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Feature

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Fukushima: The myth of safety, the reality of geoscience

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Abstract

In a report to the International Atomic Energy Agency (IAEA), the Japanese government stated that the Fukushima Daiichi nuclear disaster was caused not by the Tohoku earthquake but by the tsunami it generated, resulting in a loss of power for the station's cooling systems and, consequently, three core meltdowns. The tsunami countermeasures taken when Fukushima Daiichi was designed in the 1960s were, arguably, marginally acceptable considering the scientific data then available. But, between the 1970s and the 2011 disaster, new scientific knowledge emerged about the likelihood of a large earthquake and resulting tsunami; however, this was ignored by both the plant operator, Tokyo Electric Power Company, and government regulators. The regulatory authorities failed to properly review the tsunami countermeasures in accordance with IAEA guidelines and continued to allow the Fukushima plant to operate without sufficient countermeasures, despite having received clear warnings from at least one member of a government advisory committee. The lack of independence of government regulators appears to have contributed to this inaction. The *anzen shinwa* (“safety myth”) image portrayed by the Japanese government and electric power companies tended to stifle honest and open discussion of the risks. Japan's seismological agencies are locked into outdated and unsuccessful paradigms that lead them to focus on the hazard of a supposedly imminent earthquake in the Tokai district, located between Tokyo and Nagoya, while downplaying earthquake hazards elsewhere in Japan. Consequently, regulators and the plant operator missed many opportunities to avert the calamity at the Fukushima Daiichi Nuclear Power Station.

Keywords

earthquake, Fukushima, Japan, nuclear safety, seismic, Tepco, Tohoku, tsunami

The March 11, 2011 mega-quake (with a magnitude estimated at 9.0 by the US Geological Survey) occurred off Japan's Pacific coast, generating a destructive tsunami with a maximum run-up height of 41 meters, seriously affecting more than 650 kilometers of the Pacific coast in the Tohoku region. Run-up height is the maximum height above sea level reached by the tsunami as it penetrates inland and is generally considerably higher than the maximum height of the tsunami at the shoreline.

Five nuclear power stations were in the zone of particularly strong shaking. The most severely affected were Tokyo Electric Power Company's (Tepco)

Fukushima Daiichi (meaning “No. 1” in Japanese) and Fukushima Daini (“No. 2”) stations. Four of the reactors at Fukushima Daiichi, in particular, experienced severe problems that quickly turned into a nuclear calamity. The whole world was surprised that precautions against tsunamis were so weak at a nuclear power station located on Japan's coast. How was this design permitted during the station's construction in the 1960s and 1970s, and why were no additional safety measures taken in the time since?

Fukushima’s design tsunami

Construction of the six reactors at the Fukushima Daiichi Nuclear Power Station began in 1967. Relatively little was known about tsunami hazards at that time, and there were no significant run-up readings for earlier tsunamis in the vicinity of the power stations. Figure 1 shows the historical tsunami run-up data from the year 800 until 1965 for the Tohoku region.[1] This information paints roughly the same picture that would have been available to the

