The 11 March 2011 Tohoku (Sendai), Japan earthquake

The 11 March 2011, *Mw* 9.0 Tohoku earthquake, already among the most destructive earthquakes in modern history, emanated from a fault rupture that extended an estimated 450 km along the Pacific coast of Honshu, the largest Japanese island. What makes some experts, including Hiroo Kanamori who has spent a lifetime studying subduction zone earthquakes, wonder is the size of the earthquake and the consequent unprecedented damage that it wreaked on the northeast coast of Japan (*Science*, 18 March 2011). This earthquake is the fourth among five of the strongest temblors since AD 1900 and the largest in Japan since modern instrumental recordings began 130 years ago. With the most advanced and dense network of seismic and global positioning system (GPS) stations, it is among the best instrumentally documented great earthquakes ever.

Every great earthquake poses newer challenges to humanity because there is much more to be understood about earthquakes and their primary and secondary effects. An example closer to home was the 2004 Andaman–Sumatra earthquake that ruptured 1300 km of the plate boundary between the Indian and Eurasian plates and generated a tsunami that reached shores as far as the coasts of India and Somalia. Until then, the threat from mega tsunamis in the Indian Ocean was not an active issue in any of the affected countries.

If the Tohoku earthquake turns out to be one of the worst disasters in modern history, one cause will be the mix of natural and human forces that allowed a tsunami to disable some of the nuclear power plants in the region. Another will be the hubris of sea walls and floodgates that were to protect coastal towns and cities from this tsunami. Damage from the earthquake per se was minimal owing to the structural integrity of the buildings and much of the damage and deaths (>20,000) were due to the tsunami. While the reactors at Fukushima Daiichi nuclear power plant complex withstood the 9.0 earthquake, the 10 m-high tsunami wave reached 2.5 m above the safety margin.

From the tectonic point of view, this earthquake in fact is hardly surprising. Japan and its nearby islands lie across four major tectonic plates that are grinding past each other. These are the Pacific plate, Okhotsk microplate (a subdivison of the North America plate), Eurasia and Philippine plates falling within the Kuril–Japan–Kamchatka–Aleutian trenches which have generated several $M > 8$ and three $M > 9$ earthquakes (Figure 1 *a* and *b*). Their interactions and consequent stress buildup have made this region one of the most seismically active regions in the world. Deformation of the overriding plates generates shallow crustal earthquakes, whereas slip at the plate interface causes interplate earthquakes that extend from near the base of the trench to depths of 40–60 km. Further down the slab, earthquake sources extend to nearly 700 km along these trenches (Figure 2 *a*).

The 11 March earthquake (*Mw* 9.0) with its rupture starting at 24.4 km, according to the Japan Meteorological Agency (JMA) occurred at the boundary where the Pacific Plate is being underthrust at the Japan Trench. At this latitude, the Pacific Plate moves approximately westwards with respect to the North America plate at a velocity of 80–90 mm/yr (ref. 1). The general seismicity along the plate boundary and the region where the 11 March event occurred are shown in Figure 1 *a* and *b*. The main shock occurred by reverse faulting on an ENE oriented plane, consistent with the trend of the trench axis (Figure 2 *b*). A fault length of 450 km, width of 150 km and maximum slip of 18 m are inferred on the basis of preliminary slip models by JMA.

While reviewing the past great earthquakes in the region, two earthquakes that occurred in 1896 and 1933 appear remarkable due to the large tsunamis. The 15 June 1896 earthquake occurred near the town of Rokugo (modern name: Aomori) located about 350 km north of Sendai. This weak earthquake, scarcely felt onshore, nevertheless generated one of the most devastating tsunamis in Japanese history, destroying about 9,000 homes and causing at least 22,000 deaths. The tsunami attained a height of 25 m and instantly swept away all the houses. On 2 March 1933, an earthquake of magnitude 8.4 occurred very close to the location of the 1896 event. This earthquake resulted from tensional faulting in the Pacific plate just seaward of the Japan trench. It produced strong ground motions and tsunami along the coast of Honshu. Maximum wave heights of 28.7 m were observed at Ryori Bay, Honshu; there were more than 3000 fatalities.

