LESSONS FROM FUKUSHIMA

by Ken Kostel

What have scientists learned about the causes and consequences of the 2011 earthquake and tsunami in Japan?

When the ground in Japan started shaking on March 11, 2011, the Japanese, who are well-accustomed to earthquakes, knew this time was different. They weren't surprised—the fault that ruptured has a long record of seismic activity. But this time the trembling continued for six minutes. When it finished, many turned their eyes to the sea off the country's craggy and quake-scarred coast, as they are taught, and waited for the waves to come.

But the last time something remotely similar had happened was more than 1,000 years ago and, even in a country that prides itself on its shared cultural memory of the distant past, that event had been largely forgotten. Since that time, much has changed. People and development have sprung up on the coast, along with a string of nuclear reactors. Everything, it seemed, had changed in the intervening millennium—except the ocean.

Compared with other large earthquakes in recent memory, the magnitude-9.0 Tohoku earthquake, as it became known, was different in many ways. Temblors off Chile in 2010 (magnitude 8.8) and Sumatra in 2004 (magnitude 9.1) involved faults that extended partly onto land, but the Tohoku earthquake occurred entirely under the ocean—nearly 19 miles below the seafloor in some places. In Japan, the combination of natural forces and greater human presence created a domino-like sequence of events, from earthquake to tsunami to the release of radiation from the mangled nuclear power plant near Fukushima. (See Page 37.)

The majority of these events played out in the ocean, noted Jian Lin, a seismologist at Woods Hole Oceanographic Institution (WHOI). The Tohoku earthquake also triggered a scientific cascade, as geologists, geophysicists, chemists, modelers, physical oceanographers, and marine biologists mobilized to understand the quake's causes and consequences.

Where the fault lies

The undersea fault that ruptured along 300 miles on March 11 extends north-south, roughly parallel to the northeast coast of Japan. It is a mega-thrust fault in the Japan Trench, where the massive Pacific Plate pushes westward, and beneath, the continental Eurasian Plate. Where the two tectonic plates grind against each other, gargantuan stress builds over time in the seafloor crust. Hundreds of large and small earthquakes dot the fault each year as stress exceeds the breaking point of rocks and suddenly releases.

The immense forces of two colliding plates, said Lin, have compressed the Japanese island of Honshu like an accordion, pushing up the mountain ranges that fill much of the island's interior and creating a spider web of smaller, land-based faults that periodically rupture. As a result, the Japanese have made living with seismic activity part of their daily life and national culture. Each year, schools and businesses across the country mark Disaster Prevention Day on Sept. 1, the anniversary of the 1923 earthquake that devastated Tokyo, by participating in drills and other activities to prepare for a large earthquake. Building codes are laden with requirements intended to prevent high-rise buildings from collapsing during violent shaking. Even the iconic bullet train is connected to a network of seismic sensors designed to automatically stop any moving train before shaking from a large offshore earthquake can reach shore.

When the shaking on March 11 stopped, the city of Sendai (population 1 million), the largest urban area near the epicenter, was largely spared—even though the temblor turned out to be the world's fifth largest ever recorded. In Tokyo, less than 200 miles away, frightened office workers safely evacuated or rode out the six-minute quake as buildings swayed, but did not fall. On the busy railway corridor running north of Tokyo, trains slowed and stopped with very few derailments. In fact, the earthquake produced surprisingly little damage, despite the fact that national hazard maps for the region, based on data from only the past few hundred years, directed officials to prepare for a maximum magnitude of 8.0.

"This fault has magnitude 5s, 6s, and 7s all the time," said WHOI geophysicist Jeff McGuire. "They thought it was too broken up to produce anything more than an 8."

Colossal movement of land and sea

Their intense focus on Earth's seismic activity has also spurred the Japanese to create perhaps the world's most comprehensive seismic detection network, which blankets the archipelago and some of the nearby ocean floor with more than 1,200 sensors to monitor position and movement of continental and ocean crust. The Japanese government and scientific community have also encouraged a culture in which scientists share their data with colleagues around the world, especially after the 1995 magnitude-6.9 Kobe earthquake that claimed more than 6,000 lives.

In fact, Shin'ichi Miyazaki, a geophysicsist at Kyoto University and one of Japan's foremost experts in using GPS data to record how earthquakes move land and seafloor, was due to travel to the United States on March 14 to meet with McGuire and others. Fortunately, he was able to leave Japan before fears of radiation choked the country's airports. When Miyazaki and McGuire sat together and looked at the data, they discovered to their surprise that, after the earthquake, portions of the Japanese island of Honshu had moved 8 meters [26 feet] to the east.

"For us to see eight meters on shore, the fault could have moved as much as forty meters [130 feet] on the seafloor," said McGuire. "The shallow portions of the fault could have moved even more."

