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The Mw 9.0 Tohoku-Kanto,Japan Earthquake of 10 March 2011

Paul Somerville and Tetsuya Okada, Risk Frontiers

The Mw 9.0 Tokoku-Kanto earthquake was a subduction earthquake off the east coast of Northern Japan that occurred at 05:46 UTC (14:46 local time) on 11 March 2011 (Figure 1). It was the largest recorded earthquake in Japan, and one of the five largest earthquakes in the world since modern record-keeping began. On July 13, 869 a magnitude 8.6 earthquake occurred in the same region off the coast of Iwate Prefecture destroying many homes, and the ensuing tsunami swept more than 1,000 people away.

The earthquake was preceded by a number of large foreshocks, beginning with a 7.2 Mw event on 9 March approximately 40 kilometers from the mainshock epicentre, followed by another three aftershocks of magnitude Mw larger than 6 on the same day. One minute before the earthquake was felt onshore, The JMA Earthquake Early Warning system provided early notification of impending strong ground motion, broadcast on NHK television, following detection of the event by seismic networks that include ocean bottom instruments. The JMA has warned that further strong aftershocks, with magnitudes of 7 or larger, are still expected to occur.

Over a longer time scale, the earthquake was preceded by the Mw 7.2 Iwate-Miyagi Nairiku Earthquake of June 14, 2008 as well as by a sequence of five damaging earthquakes further west in the Niigata Chuetsu region on the west coast of Japan, beginning with the Mw 6.6 earthquake of November 3, 2004 and culminating in the Mw 6.6 earthquake that occurred directly beneath the Kashiwazaki-Kariwa nuclear power station, the largest group of nuclear plants in Japan. The occurrence of these precursory earthquakes, consistent with previous seismicity in Japan, supports the hypothesis of Shimazaki (1984) that, as the stress builds up in preparation for large subduction earthquakes along the Pacific coast of Japan, earthquakes are triggered inland to the west of the subduction zone.

The earthquake occurred on the interface between the Pacific plate and the North American plate (Figures 2 and 3), and was caused by the subduction of the Pacific plate beneath the North American plate. The earthquake caused the Tohoku region of Japan to rebound 2.4 metres to the east. The rupture model of the earthquake (Figure 4) shows the distribution of slip on the plate interface. The part of the fault that had significant slip had a length of about 500 km and a width (down dip) of about 200 km. In the central part of the fault, the average displacement was about 7 metres and the largest displacement was about 15 metres.

The expected extent of fault ruptures on the plate interface off Tohoku identified by the Earthquake Research Committee (2006) is shown by the brown rectangle in the centre of Figure 5. The Tohoku-Kanto earthquake ruptured not only that segment but also several fault segments that lie south of this segment, off Kanto. Consequently, the magnitude of this earthquake was larger than the maximum magnitude that was expected to occur off northeastern Japan.

The earthquake caused strong ground shaking over a very wide region of northern Japan (Figure 7). Damage to buildings occurred as far south as Tokyo and Machida, about 50 km south of Tokyo. The recorded peak acceleration and peak velocity of the ground is generally lower than that predicted by current ground motion prediction models. Horizontal back and forth ground displacements as large as 1 metre were recorded in Tokyo (Figure 8), but these occurred over a period of about 30 seconds, resembling the motions of a ship at sea.

The ground motions shown in Figure 7 were below building code levels. It appears that most of the damage produced by the earthquake was caused by the tsunami, not by strong ground shaking. The ongoing emergencies at nuclear power plants, described below, appear to be attributable to the tsunami, not to ground shaking. The earthquake triggered tsunami warnings and evacuations from Japan's Pacific coast and at least 20 countries, including the entire Pacific coast of North America and South America. The earthquake generated tsunami waves up to 10 meters high that struck Japan and many other countries. In Japan, the waves travelled up to 10 kilometers inland. The predicted distribution of peak tsunami amplitudes in the Pacific Ocean is shown in Figure 9. The predicted peak shoreline amplitudes in western North America (Thio et al., 2011), shown in Figure 10, are in good agreement with measurements of one to two metres. The tsunami is estimated to have caused $50 million in damage in California.