The subduction zone off Tohoku, where the Pacific plate is forced under the Okhotsk plate, has been noted for the occurrence of large earthquakes every 40 years. Earthquakes of magnitude 7.5 or so recur every 30–40 years[2]. Kawakatsu and Seno report that the rupture zone of the 1978 Miyagi-Oki earthquake has experienced large earthquakes ($Ms \sim 7.4$) about every 40 years at least since 1835: 1835, 1897, 1936 and 1978 (only $Mw \geq 7.5$ are shown in Figure 1 *b*, see also Table 1). The *M* 7.4, 1978 event – the most recent one prior to the 2011 – killed 28 people and triggered a small tsunami. Strain buildup in this part of the plate boundary was evident from the GPS based deformation estimates based on the data collected from northeast Japan during 1995–2002. These models imply strong coupling in northeast Japan between Miyagi-Oki and Toakachi-Oki based on which it was suggested that the region holds large potential for future earthquakes[3].

The next large event (*Mw* 7.2) occurred this year on 9 March after an interval of 33 years. Perhaps the anticipation of an earthquake every 30–40 years left no room to suspect this to be the forerunner of the great event that was to follow. In an interview given to *Science* (18 March 2011), Nishimura states that they did not foresee this large event, whose rupture zone overlaps with the 50 km length of the 1978 earthquake rupture. More earthquakes occurred as part of a tight cluster during the 10 days prior to the great 11 March earthquake (Figure 2 *b*). Aftershocks continue to occur in the region, several of them magnitude > 6.0, and activity spreading up-dip as well as down-dip of the subducting slab (Figure 2 *c*).

Tsunami geology explorations and the archival information in the Sendai region suggested an unusually large tsunami in AD 869 (ref. 4). The tell-tale evidence of a marine sand layer buried in marshy deposits located 3–4 km inland from the coastline revealed that an ancient tsunami must have reached that far inland. Written records date this event, referred