That so much energy was released from shallow portions of the fault was another surprise for McGuire and other seismologists. The waterlogged sediment overlying the fault, instead of absorbing seismic energy, broke and continued breaking, all the way to the surface of the seafloor in places. "The fault motion actually got stronger as it got to the surface," said McGuire. "That's why the tsunami was so big."

Had the earthquake occurred and nothing more, the Japanese people might have mourned their dead and counted themselves relatively lucky. Disaster officials would have realized their mistake and begun preparing for the possibility of larger earthquakes in the future. Geophysicists would have puzzled over the fault's ability to release so much energy.

But the quake turned out to be just the beginning. When the mega-thrust fault broke, it released the Eurasian Plate that was wedged in by the downgoing Pacific Plate. The plate sprang eastward and upward, propelling huge amounts of water upward, raising the sea level over the fault in an instant. The pulse of

Amy Caracappa-Qubeck, WHOI

water raced away from the epicenter, spreading rapidly in all directions in the form of a complex ripple as deep as the ocean. In open water, that ripple would have been barely noticeable. When it reached the continental shelf and then the shallower coastal waters around Japan, however, the wave reared up and exposed its full size, sweeping ashore for miles in some places.

Simulating the tsunami

Like most people who saw the news that day, Changsheng Chen and Robert Beardsley were amazed by the wave's power. But they also took professional interest in the tsunami and its path of destruction.

Chen, a professor at the School of Marine Science and Technology at the University of Massachusetts-Dartmouth and an adjunct scientist at WHOI, has been studying ocean circulation since the late 1980s when he was a graduate student in the MIT/WHOI Joint Program. His advisor was WHOI physical oceanographer Beardsley, and the two have collaborated ever since. In 2000, he and Beardsley developed the Finite Volume Community Ocean Model (FVCOM), a somewhat unorthodox model of global ocean circulation that can recreate currents and patterns in complex environments such as the coastal ocean and estuaries.

To understand how FVCOM differs from standard models requires complex physics and mathematics that may be simplified to this: Most models divide the ocean into a rigid horizontal grid of squares and then calculate changes among the squares in surface elevation, currents, temperature, salinity, density, and other properties driven by surface forces (such as wind) and by the horizontal transfer of mass, momentum, and energy. FVCOM, however, divides the marine realm into a horizontal grid of triangles of varying shapes and sizes.

The difference is more than aesthetic. The triangles permit Chen to make on-the-fly changes in the resolution of particular locations. Using the model, he can, for example, produce highly detailed simulations of ocean circulation in a focused region of the ocean (such as near the Fukushima Dai-ichi nuclear plant). And at the same time, he can link what's happening in those focused regions to broad, less-detailed circulation patterns across the entire Pacific Ocean, something typical models cannot easily do. In addition, FVCOM's grid of triangles offers more nuanced views near shore, because they can be fitted more precisely into the irregular shape of coastlines and seafloor—such as those of northeastern Japan.

After the tsunami struck, many were surprised by the extent of inundation along the coastline. Among those was Chen and Beardsley's colleague Jun Sasaki, a professor of civil engineering at Yokohama National University. Sasaki and others quickly catalogued the extent of the flooding and produced detailed inundation measurements of the coast.

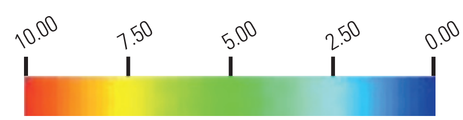
With these data, FVCOM was primed to recreate the wave and show just how it formed, approached, and ultimately inundated the coast. Chen and Beardsley already had high-resolution data for winds, tides, currents, temperature, salinity, and other ocean conditions in the region where the tsunami hit. But the earthquake had fundamentally and instantly changed sections of the Japanese coastline. Not only had the coastline moved a substantial distance to the east, but in some places had subsided as much as 2 meters [6.5 feet] as the underlying crust relaxed. For FVCOM to produce the most accurate results, Chen and Beardsley needed accurate maps of the "new" Japanese coast, which they got from Sasaki, but they also needed help from a source they had never turned to before: marine geologists.