There have been more than 1,600 reported deaths and as many injuries, and at least 10,000 people are missing in six prefectures. Large numbers of people remain unaccounted for in coastal towns such as Rikuzen Takada, Kasen Numa, Soma and Minami Sanriku; in the latter town, 9,500 people are unaccounted for. More than 12,000 people have been rescued, many by helicopter because of lack of access by other means.

The earthquake caused extensive damage in Japan, including heavy damage to roads and railways as well as fires in as many as 80 locations, including one in an oil refinery in Ichihara on the eastern shore of Tokyo Bay, and a dam collapsed in Fukushima Prefecture, washing away several houses. About 6 million households in northeastern Japan were left without electricity and 1.4 million without water.

Eleven nuclear reactors underwent automatic shutdown due to the detected ground shaking level. Tsunami inundation at the Fukushima I and II sites caused failure of the backup diesel generators that are needed to pump cooling water through the reactor cores after shutdown. Four of these were damaged, which prompted evacuation of the affected area, and a state of emergency was established. Unit 1 of Fukushima I Nuclear Power Plant experienced a hydrogen explosion outside the containment structure almost 24 hours after the initial earthquake. A day later, concern about a potentially similar event in Unit 3 developed. Approximately 200,000 residents within a 20-kilometer radius of the Fukushima I Nuclear Power Plant and a 10-kilometer radius of the Fukushima II Nuclear Power Plant were evacuated.

References

Earthquake Research Committee, 2005. Report: National Seismic Hazard Maps for Japan (2005). March 23, 2005 (in Japanese); March 31, 2006 (in English).

Shimazaki, K. (1978). Correlation between intraplate seismicity and interplate earthquakes in Tohoku, northeast Japan. Bull. Seism. Soc. Am. 68, 181-192.

Thio, Hong Kie, Paul Somerville and Jascha Polet (2011). A preliminary analysis of the far--field tsunami of the 2011/03/11 Sendai earthquake. Unpublished manuscript.