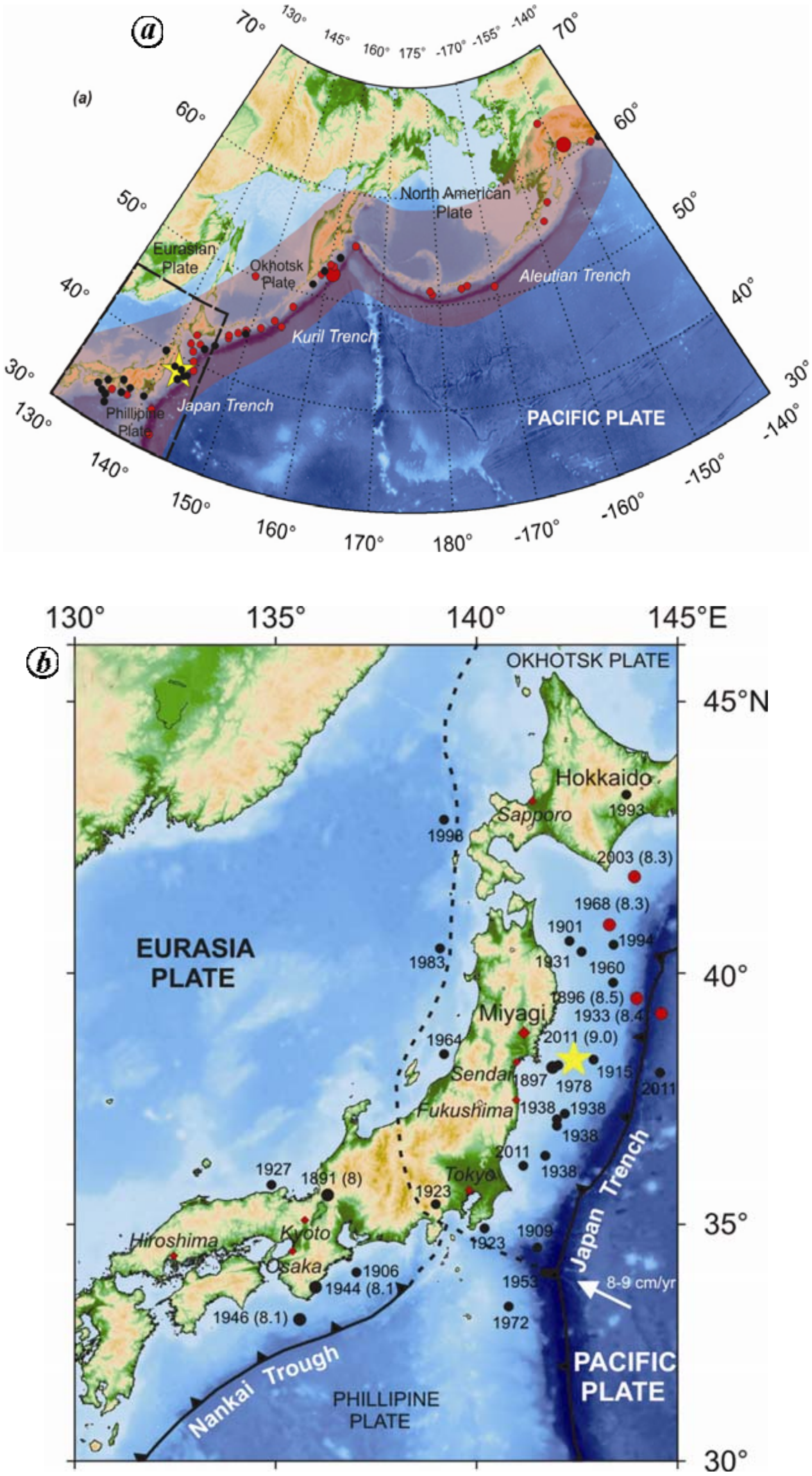

Figure 1 ***a.*** Locations of great earthquakes ($M \geq 8.0$) on Japan, Kuril, Kamchatka and Aleutian trenches since AD 869. Filled black circles: pre-AD 1900; filled red circles: post-1900; larger red circles: $M \geq 9.0$; yellow star, 11 March 2011 (Data source: USGS, NEIC and other published literature). The shaded region depicts the Pacific ring of fire. Note that the apparent colour change across the subduction front is an artifact of the background image. Box in the left corner is expanded in Figure 1 *b*. ***b***, A tectonic map with the historical and instrumentally recorded events (1891–11 March 2011; $M \geq 7.5$ only) around the source region of the 11 March 2011 event (marked by a yellow star). Smaller black dots indicate M 7.5–7.9 while the larger black- and red-filled circles represent M 8.0–8.2 and M 8.3–9 respectively. This data is compiled from the US Geological Survey databases on historical earthquakes and various published literature. The dashed line marks the boundary between Eurasia and Okhotsk plates (after Satake[8]).

to as the Jogan earthquake, to 13 July 869 (refs 4 and 5). The computed inundation model based on the observed distribution of paleotsunami deposits (about 3 km from the coast) suggested a magnitude of 8.3 to the causative earthquake. Based on the computed inundation area and the distribution of tsunami deposits, it has been suggested that only an interplate earthquake source with 100 km width could have generated the observed distribution of tsunami deposits. Further, they proposed that the source of this earthquake is much larger (*Mw* 8.1–8.3) than the anticipated $M \sim 7.5$ earthquake on this segment[4,5].

Giant tsunamigenic earthquakes of the kind that the world just witnessed invariably toss the question as to whether this could have been anticipated or at least identified within a time-window, with projection on the extent of the disaster. The last decade has witnessed several devastating earthquakes and tsunamis: 25 December 2004, Sumatra (*Mw* 9.2); the 12 January 2010, Haiti (*Mw* 7.0) and the 27 February 2010, Chile (*Mw* 8.8) among them. Perhaps the Haiti earthquake was the closest that Earth Scientists could get to really predicting imminence of an earthquake. In a paper published two years prior to the event, Manaker *et al.*[6] had suggested, based on GPS based models, that the Enriquillo-Plaintain Garden fault zone (EPGFZ) in southern Haiti was ready for a *Mw* 7.2 earthquake any day. The 2010 Chile earthquake is, however, remarkable for the absence of any precursory GPS signals. The scientific discussion on the Sendai earthquake will continue for years. In these discussions, the precursory patterns, if any, with respect to this earthquake will be hotly debated as this is one region that can boast of the best instrumental and historic documentation and several past earthquakes to learn from.