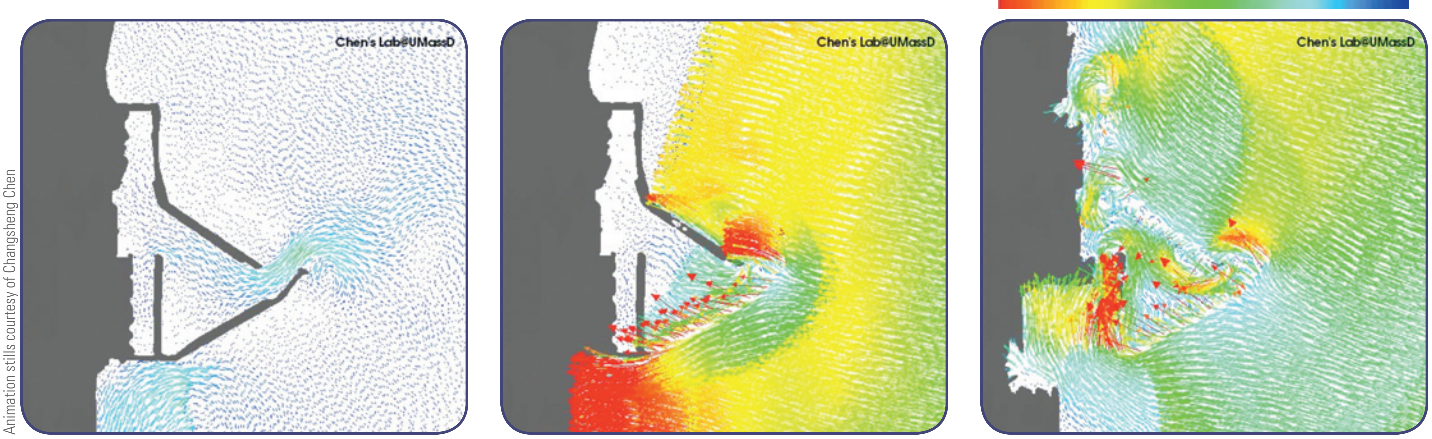
Unusual scientific bedfellows

Jian Lin has been studying large earthquakes since the 1970s, including recent ones in Algeria, Sumatra, China, Haiti, and Chile. He, like McGuire, was astounded by how much sensors in Japan's seismic network had moved after the earthquake. By studying the pattern of the movement, Lin and colleagues were able to approximate how the fault ruptured and how much the surrounding crust actually changed shape. This helped Lin determine where the March 11 rupture had shifted stress to neighboring parts of the fault, north and south, dramatically increasing stress—and the likelihood of future earthquakes—in those places. The fault's southern portion is notable for the fact that it has ruptured before; in 1855 a large earthquake on the segment laid waste to

Physical oceanographers Changsheng Chen and Robert Beardsley developed a mathematical model that can recreate complex currents and circulation patterns in coastal ocean environments. They used it to make finely detailed simulations of how the tsunami swept ashore at the Dai-ichi Nuclear Power Plant in Fukushima. Freeze frames from the simulation show how waves reaching 33 feet high completely submerged the 20-foot-high seawalls protecting the plant.