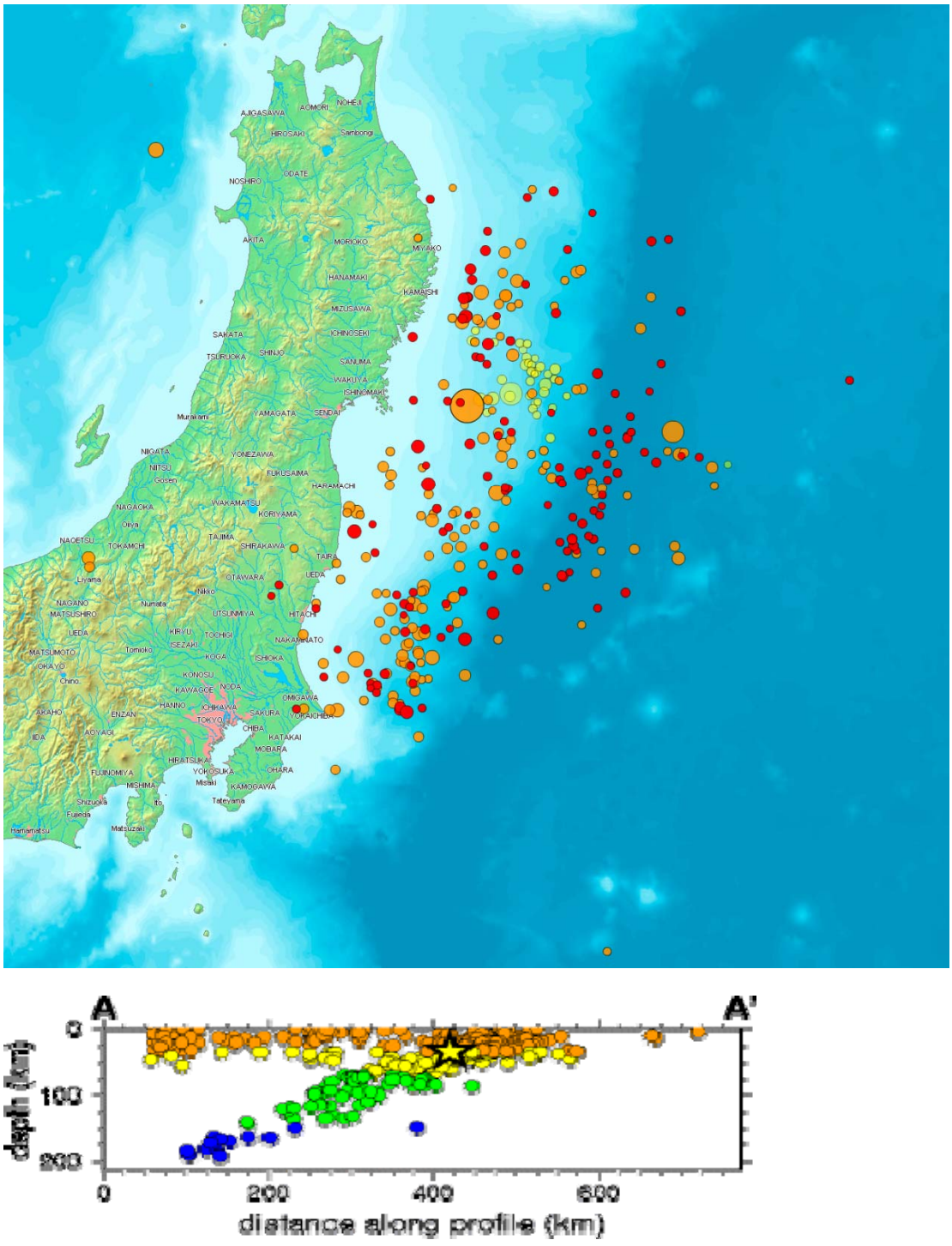


Figure 1. Top: map showing the locations of the mainshock (large orange circles) and aftershock (red dots). Bottom: West – East cross section across Tokoku showing the location of the hypocentre (yellow star). The green and blue circles are earthquakes that indicate the location of the subducting Pacific Plate. The plate interface on which the earthquake took place is located on the upper edge of that plate. On this interface, the Pacific Plate is subducting beneath the North American plate, indicated by the orange and yellow circles on the left side of the hypocentre. Source: USGS.

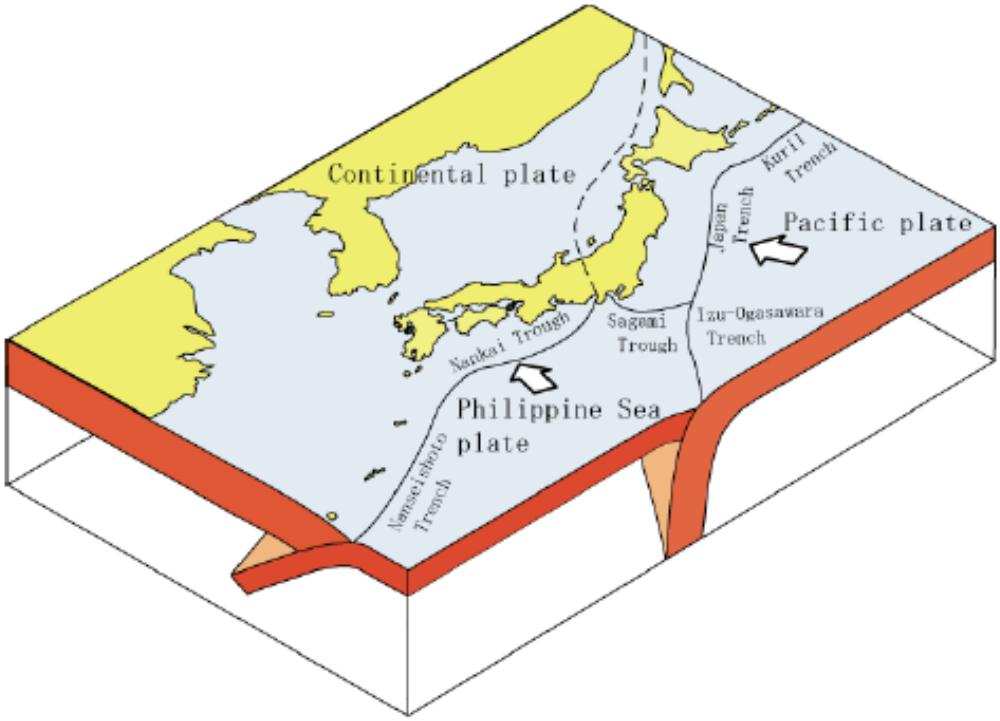


Figure 2. Locations of plates in and around Japan. Northern Japan is on the North American continental plate, and Western Japan is on the Eurasian continental plate. Source: ERC.

