Utter destruction. Noda village in Iwate Prefecture was wiped out by the tsunami.

JAPAN DISASTER

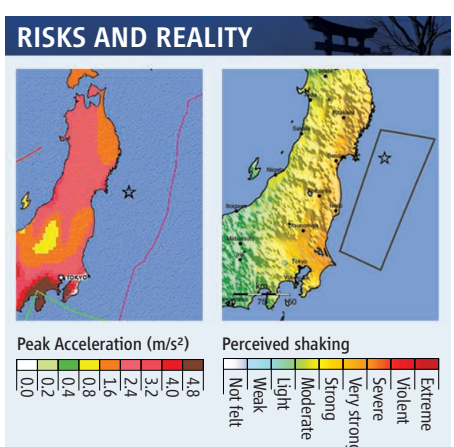
Devastating Earthquake Defied Expectations

TOKYO—Even for a nation inured to temblors and bracing for the Big One, last week's devastating earthquake and tsunami were beyond imagination. Experts, too, were caught off-guard. "I never thought this kind of [event] could happen" in this region, says Hiroo Kanamori, a seismologist at the California Institute of Technology in Pasadena.

The earthquake's astonishing power and unexpected location also expose the futility of forecasting where and when the next Big One will hit, says Robert Geller, a geophysicist at the University of Tokyo. Even in a country as extensively instrumented and thoroughly studied as Japan, he says, major quakes always "seem to be ones not expected."

The 11 March Tohoku earthquake ranks among the five strongest temblors recorded by modern instrumentation. The U.S. Geological Survey and the Japan Meteorological Agency now peg the magnitude at 9.0. The quake ruptured more than 400 kilometers of crust along the Japan Trench subduction zone, where a tectonic plate is diving beneath the northeast coast of Honshu Island. Its epicenter was 130 kilometers east of Sendai, a city of about 1 million people in Miyagi Prefecture, and 373 kilometers northeast of Tokyo. Authorities expect the death toll to top 15,000. Tsunami waves that exceeded 7 meters in height when they came ashore washed away scores of communities and inflicted damage as far away as California. The tragedy may yet be compounded by ongoing crises at two nuclear power plants, where workers were racing to prevent reactor core meltdowns and contain radiation leaks as *Science* went to press.

Japan sits on the Pacific Ring of Fire, where about 90% of the world's earthquakes occur as tectonic plates bump and grind over and under one another. Along the Japan Trench, the Pacific Plate is being forced under the Okhotsk Plate. In some regions, the subducting plate slides smoothly under the overriding plate. In other areas, plates couple, or stick together, at their interface. If strongly coupled, the plates' boundary regions are twisted until the rock can no longer bear the strain. At that point, a slip or rupture along the boundary allows the plates to snap back into lower-stress positions, releasing accumulated energy as earthquake waves. The concurrent sea-floor movement produces tsunamis.



Unexpected location. The 11 March quake shook up a region (*right*) outside the areas expected to bear the highest seismic risks (*left*).

To assess earthquake risk in a given region, scientists look to past events for guidance. Records for northeastern Japan go back more than a century. Along the Japan Trench, earthquakes of magnitude 7 to about 8.3 have struck at 30- to 50-year intervals. According to Kanamori, recent earthquakes along the subduction zone relieved so much stress that it would have been hard to see where in the region enough strain had accumulated to produce a great earthquake. "Truthfully, we didn't foresee this," says Takuya Nishimura, a geodesist at the Geospatial Information Authority of Japan in Tsukuba who co-authored a 2004 paper in *Geophysical Journal International* detailing the buildup of crustal deformation in the region.

An earthquake was anticipated off the coast of Miyagi where the 11 March event occurred, but it was expected to be much smaller. Historical records and instrumental observations indicated that for this smaller section of the subduction zone, earthquakes of magnitude 7.5 or so recur every 30 to 40 years. The most recent was a magnitude-7.4 event in 1978 that killed 28 and triggered a small tsunami. The rupture zone of the 11 March earthquake "overlaps but is much greater than the source area of the 1978 earthquake," which ruptured only about 50 kilometers of the fault, Nishimura says.

Peering deeper into the past, researchers a few years ago recognized an event of similar intensity to the 11 March disaster. Historical records tell of a large earthquake and the coastal plain becoming a "wilderness of water" in the year 869. A telltale marine sand layer buried in marshy deposits on the Sendai Plain revealed that the ancient tsunami must have run as much as 3 to 4 kilometers inland from the coastline at the time. Based on the extent of the inundation, researchers estimated the magnitude of the Jogan earthquake at roughly 8.3. Local media report having found traces of last week's tsunami 5 kilometers or more inland.

If the Tohoku earthquake was a reprise of Jogan, supercycles of massive earthquakes

CREDITS (TOP TO BOTTOM): LANDOV; SOURCE: USGS

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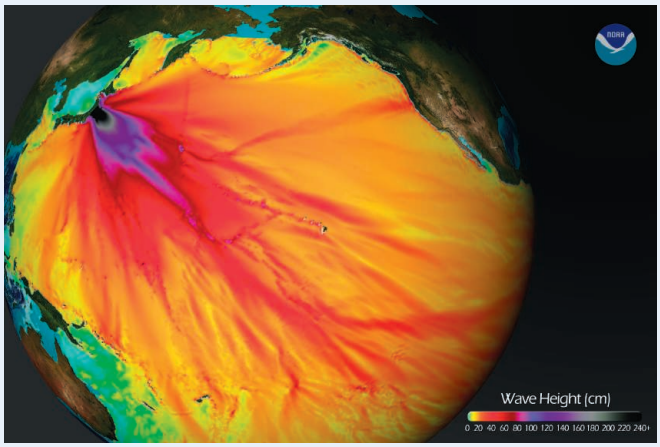

Code red. Computer-generated prediction of wave heights as the tsunami sped across the Pacific Ocean on 11 March.