Height of tsunami in meters



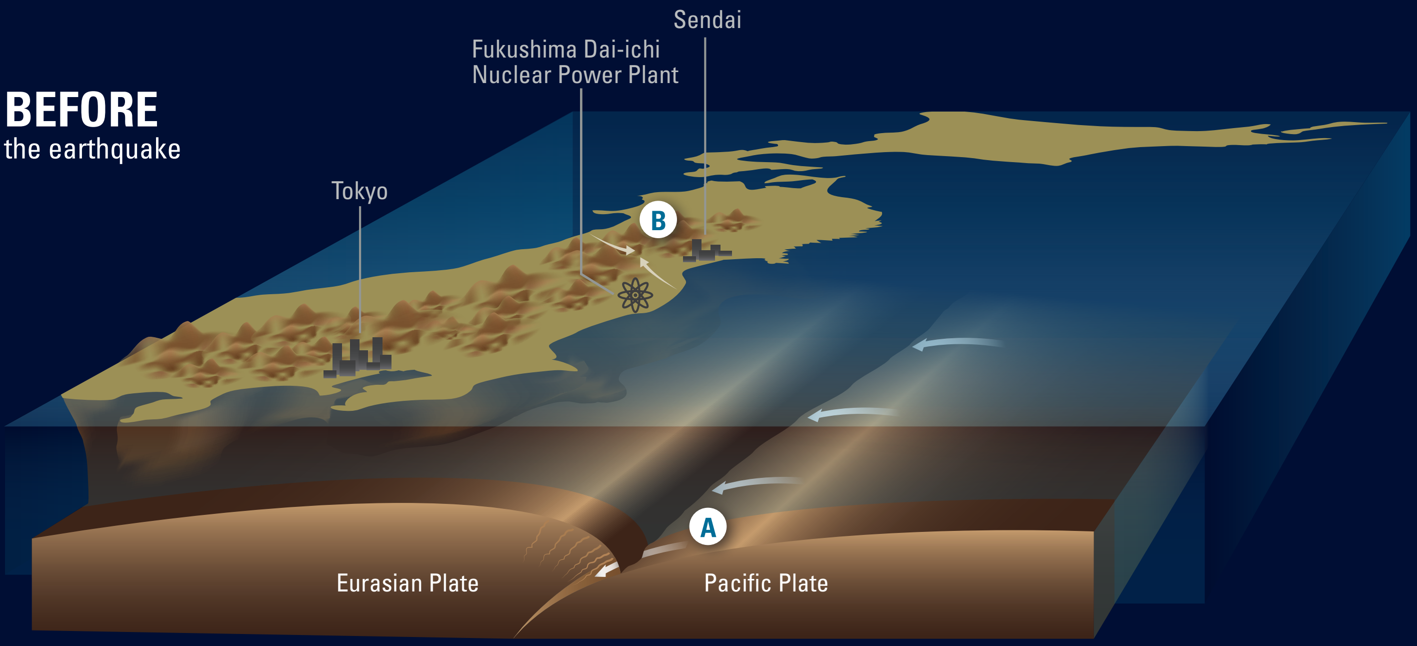


Animation stills courtesy of Changsheng Chen

ANATOMY OF A DISASTER

On March 11, 2011, an undersea fault ruptured about 80 miles off Japan, triggering a cascade of devastating events.

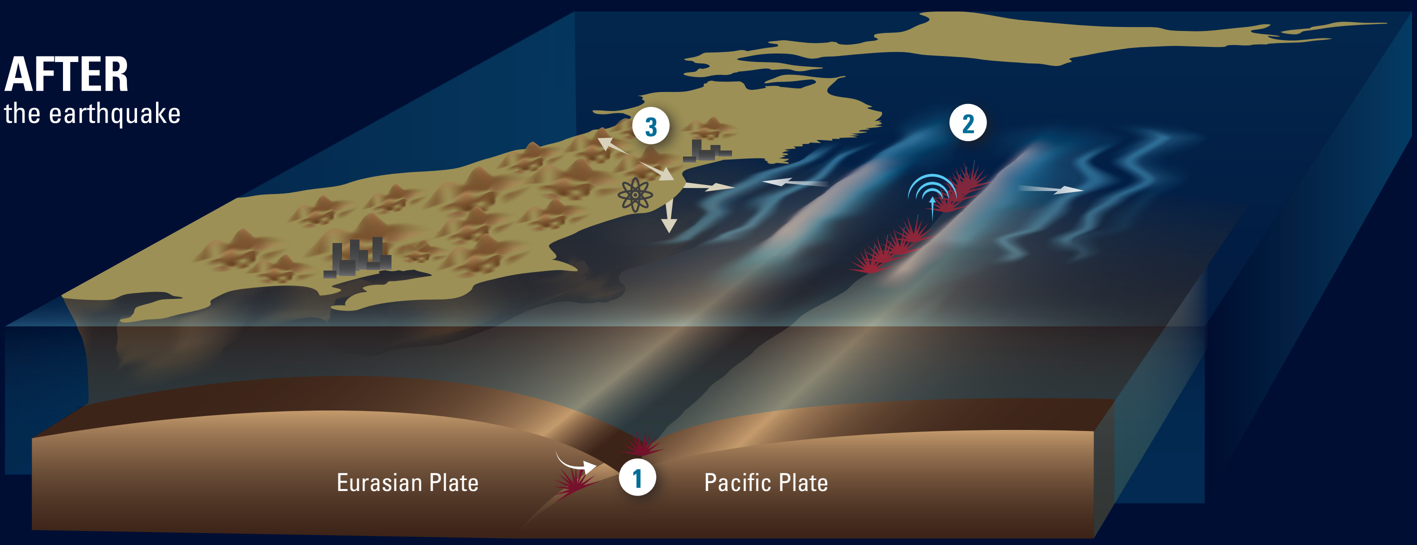
BEFORE
the earthquake



A The Japanese islands sit atop the Eurasian Plate near where it forces the Pacific Plate down into the Japan Trench. Huge stress builds where the two plates grind against one another.

B The stress has also compressed the Japanese island of Honshu like an accordion, pushing up dramatic north-south mountain ranges in the island's interior.

AFTER
the earthquake



1 On March 11, 2011, a section of a fault 19 miles beneath the seafloor broke, releasing pent-up stress and causing the seafloor to spring up violently in places.

2 The sudden lifting of the seafloor pushed up huge amounts of water, creating a massive "ripple" in the ocean that spread outward. In the deep ocean, this ripple was a few inches high. In shallow water, it formed a devastating tsunami that swept inland several miles.

3 The sudden release of stress along the offshore fault also released compression on the islands, causing the coastline to move eastward as much as 26 feet and to subside by as much as 6.5 feet.