The ability to identify and narrow down the windows for short term predictions and to estimate the size of future earthquakes, at least in some better-studied earthquake source zones, has certainly improved over the last couple of decades. In fact, the ability to make short-term predictions is not the real issue here. What was conceivably missed out in Japan is the widespread recognition that such an earthquake could even happen in spite of the data available. Another issue is the risk assessment in the event of such an earthquake. Despite

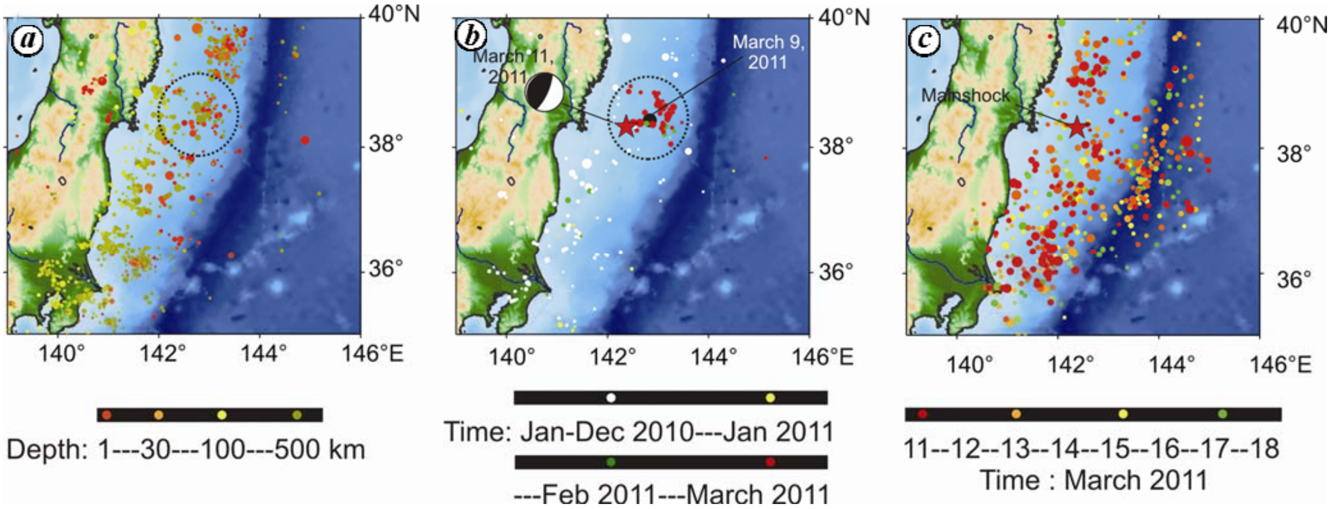

Figure 2. ***a***, Seismicity during 1973–9 March 2011. A total of 3500 earthquakes in the magnitudes 5–8.3 are plotted; ***b***, Seismicity in the same region during January 2010–10 March 2011 with the 11 March event identified by a red star. Earthquakes during 1–10 March 2011 are shown as red-filled circles; 45 of these fall in cluster close to the epicenter of the 11 March earthquake. The largest of these (*Mw* 7.2) that occurred on 9 March is shown as a black-filled circle. Focal mechanism of the main event is from the Japan Meteorological Agency. ***c***, Plot of epicenters of the aftershocks during 11–18 March (10:39 UTC). The color scheme (red-orange-yellow-green) indicates a temporal progression, green representing the latest events. A total of 1062 earthquakes (*M* 5–7.1) are plotted. As expected for typical interplate earthquakes, up-dip migration of seismicity is noted soon after the main earthquake as indicated by the red- and orange-filled circles close to the trench axis. (Source: NEIC)

