slipped the most—40 meters or more—lay within a 50- to 100-kilometer-long segment. "This is not something we have documented before," says Simons. "I'm sure it has happened, but only in the past 10 to 15 years has technology advanced to the point where we can estimate localized slips accurately."

The devastating tsunami occurred because the high-slip zone extended up the fault plane almost to the seafloor, as geologist Jean-Philippe Avouac, director of Caltech's Tectonics Observatory, pointed out in an online Nature commentary June 15. "The large quantity of slip at shallow depth came as a real surprise to me," says Avouac. Conventional wisdom holds that megathrust earthquakes originate at great depths, usually 30 to 40 kilometers underground, where the crushing mass of rock above keeps the plates firmly pinned together. But Tohoku's hypocenter—the point within the earth where the shaker started—was only about 24 kilometers down. "The common belief is that the topmost 10 kilometers of a subduction zone is buttered with clays that promote aseismic sliding, or gentle moving of the plates that doesn't produce seismic slip," he says. The lesson here, says Avouac, is that we need to rethink how we model the way that plates lock into place along different areas of the fault. Current methods tend to assume minimal locking near the surface if the available geodetic data is sparse, as was the case here. The fault rupture began approximately 100 kilometers offshore, far from GeoNet's coverage area.

The amount of slip also surprised seismologist Hiroo Kanamori, who was in Japan at the time of the quake and has been studying the region for many years. It was believed that the relatively soft material of the seafloor could not hold much stress before giving way. Because the zone of maximum displacement was so small, "the local strain was nearly five to 10 times greater than we normally see in large megathrust earthquakes," he notes.



The fault responsible for the Tohoku quake starts at the Japan Trench, as indicated by the barbed line, and dips under Japan. In this model of the event, estimated fault slip is shown by colors and by eight-meter contour intervals. The earthquake potential to the south (the question mark) remains unknown.



"It has been generally thought that rocks near a trench could not accommodate such a large elastic strain." (Incidentally, "stress" and "strain" are not the same: if you are hoisting a barrel of bricks with a winch and pulley, the stress is the degree of tension on the rope and the strain is the amount that the rope stretches.)

The researchers are still unsure how so much strain accumulated. One possibility is that the subducting seafloor has something unusual on it—an underwater mountain range, perhaps—that caused the plates to get stuck.

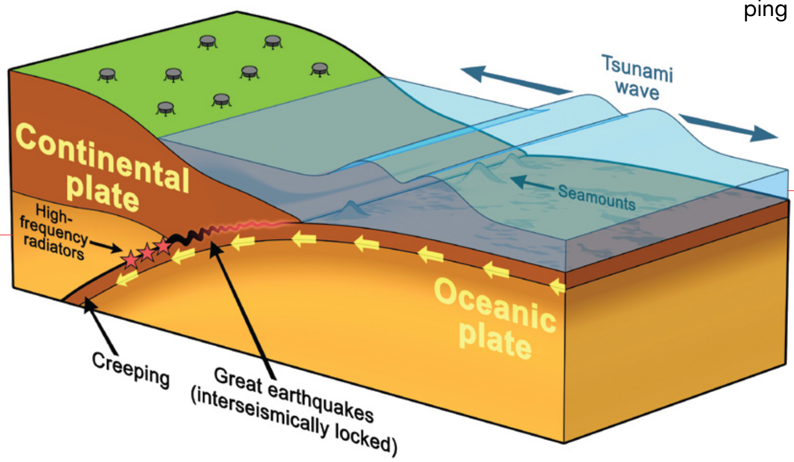
"Whatever the cause, the Pacific Plate and the Okhotsk Plate had been pinned together for a long time, probably 500 to 1,000 years, and finally failed in this magnitude 9.0 event," says Kanamori. "Hopefully, detailed geophysical studies of seafloor structures will eventually clarify the mechanism of local strengthening in this area."

Avouac advocates paying closer attention to anelastic deformation, also known as creep. Elastic strain stores up stress that is released in large earthquakes, while anelastic strain dissipates stress and lowers the potential for strong shakers. Measuring anelastic strain "is a hard problem, but it is high time to try to address it," he says. "It affects the rate at which elastic strain builds up, and therefore our estimates of the probability of large earthquakes."

The conventional wisdom was shaken yet again when seismologist Jean Paul Ampuero, who studies earthquake dynamics, noticed that the high- and low-frequency seismic waves came from different areas of the fault. "The high-frequency seismic waves in the Tohoku earthquake were generated much closer to the coast, away from the area of the slip where we saw low-frequency waves," he says.