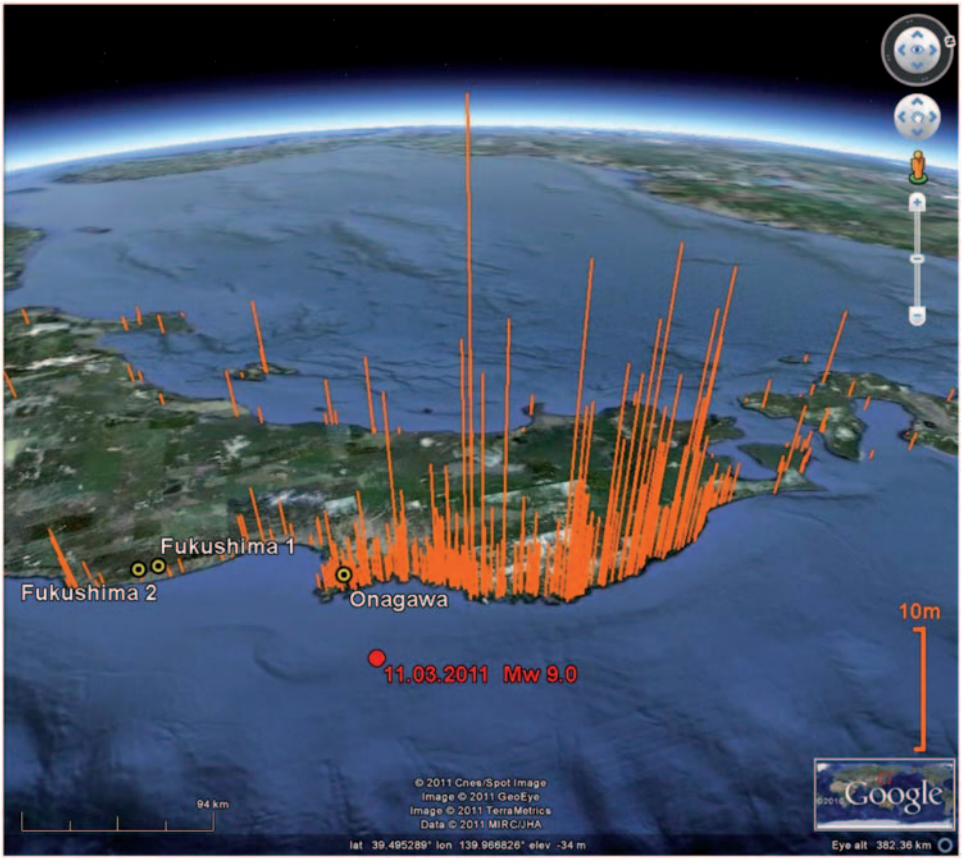

Figure 1. A map of reported historical tsunami run-ups along the Tohoku coast. Data from the database of the Novosibirsk Tsunami Laboratory are shown for the time period from AD 800 until 1965. Vertical scale is shown at lower right.

designers of the Fukushima plant in the mid-1960s.

At the time of the plant's construction, the design for tsunami height was set to 3.1 meters; this was based on the tsunami height observed at Fukushima during Chile's magnitude 9.5 earthquake in 1960. In 2002, Tepco and the regulators re-evaluated design heights based on a report by a subcommittee of the Japan Society of Civil Engineers and decided that tsunami heights of 5.4 meters to 5.7 meters were appropriate for the various reactors at Fukushima Daiichi, after considering the magnitude 7.9 Shioyazaki earthquake of 1938.

The 2011 Tohoku earthquake and tsunami occurred in one of the most active parts of the Japanese subduction zone. Strong tsunami-generating earthquakes have repeatedly occurred there in the past. Altogether the historical catalogue counts up to 70 tsunamis generated by submarine earthquakes that have occurred since AD 869 near the eastern Tohoku coast (Iida, 1984; Watanabe, 1998). They include at least six destructive tsunamis (see Table 1) that resulted in run-ups of 25 to 38 meters and thousands of fatalities.

The run-up data in Figure 1 clearly show a high level of tsunami hazard for some areas along the Pacific coast. But they also show that, when the Fukushima Daiichi station was designed and built, no large tsunamis were known to have hit that particular section of the coast. So in one sense a design tsunami with a height of 3.1 meters might arguably be said to have been reasonable.

Table 1. Basic parameters of the largest historical tsunamis in the Tohoku region

Date	Magnitude	Maximum run-up (meters)	Fatalities	Comments
869, July 3 (Jogan)	$M > 8.5$	unknown	>1,000	Giant earthquake in Tohoku region. Sendai plain was flooded up to four kilometers inland.
1611, Feb. 2 (Keicho)	$M > 8.0$	25	>5,000	Strong earthquake in Sanriku. Entire northeast coast of Honshu Island was flooded by tsunami.
1896, June 15	$M = 7.6$	38	27,122	Quiet earthquake generated a destructive tsunami.
1933, March 2	$M_s = 8.1$	28	3,000	Strong earthquake with destructive tsunami. In Sanriku more than 6,000 houses were destroyed.
1960, May 24	$M_w = 9.5$	5–7	142	Giant earthquake in Chile generated trans-Pacific tsunami, which destroyed more than 10,000 houses in Japan.
1968, May 16	$M_w = 8.3$	4–5	0	Strong earthquake, but resulting tsunami was moderate and resulted in no fatalities.
2011, March 11	$M_w = 9.0$	40	20,202	Giant earthquake and catastrophic tsunami along the entire Tohoku coast. Despite timely warning, more than 20,000 people died, mostly from tsunami.