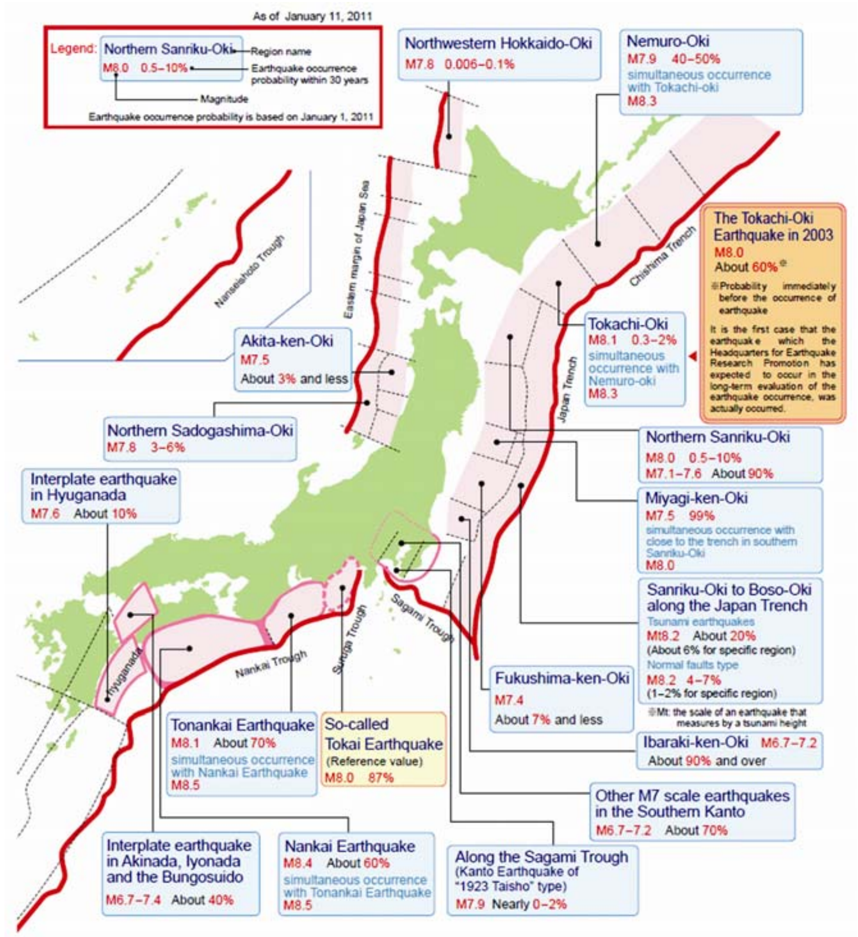

Figure 3. The probability estimate map prepared by the Headquarters of Japan's Earthquake research program, updated on 11 January 2011. (Source: http://www.jishin.go.jp/main/img/w_shokai-e_kaiko.gif)

advances by the Japanese in monitoring systems and the ability to assess hazards, there were inevitable uncertainties about the cascading impacts. The aftermath of the 2011 Tohoku earthquake – the large tsunami inundation and the mishap at the nuclear power plants – are the unforeseen or underestimated fallouts.

If the 2011 Tohoku earthquake was a repeat of the AD 869 earthquake, the Japan subduction zone may have two types of cycles. The shorter cycles could be for the $M \sim 7.5$ earthquakes. The larger earthquakes that seem to overlap the ruptures from smaller earthquakes may occur over longer intervals, a size variability that is observed in subduction zones off Chile, western North America as well as the adjoining Kuril subduction zone[7], and may be extendable to the Andaman–Nicobar segment. Another question is whether the Sendai earthquake has occurred in isolation or is there a potential pattern of temporal clustering of the major plate boundary earthquakes starting from the 27 February 2010, Chile and the 8 September 2010, New Zealand earthquakes.

Although it is a cliché to state that extreme preparedness and unflappable vigilance are qualities that are required to mitigate such tragedies, the Japanese example ironically provides a case for what could go wrong when the real threat is underestimated. True preparedness