It turns out that the largest load on the plates, which is what generates the highest-frequency waves, occurred at the *edges* of the slip—not near the center, where the fault began to break. Simons compares it to ripping a piece of paper in half. "The highest amounts of stress aren't found where the paper has just ripped, but rather right where the paper has not yet been torn," he explains. "We had previously thought high-frequency energy was an indicator of fault slippage, but the two don't correlate in our models of this event." How the fault reacts to the stress is equally important; it appears that only the deeper segments produced the high-frequency energy.

Ampuero's findings highlight the need to look more closely at the mechanical properties of faults, he says, and to integrate that information into risk-assessment models. The waves that do the most damage to a building are the ones at its resonant frequency. The building wants to shake at that frequency, and resonant waves pump energy into the building like a grownup pushing a kid on a swing set. These resonant waves are the "high-frequency" ones described above, although the average person wouldn't think of them as such. The lowest frequencies audible to the human ear begin around 15 hertz, while a 100-story skyscraper responds to waves of around 0.1 hertz. Moving up the scale, 1-hertz waves are tuned to 10-story midrise buildings, and 10-hertz waves are the source of bad vibes for single-story structures. Predicting how those waves travel



In this diagram, the rippling line between the continental and oceanic plates represents the area that slipped in the earthquake. The high-frequency waves radiated from regions at the deepest edge of the slip zone, closest to the shore. The gray circles represent the locations of GPS instruments.

will help scientists quantify earthquake hazards.

"We learn from each significant earthquake, especially if it is large and recorded by many sensors," says Ampuero. "The Tohoku earthquake was recorded by upwards of 10 times more sensors at near-fault distances than any previous one. This will provide a sharper, more robust view of earthquake rupture processes and their effects."

PREDICTING THE UNPREDICTABLE

"We learned a certain amount of humility with this earthquake," says Simons. "The mistake we made was that we did not adequately describe what we don't know."

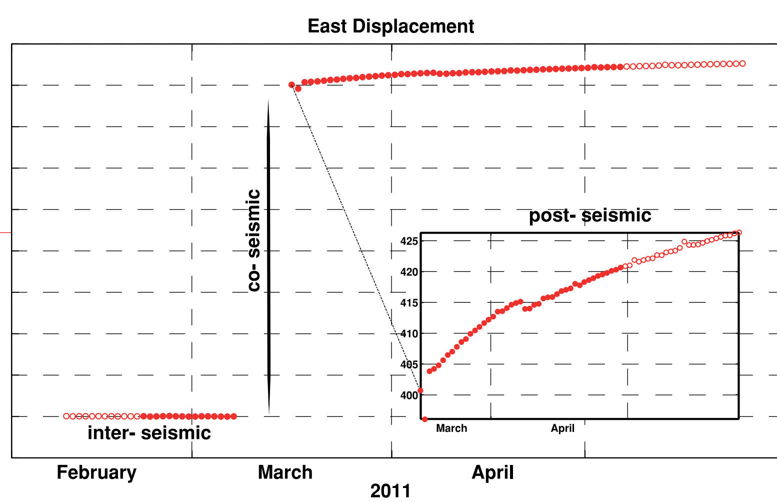
In fact, very little was known about the area, due to its historical quiescence. However, many seismologists assumed that a large megathrust event was unlikely to occur there. For example, Kanamori and others had theorized that where a plate is very young, it tends to produce big earthquakes. The quake in Chile last year happened on a plate that is 10 million years old—a baby in geologic terms.

"Where old plates are subducting, we don't normally have giant earthquakes," says Kanamori. "This explanation usually works. However, the plate off the coast of Tohoku where this earthquake occurred is old, about 130 million years. This event was exceptional because it revealed an unusually strong coupling near the Japan Trench that we did not know about."

Simons points out that many models of the area existed, all of which predict relatively frequent earthquakes of magnitude seven or eight. The *Science* paper presented a new model, consistent with the buildup of more than a thousand years' worth of elastic strain, that was capable of producing a magnitude nine. "I think that it behooves us to spend much more time thinking about describing the family of allowable models, as we are here at Caltech, and not just focusing on single models," he says.