M = macroseismic magnitude (i.e., estimated from damage reports); M_s = surface-wave magnitude; M_w = moment-magnitude. Fatality data for the 2011 earthquake are from the National Police Agency home page, as of August 27, 2011.

On the other hand, even at that time many large tsunamis were known to have hit other areas of the Tohoku region. These included the 1896 Sanriku earthquake, which had a run-up height of 38 meters, and the 1933 Sanriku earthquake, which had a run-up height of 27 meters. A prudent geologist would not have excluded the possibility of a tsunami comparable to the Sanriku events at Fukushima Daiichi.

Measuring magnitude

When the construction of the Fukushima Daiichi plant began, seismologists quantified the size of an earthquake using "surface-wave magnitude," inferred from measurements of relatively short-period seismic waves propagating through the Earth's crust and upper mantle. Instruments for recording longer-period seismic waves, which more accurately reflect the size of extremely large earthquakes, were just starting to be widely used. The largest earthquakes known in the 1960s had surface-wave magnitudes of about 8.5. Magnitude 9 earthquakes (mega-quakes) were not known to exist at that time.

In the mid-1960s, seismologists began quantifying the size of an earthquake by its "seismic moment," using seismographs capable of recording longer-period waves. Comparing surface-wave magnitude and seismic moment for several earthquakes, they found that surface-wave magnitude maxes out at about 8.5 regardless of how large the seismic moment is (Kanamori and Anderson, 1975). By the mid-1970s, seismologists agreed that seismic moment, rather than surface-wave magnitude, should be used to quantify the size of earthquakes.

But if almost all seismologists were familiar with the concept of seismic moment by the mid-1970s, engineers, government officials, and the general public were not. It would have been possible to abandon the use of earthquake magnitude altogether, but this would have required a vast explanatory campaign. To avoid that, Hiroo Kanamori, a seismologist at the California Institute of Technology, proposed a formula for converting seismic moment to a new, moment-magnitude scale (1977). His formula has the following advantage: For magnitudes of 8 or less, the new scale gives more or less the same results as surface-wave magnitude, but the largest events go up to magnitude 9 and higher, reflecting their true size.

Since 1977, there have been two mega-quakes: the 2004 Sumatra earthquake, a moment-magnitude of 9.3 (Stein and Okal, 2007), and the 2011 Tohoku event of magnitude 9.0. Kanamori[2] recently determined that the values for these two events, calculated using the earlier surface-wave-magnitude scale, were, respectively, 8.6 for Sumatra and 8.2 for Tohoku. These values show that, prior to the availability of the new scale, the 2004 and 2011 events would not have been properly appreciated as mega-quakes. The knowledge, generally available by about 1980, that magnitude 9 mega-quakes existed as a class should probably have triggered a re-examination of the earthquake and tsunami countermeasures at the Fukushima power station, but it did not.

Progress in paleo-tsunami research

Tsunami research has made great progress in the years since construction of Fukushima Daiichi began. Instruments that can record tsunamis have been installed on the ocean floor, and some of their readings are available in real time. Numerical models for calculating tsunami generation, propagation, and run-up have become widely available. The most important progress has been in the field of paleo-tsunami research: Geologists have learned how to identify and interpret sedimentary rocks deposited by tsunamis up to several kilometers from the shoreline and have thus obtained the ability to delineate the extent of flooding caused by tsunamis over the past several thousand years. This has enabled geologists to obtain reliable evidence of past mega-quakes.

The tsunami caused by the 1983 Sea of Japan earthquake on the Asia-facing coastline of the Tohoku region deposited sediments that gave geologists important clues about what to look for when seeking evidence of past tsunamis. Geologists employed by Tohoku Electric Power Company's Onagawa Nuclear Power Station (Abe et al., 1990), as well as others working independently (Minoura and Nakaya, 1991), used this knowledge to show that a very large tsunami had struck the Sendai plain after a large earthquake in the year 869 (part of the "Jogan" era of Japanese history, named after the reigning emperor at that time). In terms of the seismic and tsunami safety of nuclear power plants in the Tohoku area, including Fukushima Daiichi, the 1990 study provided the first and most important indication of a high tsunami risk.