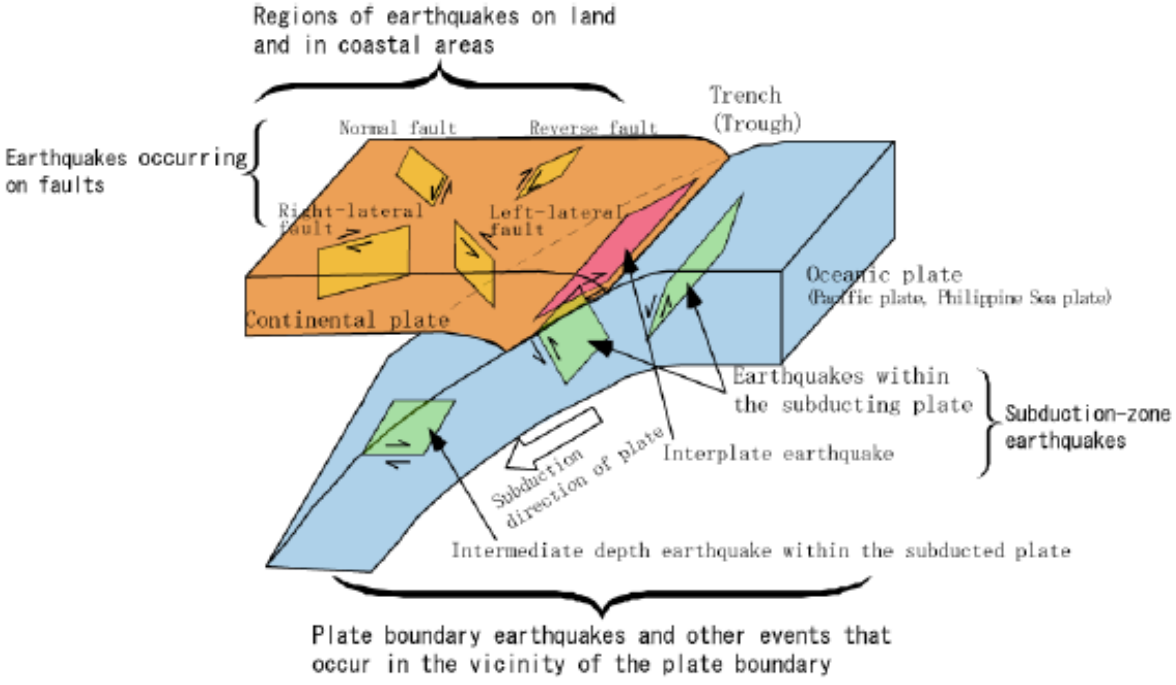


Figure 3. Different categories of earthquakes; the Tohoku-Kanto earthquake was a plate interface event (red). Source: ERC.