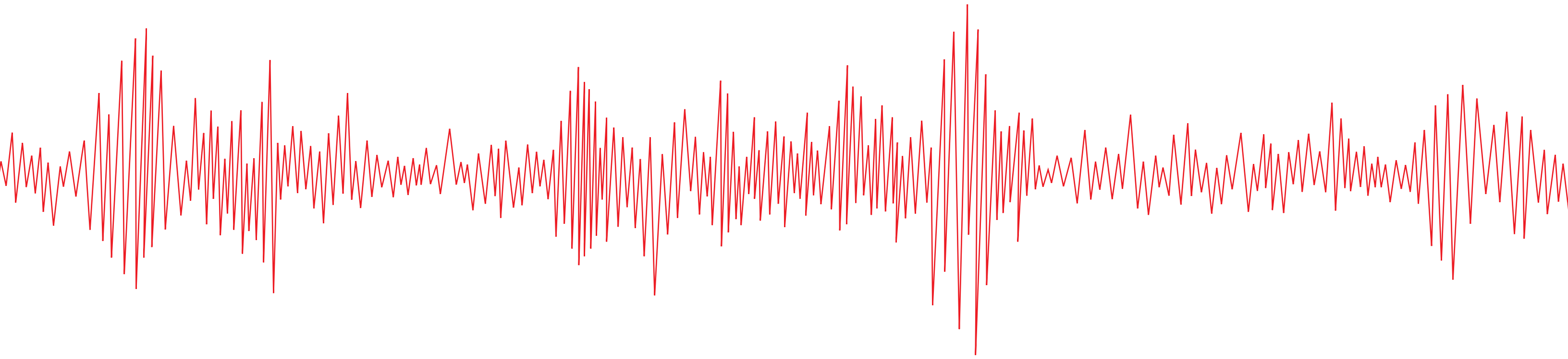
Combining innumerable bits of information from different technologies and various sources has taught the researchers the power in not being too provincial. "What was key with our *Science* paper is that it involved the geodesists and the seismologists, all trying to come together with one coherent picture that made sense," says Simons. "For us, that is the joy of being in the Seismo Lab. It was a great opportunity to put our minds together. Of course, our picture will no doubt evolve over the next year, as more data become available and as our models get refined."

Pooling their resources enabled the Caltech/JPL team to post some preliminary findings online within weeks of the quake, and the time between the event and the *Science* paper was only two months. But the most critical information went public almost immediately. The team posted the earth-movement vectors as they were calculated from the GeoNet data, and within a week they had been downloaded a couple thousand times. "This is a highly specialized product, not a YouTube video," says Simons. "And yet, there is clearly an audience for this kind of information, and a need to disseminate it rapidly, so that response agencies and other scientists can act on it."



This plot from a GPS receiver in northern Japan tracks the station's daily positional changes along an east-west axis in the month before and the two and a half months after the March 11 earthquake. Having this kind of data covering all the phases of the seismic cycle is critical for developing detailed mechanical models of fault systems.

The data was processed by ARIA, a Caltech/JPL collaboration, and rendered by grad student Francisco Ortega (MS '08).



AN UNCERTAIN FUTURE

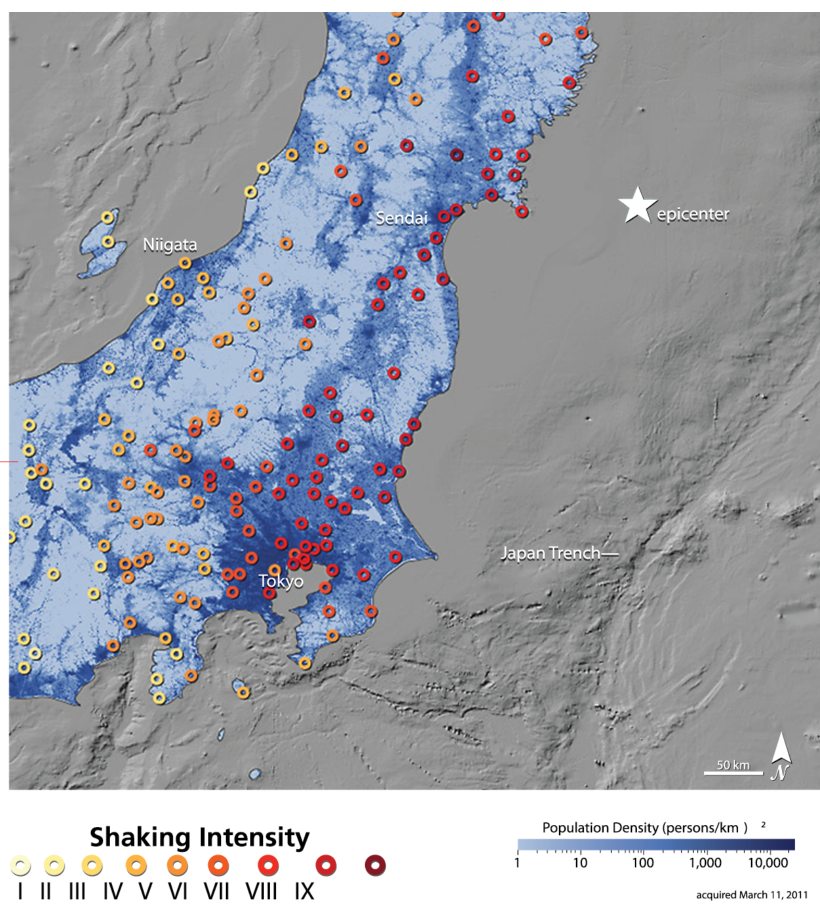
The data crunching continues, as does the assessment of how different technologies worked (or didn't) to produce reliable information. The lessons learned will help usher in a new era in earthquake science.