The geological evidence obtained by paleo-tsunami studies lends important perspective to historical documents. It is one thing to read in historical chronicles that the Jogan tsunami "killed 1,000 people," but when this information is complemented by paleo-tsunami evidence showing that flooding reached as far as four kilometers inland, this suggests a very large earthquake. By comparing the known extent of the areas flooded by the 1896 and 1933 Sanriku tsunamis, geologists conclude that the Jogan earthquake must have had a greater magnitude than the value of 8.3 to 8.5 inferred by some previous studies.

In 2001, Koji Minoura and colleagues at Japan's Tohoku University not only suggested that the Jogan tsunami was much larger than others generated by normal (magnitude 8 class) subduction earthquakes but also presented geological evidence of two other comparable prehistoric paleo-tsunamis, for a total of three mega-tsunamis in the past 3,000 years. These three paleo-tsunamis were roughly the same size as the March 11 tsunami. Minoura's group presented convincing evidence that the Sendai plain experiences mega-tsunamis every 800 to 1,100 years, on average, and concluded their paper with the following statement: "More than 1,100 years have passed since the 869 Jogan tsunami and, given the recurrence interval, the possibility of a large tsunami striking the Sendai plain is high. Numerical findings indicate that a tsunami similar to the Jogan one would inundate the present coastal plain for about 2.5 to 3 kilometers inland" (Minoura et al., 2001: 87).

Since earthquakes are not strictly periodic, the evidence for three mega-tsunamis in the Tohoku region should not necessarily have been regarded as evidence that a mega-quake was imminent. However, it seems indisputable that the above studies provided clear evidence of mega-tsunamis repeatedly striking the Tohoku region every thousand years or so. Nonetheless, Tepco, Japanese regulators, and even most seismologists did not pay sufficient heed to paleo-tsunami research.

The 2004 Sumatra earthquake

The tsunami generated by the magnitude 9.3 Sumatra earthquake in 2004 caused devastation throughout the Indian Ocean. Prior to this earthquake, some geoscientists had thought that mega-quakes could occur only at certain types of subduction zone and that regions such as Sumatra and Tohoku were not at risk for these quakes. But, two notable studies pointed out, the Sumatra earthquake showed that this idea was a fallacy (McCaffrey, 2008; Stein and Okal, 2007). And in any case, even before 2004, the paleo-tsunami evidence had already shown that mega-quakes had occurred in Tohoku.

After the Sumatra earthquake and tsunami, the Nuclear Safety Commission of Japan revised its seismic guidelines (NSCRG, 1978) for nuclear plants in 2006. The new precautions against tsunamis were general in nature and did not result in a significant upgrade of tsunami countermeasures at Fukushima or other plants. Tepco and its university collaborators (Yanagisawa et al., 2007) took the approach of first assuming a particular source model for an earthquake and then trying to calculate the maximum tsunami height using numerical simulations, but they downplayed historical and paleo-tsunami data in these efforts.

Hearings in 2009

In 2009, Tepco and government regulators passed up another chance, which turned out to be the last chance, for reassessment and design improvement. A Japanese government committee held a series of hearings to review seismic and tsunami safety at nuclear power plants. At one hearing in June 2009,[3] one of the committee members, Yukinobu Okamura, a senior geologist at a government-affiliated research laboratory, issued a strong warning about the risks of a large tsunami based on the Jogan data. Tepco representatives did not respond to the most important implications of Okamura's warning in their presentation at the next meeting of the committee, in July 2009. Tepco produced simulation results showing that, in one particular model of the Jogan earthquake, the design standards for seismic safety would not be exceeded at Fukushima Daiichi. However, Tepco representatives did not discuss the possible risks posed by a mega-tsunami of the size caused by the Jogan earthquake.