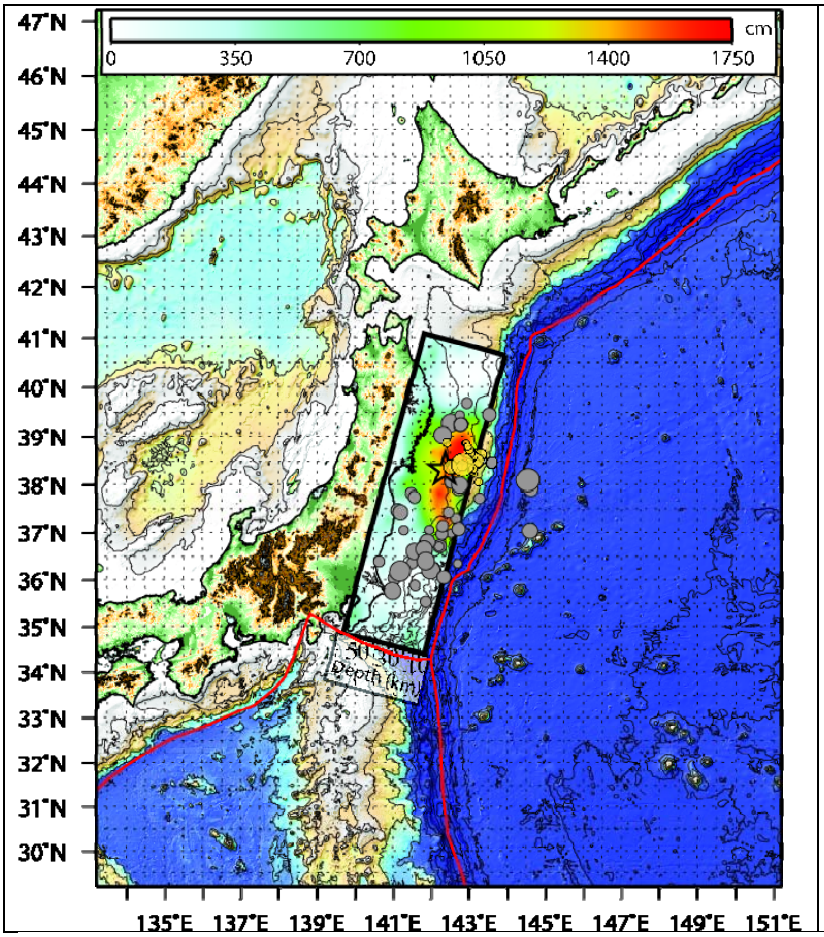


Figure 4. Slip map of the earthquake, with slip in metres indicated by the colour code at the top of the figure. The central part of the fault has a slip of about 7 metres (green), with two areas of about 15 metres of slip (red). Source: Gavin Hayes, USGS.