"We have long relied purely on seismology to respond to earthquakes on a very short timescale," says Simons. "Now we are entering the age of GPS and other remote-sensing techniques." Space-based geodesy, which includes GPS and satellite radar techniques, can measure subtle deformations in the earth's surface over thousands of square kilometers.

Simons points to two Caltech-led projects that are pushing the boundaries on how we could potentially gather data about disasters and get that information out fast to fire fighters, FEMA field agents, and other people who need it. One is a collaboration with JPL called the Advanced Rapid Imaging and Analysis (ARIA) project, which is currently in the prototype-development phase. "The goal is to make space geodesy more relevant to rapid response by producing processed, useful data within hours of an event, as well as to produce physically based models constrained by the data," he says. "The current focus is earthquakes, but we expect to extend the capability to volcanoes, floods, fires, and other natural disasters."

The other is a concerted effort to drum up support for a NASA satellite designed specifically for interferometric synthetic aperture radar, or InSAR. InSAR compiles radar swaths taken in successive orbital passes to map surface deformation, such as fault creep, in three dimensions over time. "InSAR is an important part of ARIA," says Simons, "as is GPS and seismology. But the current handful of InSAR-capable satellites from which one can get serendipitous data are European or Canadian." (The Japanese satellite that imaged the Tohoku event was shut down just a few weeks later after an onboard power failure.)

"We see time and time again that the rapid dissemination of information is important, yet we're going in the wrong direction in terms of getting into space the assets that would enable dissemination," says Simons, who notes



Left: The colored circles on this map represent shaking intensities compiled from USGS data. IX is "violent"—heavy damage, up to total collapse of some buildings. Note the number of VIIs and VIIIs near Tokyo, well away from the epicenter (red star). The blue hues are population-density data from the Oak Ridge National Laboratory.

Right: A solar-powered GPS station outside the town of Putre in northern Chile, near the Bolivian/Peruvian border, installed by Caltech geophysicists to monitor earthquake-cycle related deformation. The dome on the rock houses the GPS antenna; its tripod is mounted deeply and permanently into the ground.

that current federal budget proposals include a cut in funding for such advanced technologies.

Kanamori agrees that getting the data out quickly after a big event is vital for hazard mitigation. He says that information needs to be collected on a global scale, since local systems often fail during a natural disaster nearby. This requires good coordination between agencies in different countries so that "in the case of an emergency, they can exchange information and take immediate action," he says.

But while seismology's rapid advances in data collection and analysis may improve the way we deal with emergencies, "natural events do not repeat in exactly the same way, so we do not have the benefit of reproducible experiments," Kanamori says. "We have to deal with often-unpredictable nature, so using rapid, reliable information to prepare for the unexpected is very important." E&S

Mark Simons is a professor of geophysics; Jean-Philippe Avouac is a professor of geology; Hiroo Kanamori is the Smits Professor of Geophysics, Emeritus; and Jean-Paul Ampuero is an assistant professor of seismology.

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DATA HITS HOME

Ever wonder how much your house might *really* be rocking and rolling during an earthquake? If you're in the Pasadena area, you may have the opportunity to find out. A new project out of Caltech's Seismo Lab is collecting data by installing small seismometers in local homes to create block-by-block "shake maps." The data collected by the Community Seismic Network (CSN) will be used to direct fire trucks and ambulances to the hardest-hit areas shortly after an earthquake.

Because of local differences in the geology that underlies Los Angeles, it's very likely that one block could sustain more devastation than the next depending on how the land responds to the energy of the quake. The CSN deployment is intended to demonstrate how these high-resolution shake maps can be used as a proxy for damage, and the project is slated to last several years.

"Major earthquakes such the March event in Japan increase the public awareness of the hazards of earthquakes and point out the need to provide emergency responders with a map of damage in the minutes to hours following an earthquake," says geophysicist Robert W. Clayton, who is principal investigator on the CSN grant from the Gordon and Betty Moore Foundation that is funding the placement of 1,000 or so sensors in quaint bungalows, stately mansions, and towering office buildings across the greater Pasadena area. "A dense set of measurements of the ground shaking can also be very useful in planning how to rebuild."

Participants will be able to see the information they are contributing to the network. "You can tap the sensor and see how the 'pick' that is generated shows up on the CSN webpage," explains Clayton.

Visit www.communityseismicnetwork.org to volunteer your home or office as a seismometer location. For more information about additional CSN projects, check out "E/Q Phone Home" in the Spring/Summer 2011 issue of *E&S*. —*KN* E&S

PICTURE CREDITS:
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