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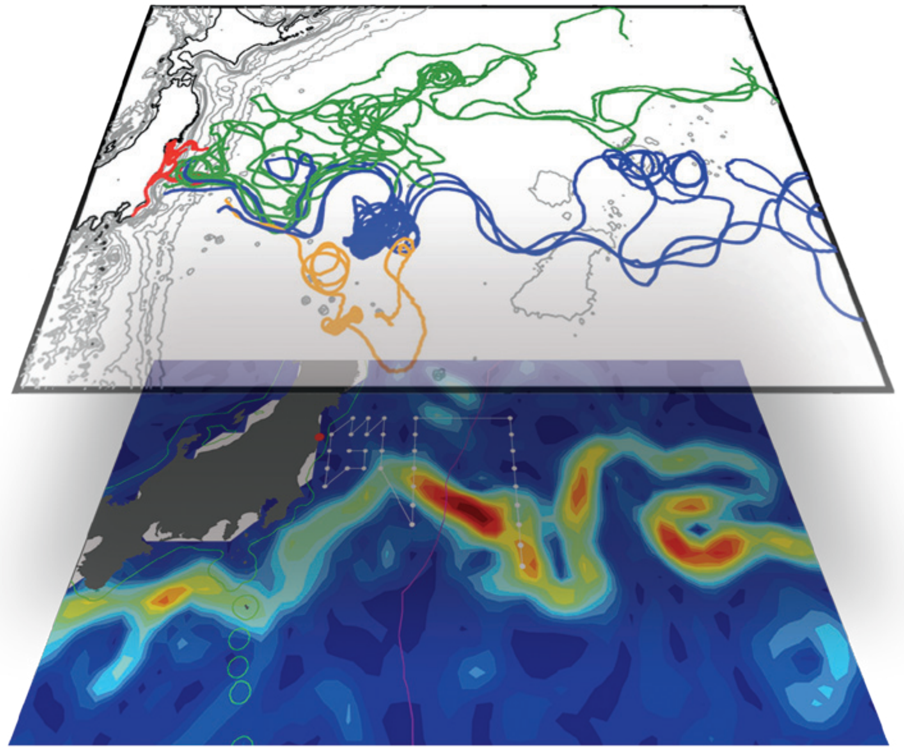
Edo, today known as Tokyo.

This time, however, Lin's work found a new and unexpected use. Ten days after the earthquake, Chen contacted Lin looking for data on how much the height of the seafloor had changed. He could convert these data into sea surface changes, which would serve as a starting point for FVCOM to model the formation and spread of the tsunami. Lin produced several possible scenarios, from which the team created a model simulation that agreed with both the geologic and the tsunami inundation record. Their work provided the first scientific visualization of the waves that slammed into the coast and the reactors at Fukushima. (See Page 36.)

"This was the first time I worked with a group of physical oceanographers to look beyond the geologic processes," said Lin. "This kind of work would not have been possible without the superb ocean modeling capability of our physical oceanographer colleagues."


Steven Jayne, WHOI

BOTTOM: An international scientific team led by WHOI marine chemist Ken Buesseler completed a research cruise in June 2011 to assess the levels and dispersion of radioactive substances from the Fukushima nuclear power plant and their potential impact on marine life. This map shows the sampling stations and cruise track near the Kuroshio Current (shown in yellow and red). Sampling began 400 miles offshore and moved to within 20 miles of the nuclear complex.

TOP: WHOI physical oceanographer Steven Jayne released two dozen surface drifters, which transmitted their locations via satellite while they moved with ocean currents. The color-coded track lines from individual drifters, combined with radionuclide data, indicated that the powerful Kuroshio Current acted as both a highway and a barrier, carrying much of the radiation quickly away from shore while also largely preventing it from spreading south.

Déjà-vu all over again

Almost exactly 25 years before the Tohoku earthquake, Ken Buesseler was a young marine chemist with a brand-new Ph.D. from the MIT/WHOI Joint Program. His thesis focused on the slight but measurable fingerprint of natural and manmade radiation in the Atlantic Ocean. In April 1986, Buesseler was at the Savannah River Laboratory near Aiken, S.C., measuring samples of seawater for plutonium, a byproduct of nuclear weapons testing in the 1950s and '60s, when the first reports broke about a disaster unfolding at a Soviet nuclear power plant known as Chernobyl.

For the next two decades, Buesseler refined techniques to measure the types and amounts of radioactive isotopes that Chernobyl and other events fed into the ocean. Because each radioactive isotope has a unique half-life (the time it takes for half of the atoms of a particular isotope to decay), as well as identifiable byproducts of that decay, Buesseler and others use these substances to trace currents and study how water masses mix across the depth and breadth of entire ocean basins.

"You never really know what you're going to find when you look at a sample," said Buesseler. "But if you know what to look for, you can begin to piece together how one radionuclide or another got to where you found it."