Consequences for nuclear safety design

The nuclear calamity at Fukushima shows that the plant's sea wall was insufficient. Above all, however, the poorly designed emergency power supply was unable to withstand a large tsunami. There is a clear International Atomic Energy Agency (IAEA) requirement that “postulated initiating events” (PIEs) for nuclear power plants must be taken into account when designing safety measures. PIEs are events that have a probability of occurring more than once every 10,000 years. National nuclear laws and regulations are expected to incorporate the IAEA requirement that PIEs will cause "no or minor radioactive release." The Jogan tsunami and two other similar events occurred in the past 3,000 years, and these tsunamis (or possibly an even larger one) should have been used as a PIE. The 2009 IAEA Safety Guide for Site Evaluations, and even the 2003 IAEA Safety Guide on Flood Hazard for Nuclear Power Plants on Coastal and River Sites—published a year before the Sumatra earthquake and tsunami—explicitly required a thorough consideration of historic tsunamis. In contrast, the guidelines in Japan, even after revision in 2006 (NSCRG, 1978), contained only vague statements on tsunami hazards and did not impose clear requirements on electric power companies.

An invulnerable emergency power supply for cooling systems is essential equipment for any nuclear power plant, but this requirement was not met at Fukushima. The safety margin there was too small, especially for a large tsunami that could lead to the common-cause failure of multiple safety systems, as happened on March 11. The electrical device for the main cooling pumps, its switchgear, and the emergency diesel generators should have had a much higher resistance to flooding. These systems should have been installed above the high-tide sea level, paying careful attention to water tightness.

Fukushima Daiichi also should have had a separate tsunami-safe emergency system that could provide core cooling and containment-heat removal in the event that all other normal or emergency cooling systems failed for any reason. Nuclear power plants in Switzerland have such a system, which mostly takes its cooling water from earthquake- and flood-resistant groundwater supplies located inside a bunker and separate from the normal water intake. Thanks to this extra emergency system, risk analyses of Swiss plants show that the expected frequency of core damage is very low. The Swiss system is waterproof, armored against a terrorist attack or airplane crash, earthquake-resistant with a high safety margin, and can operate unattended for 10 hours during a station blackout. The fuel tanks in the bunkered building have a sufficient supply for two days of operation. The building is sited well above the level of any nearby river to protect against extreme flooding, even if an upstream dam were to break. Swiss safety authorities have required this additional emergency system for both new and existing nuclear plants since the late 1980s. It is regrettable that Japanese regulators did not do the same. An extra emergency system, or even just an upgrade of the tsunami defenses at Fukushima, would not have been inexpensive but might well have averted the calamity that ultimately occurred, which will of course have a much higher cost than any conceivable retrofit in both economic and human terms.

Other serious deficiencies at the Fukushima plant were inoperable unfiltered containment venting systems and the absence of a hydrogen re-combiner system in the reactor buildings, which led to three explosions that released large amounts of radioactive material into the environment. Accident-stable venting systems and passive autocatalytic hydrogen-reduction systems would have prevented explosions and retained most of the radioactivity within the containment buildings.

Deficiencies in severe accident management

One consequence of the Fukushima accident will be that nuclear energy facilities around the globe will have to do a better job of planning for worst-case conditions, like long-lasting station blackouts that occur simultaneously with vast destruction caused by a severe natural disaster. The more reactors located at one site, the more important is this requirement for accident management. At Fukushima, an early reduction of the reactor pressure would have been the best way to restore evaporated water and thereby prevent rapid core damage in units 1, 2, and 3. But the necessary devices were not operable, and the emergency measures taken did not work fast enough to prevent core meltdown. Mobile generators and compressors, for recharging emergency batteries and restoring compressed air within a couple of hours, are vital for keeping relief valves open. Mobile diesel-driven pumps to inject water into the reactor and fuel pools are also important, but were not readily available at Fukushima. Such devices and all related equipment must be stored in an area safe from earthquakes, tsunamis, and other natural hazards—and kept ready for use.

Institutional problems in Japan

The Japanese government administers two large-scale programs in seismology: One is the issuance of long-term probabilistic hazard maps, and the second is a program aimed at predicting an imminent (within three days) "scenario earthquake," the "Tokai earthquake," off Japan's Pacific coast between Tokyo and Nagoya. Both programs have serious scientific problems: Damaging earthquakes in the past 30 years, including the March 11 event, have occurred in locations with a low hazard rating, suggesting that the methods used to produce hazard maps are flawed; and the chances of successfully predicting the "Tokai earthquake" are almost nil (Geller, 2011). In any case, there is no reason to suppose that a large subduction-zone earthquake in the Tokai district is any more likely than in any other area.