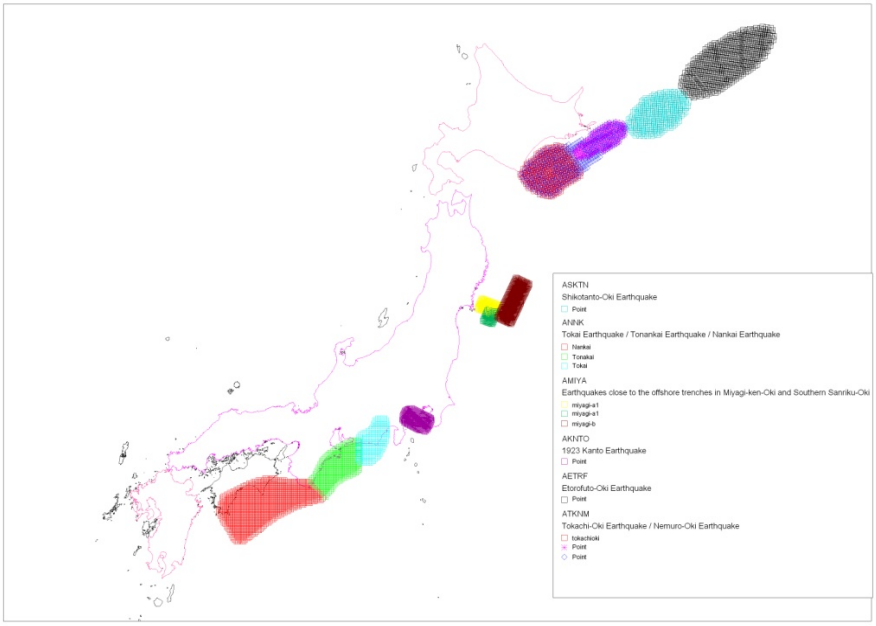
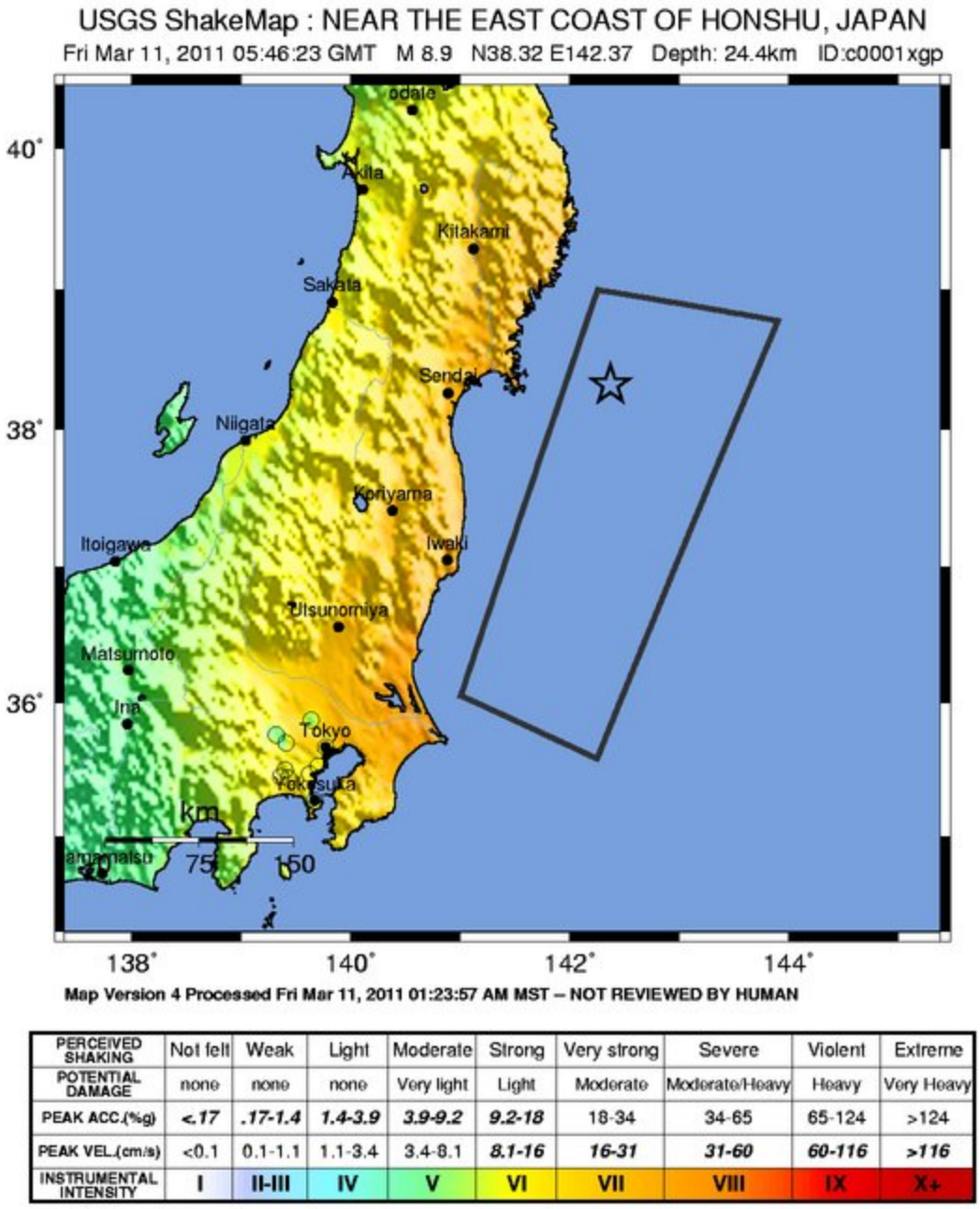


Figure 5. Location of major plate interface source zones; this earthquake was located on the Miyagi zone (brown rectangle at the centre of the map), but had a larger rupture zone. Source: ERC.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	*8.1-16*	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 6. Shakemap of the earthquake showing MMI intensity. The rectangle indicates the boundaries of the fault plane that ruptured, and the star is the epicenter. Source: USGS.