To study Chernobyl's marine impact, Buesseler looked to the nearest arm of the ocean, the Black Sea. With only one narrow connection to the Mediterranean through the Bosporus Strait, it is barely a part of the global ocean system. Its isolation and the fact that its surface and deep waters rarely mix allowed Buesseler to use the Black Sea as a "natural laboratory" and study such matters as how the sea's deep and surface waters interact, a key factor in why the deep Black Sea is largely devoid of oxygen (and why it often smells like rotten eggs as a result of sulfide buildup).

Over his career, Buesseler turned his attention to other scientific problems, but when conditions at the tsunami-damaged Dai-ichi nuclear power plant began to spin out of control, he quickly realized his expertise would be needed once again. A series of gas explosions in the buildings housing the reactors damaged the facility beyond repair, and officials were reduced to pumping tons of water on the reactors to keep them from catastrophically overheating. Much of that water became contaminated with radionuclides and had only one place to go—into the nearby ocean.

"I saw them trying to drop water on the reactors to cool them, and I saw their position on the coast and I thought, 'This is déjà-vu all over again,' " he said.

Seize the moment

Buesseler immediately set about trying to get any information he could about how much and what sorts of radioactive isotopes were being pumped into the ocean. TEPCO, the Tokyo Electric Power Company, which operated the Fukushima Dai-ichi Nuclear Power Plant, was releasing some data, including the flow of water from discharge canals at the plant, and he had limited offshore measurements coming in from Japanese colleagues. But Buesseler knew that larger questions about how the radiation was mixing into the ocean or getting into the marine food chain could be answered only with a systematic look at how specific radionuclides were accumulating and moving in the ocean—from as close as he could get to the reactors and before they dispersed far offshore.

Buesseler began to search for sources of funding, colleagues, and ships of opportunity to mount a major research cruise to make these critical measurements. The National Science Foundation awarded him a RAPID grant on April 4 to have samples collected by colleagues around the Atlantic and Pacific and mailed to his WHOI lab so he could establish a baseline for releases from Fukushima. On May 3, the Gordon and Betty Moore Foundation provided $3.7 million to allow Buesseler to charter the research vessel *Ka'imikai-O-Kanaloa* (*KOK*) from the University of Hawaii. But there was still a Japanese bureaucracy in crisis mode to deal with and six months' worth of cruise planning to do in five weeks' time. "Those were the busiest five weeks of my life," said Buesseler.

On May 15, the *KOK* departed Honolulu for Yokohama, Japan, even though Buesseler did not yet have all the permits he needed. On May 22, he received permission to sample within Japan's 200-mile exclusive economic zone. On June 6, the ship left Yokohama with a science party of 17 people from eight institutions, but still without the crucial final permission to sample at the edge of the 18-mile exclusion zone around the reactors. That finally came from the U.S. Coast Guard on June 8, while the ship was en route to the first sampling station.

Buesseler's plans called for collecting water samples at 30 locations, from the surface to 6,000 feet deep; to conduct net tows for phytoplankton, zooplankton, and nekton (free-swimming organisms) in various combinations at every station; and to sample the air and surface water continuously for radioactivity. The group also collected and packaged water samples for a total of 15 lab groups in seven countries that will eventually test the water for more than 20 different radioactive isotopes.

For two weeks, the *KOK* sailed a sawtooth course beginning 400 miles offshore, crossing the powerful Kuroshio Current

Scientists Ken Buesseler and Steven Jayne from WHOI and Taylor Broek from UC Santa Cruz (counterclockwise from right) extract seawater from a Niskin bottle, one of more than 1,500 samples collected in June 2011 off Japan. At bottom, WHOI researcher Steve Pike packs some of the 3 metric tons of seawater collected. Water samples were dispatched to 15 labs in seven countries to be analyzed for levels of a variety of radioactive isotopes, including cesium-134, cesium-137, strontium-90, plutonium-239, and neptunium-237.

Ken Kostel, WHOI

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that flows from the coast of Japan into the Pacific. The final leg of the cruise began within sight of the reactor complex at Fukushima on a clear, sunny day.

Also aboard the *KOK* was WHOI physical oceanographer Steven Jayne, who has long studied the Kuroshio Current, the Gulf Stream of the Pacific. He released two dozen surface drifters into the ocean during the cruise. These instruments deploy a parachute-like drogue just below the surface and transmit their locations via satellite while they move with ocean currents. Jayne used the data to map the strength and direction of branches and eddies in the current for months afterward.