Since about 1975, the Japanese public has been subjected to repeated discussion of the supposedly imminent "Tokai earthquake," "Tonankai earthquake," and "Nankai earthquake." These repeated announcements may have led the population of the Tohoku area to believe that they were not at risk of a large earthquake and a subsequent tsunami. The exhaustive discussion of the "Tokai earthquake" may have also allowed nuclear operators and regulators to pay insufficient attention to the tsunami risk at Fukushima.

The government's earthquake hazard maps are based on the outdated idea that "characteristic earthquakes" recur at more or less regular intervals and are of magnitude 8 or less. The March 11 earthquake, in the magnitude 9 class, released 30 times the energy of a magnitude 8 earthquake. If regulators had considered the four magnitude-9 earthquakes that occurred around the world between 1950 and 2010, rather than relying on the seemingly more detailed but in fact flawed government hazard maps, the Fukushima accident might have been averted.

A well-established national safety culture depends not only on nuclear operators to meet the highest safety standards but also on a nuclear safety authority to keep the national requirements updated and to require modernization of plants when necessary. Achieving a safety culture requires a clear distinction between the regulatory structure and the nuclear power industry. The main regulator in Japan is the Nuclear and Industrial Safety Agency, which is under the Ministry of Economics, Trade, and Industry and cannot be considered an independent agency in the sense required by the IAEA's Nuclear Safety Convention. The creation of a genuinely independent nuclear safety inspection and overview organization outside the ministry should be expedited after this accident. Also, the regulatory powers of Japan's Nuclear Safety Commission, which is tasked with reviewing the Nuclear and Industrial Safety Agency's actions, should be scrutinized and strengthened.

Conclusion

The present state of knowledge suggests that the Fukushima disaster was not an "unforeseeable" natural event. In fact, the tsunami risk was known, but the issue was left open for many years without any concrete action by decision makers. Nuclear energy will continue to play an important role in Japan's electricity supply in the future. But after the Fukushima catastrophe, reforms in the nuclear power industry and regulatory system are essential. Japan's nuclear sector can rebuild public trust and confidence only with a new openness, independent and strong nuclear regulators, an updated nuclear safety law, and safety upgrades at all plants jeopardized by tsunamis and earthquakes. Japan's nuclear sector must adopt, implement, and truly embrace a new set of values. For that to occur, international support and assistance may well be necessary.

Acknowledgements

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Notes

1. There are two main databases that have compiled catalogues of historical tsunami data from a variety of sources. One is the US National Oceanic and Atmospheric Administration's National Geophysical Data Center (http://www.ngdc.noaa.gov/hazard/tsu.shtml), and the second is the Novosibirsk Tsunami Laboratory in Russia (http://tsun.sscc.ru/nh/tsun_descr.html).
2. Personal communication in June 2011.
3. Transcripts (in Japanese) of the June 2009 and July 2009 hearings may be found at the following links, respectively: http://www.nisa.meti.go.jp/shingikai/107/3/032/gijiroku32.pdf; http://www.nisa.meti.go.jp/shingikai/107/3/033/gijiroku33.pdf.

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Author biographies

Johannis Nöggerath is President of the Swiss Nuclear Society. He is also head of the division of Safety Compliance and Technical Support in the Leibstadt Nuclear Power Plant. His main field of expertise is nuclear safety, with an emphasis on deterministic and probabilistic safety analysis. He worked for several years in the Swiss Nuclear Safety Inspectorate.

Robert J. Geller is Professor of Geophysics in the Department of Earth and Planetary Science at The University of Tokyo. His current research interests focus on numerical modeling of seismic-wave propagation and inversion of observed seismic-waveform data for the structure of the Earth's interior, but he has also written extensively on problems afflicting earthquake-prediction research.

Viacheslav K. Gusiakov is head of the Tsunami Laboratory at the Institute of Computational Mathematics and Mathematical Geophysics, Siberian Division, Russian Academy of Sciences. He obtained his doctoral degree in 1974 from the University of Novosibirsk. His research interests include numerical modeling of tsunamis, seismic and oceanographic data processing, geophysical databases, risk assessment, and hazard mitigation. He served as Chairman of the Tsunami Commission of the International Union of Geodesy and Geophysics from 1995 to 2003. He is also a member of the International Tsunami Society, the American Geophysical Union, and the Seismological Society of America.