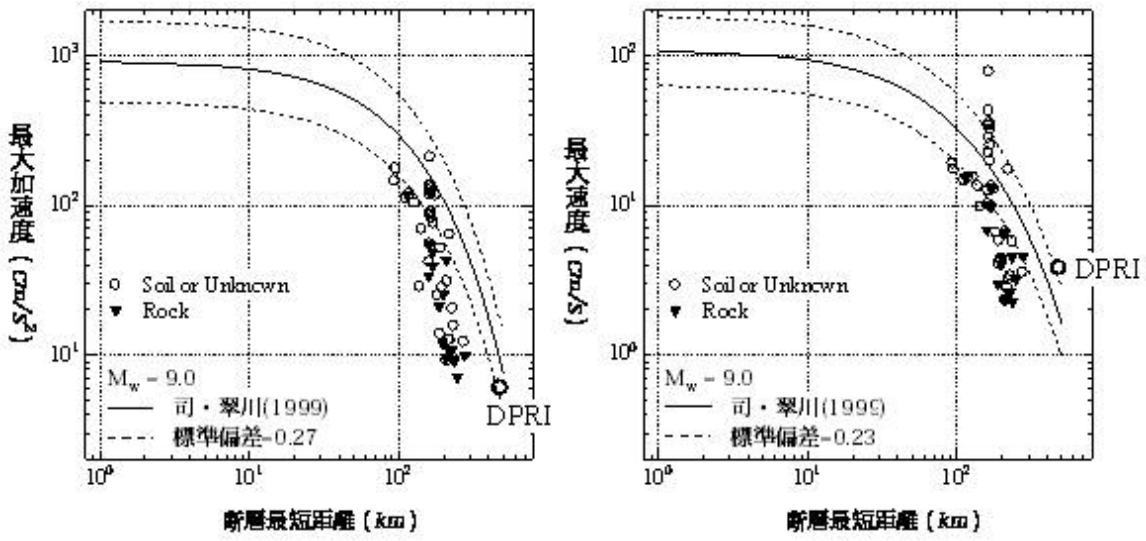


Figure 7. Attenuation of peak acceleration (left) and peak velocity (right) with closest distance (in km) to the fault (horizontal axis). The vertical axis on the left panel is in cm/sec squared; the values of 10^1, 10^2 and 10^3 correspond approximately to 0.01g, 0.1g, and 1 g acceleration respectively, where g is the acceleration of gravity. The vertical axis on the right panel is in cm/sec; the values of 10^1, 10^2 and 10^3 correspond approximately to 1, 10 and 100 cm/sec respectively. The data are from ERI and DRPI. Source: ERI.