Initial results, published April 2012 in the *Proceedings of the National Academy of Sciences*, showed that radionuclides from the reactors mixed quickly into the ocean and were diluted to levels of naturally occurring radiation within a few tens of miles of the coast. In addition, the Kuroshio appeared to act as both a highway and a barrier, carrying much of the radiation quickly away from shore while also largely preventing it from spreading south. At the same time, Jayne's drifters revealed the existence of an eddy—a swirling mass of water that sometimes breaks off from strong currents like the Kuroshio. In June 2011, the eddy had hugged the coast, likely drawing in contaminated water and maintaining higher concentrations of radionuclides.

As a result, radiation levels in the eddy were as much as 1,000 times higher than those before the accident. Yet they were still below levels of concern for humans and marine organisms and were about one-sixth the level of radiation that marine organisms receive from naturally occurring radionuclides such as potassium-40.

Samples of plankton and small fish confirmed this. Levels of cesium isotopes and another, faster-decaying isotope found in the organisms collected during the cruise ranged from undetectable to levels that, while elevated, remained within standards set for human consumption.

"The radioactivity of the fish we caught and analyzed would not pose problems for human consumption," said team member Nicholas Fisher, a marine biologist from the State University of New York, Stony Brook. "It does not mean all marine organisms caught in the region are perfectly safe to eat. That's still an open question. There are still likely to be hot spots in sediments close to shore and closer to the power plant that may have resulted in very contaminated species in those areas. Further study and appropriate monitoring will help clarify this issue."

Another open question is why radiation levels in the waters around Fukushima have not decreased since the Japanese stopped emergency cooling operations. According to Buesseler, it may be an indication that the ground surrounding the reactors has become saturated with contaminated water that is slowly seeping into the ocean. It may also be a sign that radionuclides in ocean sediments have become remobilized into seawater.

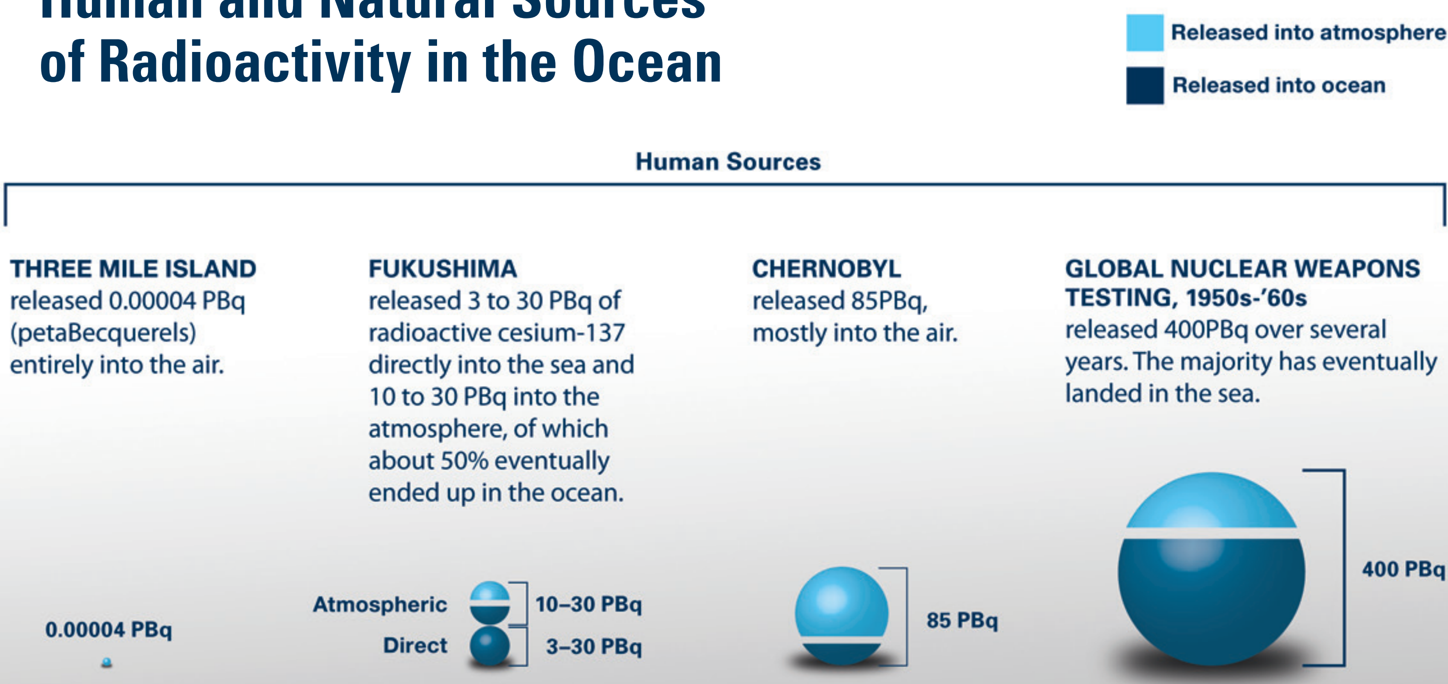
"What this means for the marine environment of the Northwest Pacific over the long term is something that we need to keep our eyes on," Buesseler said.