Table 1. Earthquakes of $M \geq 7.5$ plotted in Figure 1 *b*

Year	Latitude (°N)	Longitude (°E)	Magnitude
1891	35.6	136.3	8
1896	39.5	144	8.5
1897	38.1	141.9	8.7
1901	40.6	142.3	7.5
1906	34	137	7.7
1909	34.5	141.5	7.6
1915	38.3	142.9	7.5
1923	35.4	139	7.9
1923	34.9	140.2	7.6
1927	35.8	134.9	7.6
1931	40.4	142.6	7.7
1933	39.2	144.6	8.4
1938	36.4	141.7	7.7
1938	37	142	7.9
1938	37.1	142	7.8
1938	37.2	142.2	7.7
1944	33.7	136	8.1
1946	33	135.6	8.1
1953	34	141.7	7.9
1960	39.8	143.4	7.8
1964	38.4	139.2	7.5
1968	40.9	143.3	8.3
1972	33.3	140.8	7.5
1978	38.02	142.07	7.6
1983	40.44	138.87	7.7
1993	43.06	144.29	7.6
1993	42.71	139.28	7.7
1994	40.56	142.99	7.7
2003	42.21	143.84	8.3
2011	37.52	143.05	9.0
2011	35.92	141.38	7.9
2011	38.27	144.63	7.6

includes a realistic assessment of the hazard that primarily takes into account the knowledge about past tsunamis and the present state of earthquake sources. The probability estimate map prepared by the headquarters of Japan's Earthquake Research Program identifies the source zone of the 11 March earthquake (Miyagi-ken-Oki) as one with 99% probability, for a *M* 7.5 earthquake and an estimated maximum magnitude of 8.0. In fact the 9 March (*Mw* 7.2) earthquake did occur in the postulated location (Figure 3). It is also worth remembering that natural processes turn into major disasters only when they interact with the built environment. Coastal regions are basically interactive zones with various natural processes including infrequent but high impact tsunamis and therefore, the primary concern while locating critical facilities is to leave a buffer zone.

Tsunamis were not considered a serious hazard along the Indian coasts until 2004, although we have archival information of such predecessors on both coasts. For India, the most important lesson to be learnt is regarding the safety of its nuclear plants located on its coastal regions. There are two known sources of tsunamis in our nearby waters: the Sumatra-Andaman and the Makran subduction zones. The Indian nuclear power plants are located sufficiently far from these sources and with the Indian Ocean Tsunami Warning System operational, timely shutdown is possible. However nuclear plants, currently operational or under construction in neighboring countries, located in the vicinity of tsunamigenic sources should be a concern[9]. The Fukushima experience is a reminder that the fallout of such events transcends political boundaries and the concerns are of a global nature. It also calls for a change in our approach to probabilistic risk assessment, incorporating newer inputs and benchmarks.

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ACKNOWLEDGEMENTS. We thank the Ministry of Earth Sciences, Government of India for the project for infrastructure and manpower development, which supports our research in seismology. Comments and inputs from Brian Atwater and Kenji Satake are thankfully acknowledged.

Kusala Rajendran*, Vanessa Andrade, N. Thulasiraman and **C. P. Rajendran,** Centre for Earth Sciences, Indian Institute of Science, Bangalore 560 012, India.
*e-mail: kusala@ceas.iisc.ernet.in

Uncovering the genetics of cancer

In 2007, researchers and funding agency representatives from 22 countries agreed to launch an international consortium to study cancer genomics. The International Cancer Genome Consortium (ICGC) has set out its bold plan to decode the genomes from 25,000 cancer samples and create a resource of freely available data that will help cancer researchers around the world. The ICGC published outlines of research design and projects as well as the important ethical framework for this task in April 2010 (ref. 1). In the beginning it was considered that generating comprehensive catalogues of human cancer mutations will require tremendous amount of work and collaboration over the coming years. But studies of breast, liver and pancreatic cancer have already generated datasets which are now available on the ICGC website. Sharing ideas, resources and data across scientific and clinical disciplines will help translate advances in knowledge, which will benefit the future generation of cancer patients.

Cancer incidence and deaths are rising worldwide. It is estimated that in 2007 over 12 million new cases were diagnosed across the planet and approximately 7.6 million cancer deaths occurred; these numbers will rise to an expected 27 million new cases and 17.5 million cancer deaths in 2050 (ref. 2), if our ability to prevent, diagnose and treat cancer does not improve.

Because genomic changes are often specific to a particular type or stage of cancer, systematically mapping the changes that occur in each cancer could provide the foundation for research to identify new therapies, diagnostics and preventive strategies[3]. Therefore, cancer