Waves of Destruction

Minutes after a powerful earthquake struck off the coast of Japan at 2:46 p.m. local time on 11 March, the Japan Meteorological Agency (JMA) issued tsunami warnings that were broadcast on TV and radio. Augmenting the warnings were local sirens and announcements. Still, most deaths and much destruction were the handiwork of the tsunami: Many victims knew the waves were coming but could not escape or didn't try until it was too late.

Residents of Japan's northeast coast were attuned to the risk. Tsunamis have periodically pounded the region, much of it a low-lying plain. An earthquake in Chile in 1960 triggered a tsunami that crossed the Pacific and killed 122 people in Japan. After that quake, 10-meter-high tsunami walls were built at locations such as harbor entrances throughout northeast Japan, says tsunami geologist Kazuhisa Goto of Chiba University in Japan. Elsewhere the coast is lined by berms, intended primarily to protect against storm surges.

These berms proved no match for the towering tsunami waves last week. Video clips aired by Japan's national TV station, NHK, indicate that many residents heeded warnings or common sense and headed for higher ground. But "the Sendai plain is quite flat, so it is difficult to escape," Goto says. JMA instruments detected the towering tsunami arriving in some areas just 30 minutes after the quake, giving residents little time to flee.

Some multistory concrete buildings in the area—refuges of last resort—were not tall enough. Local media found a survivor who had joined others on the roof of a three-story building in the coastal town of Minami Sanriku. According to the man, waves washed over the roof, some 13 meters high, and swept away everybody else. He survived by climbing a ladder attached to a roof-mounted antenna.

Stringent building codes are credited with having limited structural damage from the intense shaking of last week's earthquake, which was 500 times bigger than the one that flattened buildings in Christchurch, New Zealand, last month. But there are few options for girding against monster tsunamis. Planting trees or other vegetation along coasts can help blunt the force of the waves, but buildings must be located far inland. Planners have floated measures such as building more extensive sea walls, erecting stout towers as vertical refuges, and perching buildings on pillars to let water flow underneath. Such "provisions are quite expensive and difficult," Goto says.

The most effective tsunami-mitigation strategy may be to ensure that there are adequate escape routes—and educate people to run for their lives when the sirens blare. In the Sendai area, Goto says, elders who lived through earlier tsunamis were well aware of the danger. "But younger people do not know about those events," he says. Heart-rending live TV coverage showed that many people did not attempt to reach higher ground until the waves were upon them. "This will be a case study," says Joanne Bourgeois, a University of Washington, Seattle, tsunami geologist currently at Hokkaido University in Sapporo. Japan "has planned for these kinds of events. We can look at what worked and what didn't work." **–D.N.**

may rock the region on 1000-year time scales, Nishimura says. Supercycles, of course, would not be limited to one segment of the Japan Trench, he says: "This event suggests that such kinds of great earthquakes might occur in other subduction zones." One candidate is the Cascadia fault, which runs off the coast from northern California to southern British Columbia. Last week's earthquake "is going to be the benchmark for the Pacific Northwest when the Cascadia fault breaks," says seismologist John Vidale of the University of Washington, Seattle. "We know that it can have an earthquake of this magnitude. It's a question of when, not if."

One worry is how the 11 March earthquake may influence neighboring sections of the Japan Trench. "We are really concerned" that the release of stress offshore of northeast Honshu has increased the chances of a large quake much closer to Tokyo, says seismologist Shinji Toda of Kyoto University. His preliminary calculations suggest that the earthquake loaded stress onto the fault segment offshore of Boso Peninsula, a finger of land separating Tokyo Bay from the Pacific Ocean. Historical records indicate a large earthquake and tsunami battered the area in 1677.

The Tohoku earthquake will offer sobering lessons for risk assessment. Since 1965, Japanese seismologists have diligently watched real-time data from hundreds of instruments in the Tokai region west of Tokyo. If a fault along the Nankai Trough were to grow restless, a panel of seismologists would assemble on a moment's notice to decide whether to warn of an impending magnitude-8 earthquake. Authorities have strengthened public buildings to withstand intense shaking and have built dikes and floodgates along the coast to thwart the anticipated tsunami from such a temblor.

Online
sciencemag.org
Podcast interview with author Dennis Normile.

But Japan's two great earthquakes of the past 2 decades—the 11 March event and the Kobe earthquake of 1995—showed that experts were looking in the wrong place. Similarly, Kanamori says, in California attention is focused on the San Andreas fault, even though the most damaging earthquakes of the past several decades—including the 1994 magnitude-6.7 Northridge and the 1971 magnitude-6.6 San Fernando earthquakes—occurred elsewhere.

Researchers are able to estimate how much seismic strain will accumulate in a fault over time. "What we cannot predict is the individual sequence. It may be released in a single earthquake or may be released in smaller events," Kanamori says. "In view of the inevitable uncertainty, in my opinion it's better to have a more general approach [to earthquake preparation] than to have a prioritized, focused effort." For a nation that prides itself on preparedness, a distressing realization might be that some earthquakes are just too big, and too rare, to prepare for.

–DENNIS NORMILE

With reporting by Richard A. Kerr and Sara Reardon.

CREDIT: NOAA

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