Potential hazard across the Pacific

With their knowledge of the ocean and what caused the cascade of events that resulted in 20,000 dead or missing and damage that will not soon be repaired or forgotten, another fundamental question remains: Were events beginning on March 11 avoidable? Certainly not entirely. Nothing could have prevented the earthquake or the ensuing tsunami. But with greater knowledge of how the offshore mega-thrust fault works—and of the earthquakes and tsunamis it has been capable of generating in the past—preparations along the coast could have been more extensive. Perhaps the nuclear power plant at Fukushima could have been reconfigured to lessen or prevent the damage that resulted.

Such knowledge could also inform preparations on the other side of the Pacific near another mega-thrust fault in the Cascadia Trench immediately off the coasts of Oregon, Washington, and

Human and Natural Sources of Radioactivity in the Ocean



British Columbia. The situation there is eerily similar to what happened in Japan in several ways. For one, earthquake and tsunami preparedness in many areas along the Pacific Northwest coast is based on a limited view of the fault's history. As a result, many people believe the risk is vastly underestimated.

The Cascadia Trench, however, lacks the instrumental network the Japanese have installed in the Japan Trench. In February 2012, McGuire and several colleagues received funding from the W. M. Keck Foundation to install extremely sensitive tiltmeters, similar to those placed off the northeast coast of Japan, that measure extremely small deformations in the seafloor near the Cascadia Trench. These will help give a better idea of just how much strain is building along a portion of the fault and help inform assessments of which parts of the fault are most likely to rupture.

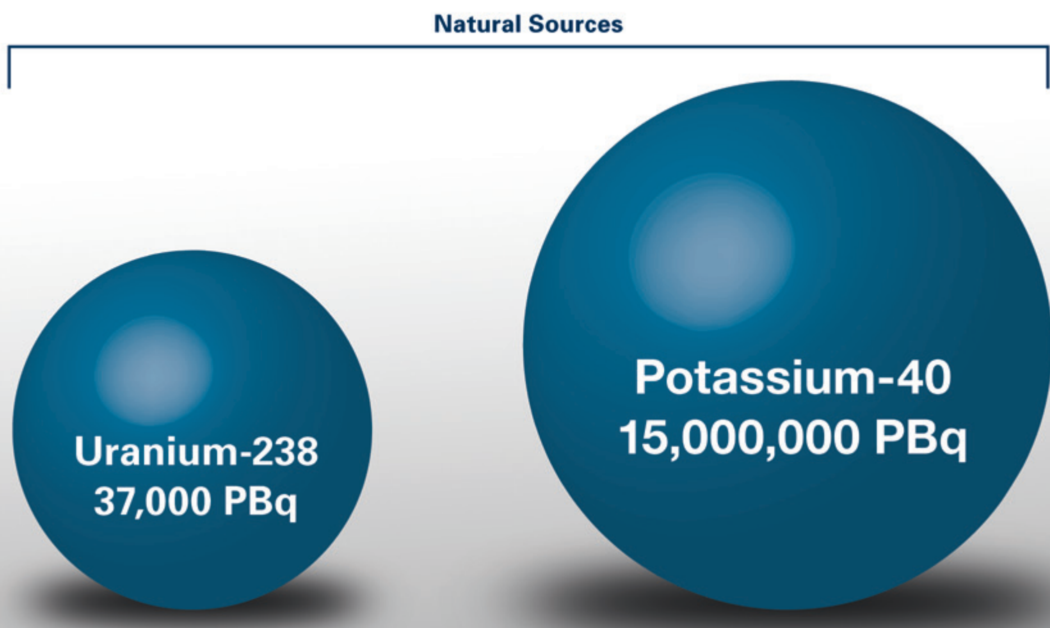
For McGuire, Lin, and others, what began on March 11 speaks to a dire need to look more closely at that first domino—the one that fell deep beneath the Japan Trench, setting in motion events that continue to unfold today.

"It shows how little we really know about the seafloor, yet we invest relatively little in studying it," said Lin. "This is our call to learn more about what happens there."

Ken Kostel, WHOI

WHOI marine geochemist Ken Buesseler pays his respects in front of the shrine of Namiwake Jinja in Sendai, Japan. Namiwake Jinja roughly translates as "split wave." The shrine marks the highest point that waters from a tsunami in 869 A.D. reached into the ancient city. That event had been largely forgotten by 2011, when an earthquake in the Japan Trench off the coast caused another tsunami that devastated Sendai.

Though serious, these totals pale compared to the abundance of radioactive substances naturally present in seawater such as uranium-238 and potassium-40.



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