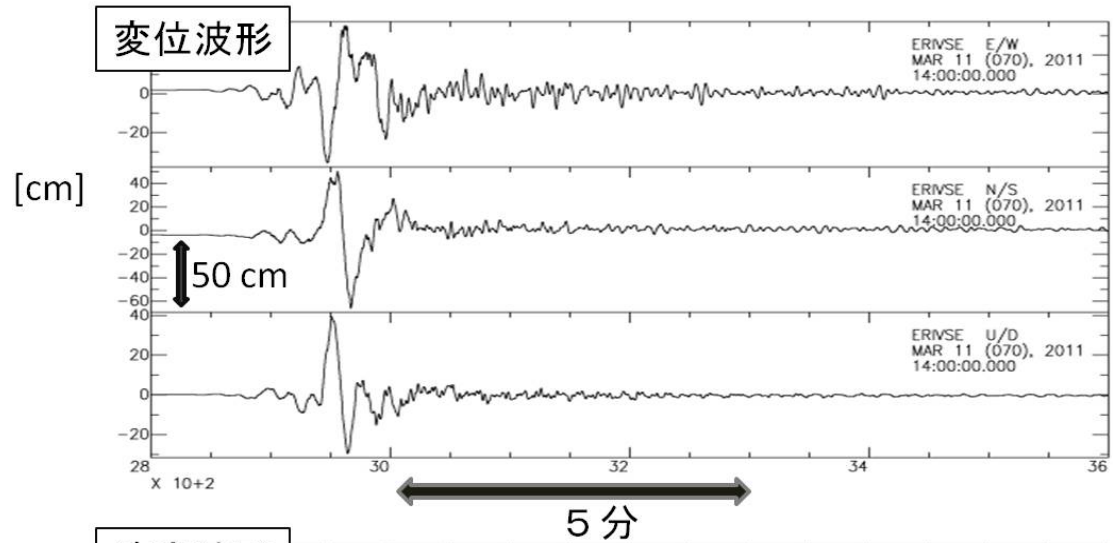


Figure 8. Recording of ground displacement at the Earthquake Research Institute, Tokyo University, in the east-west (top), north-south (centre), and vertical (bottom) directions. The vertical scale is cm and the horizontal scale is time, with the bold arrow indicating 5 minutes. The peak-to-trough ground motion in the north-south direction was 1 metre, and this motion occurred over period of 30 seconds. Source: ERI.

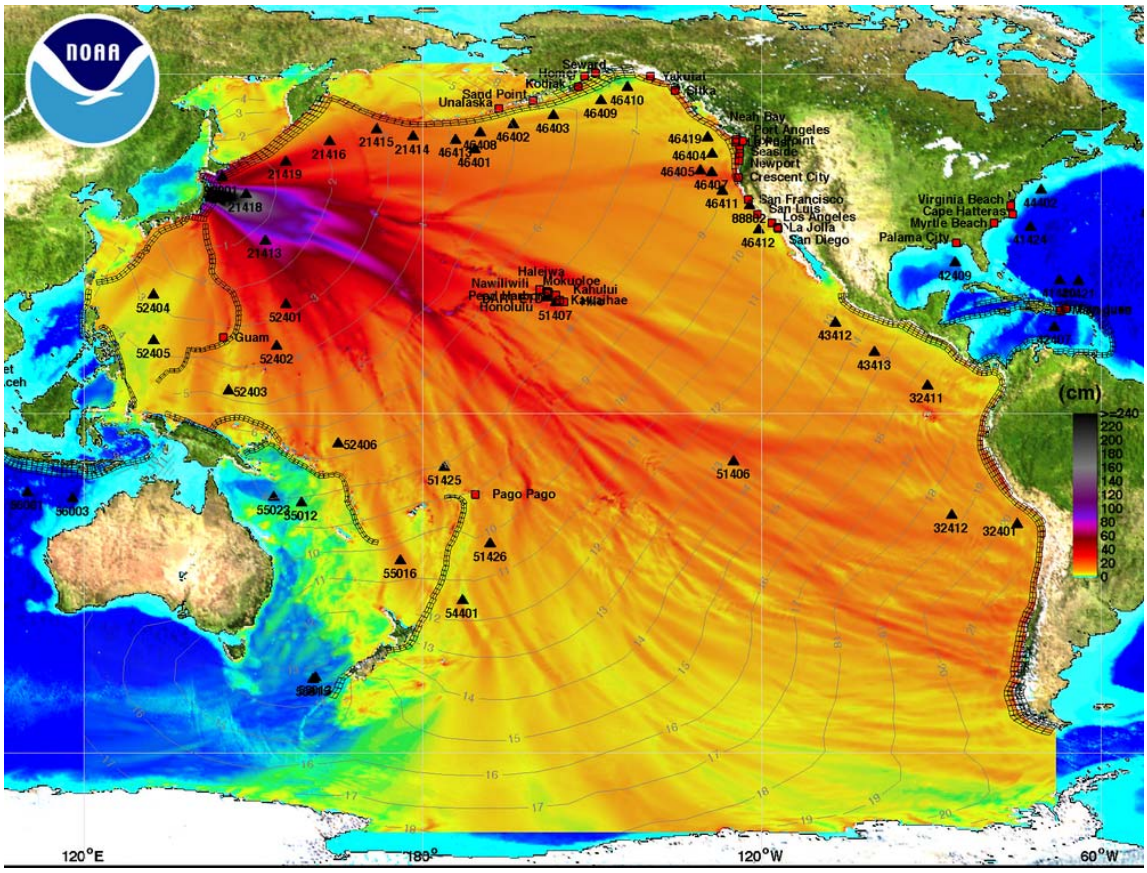


Figure 9. Predicted open ocean peak tsunami amplitude. Source: NOAA

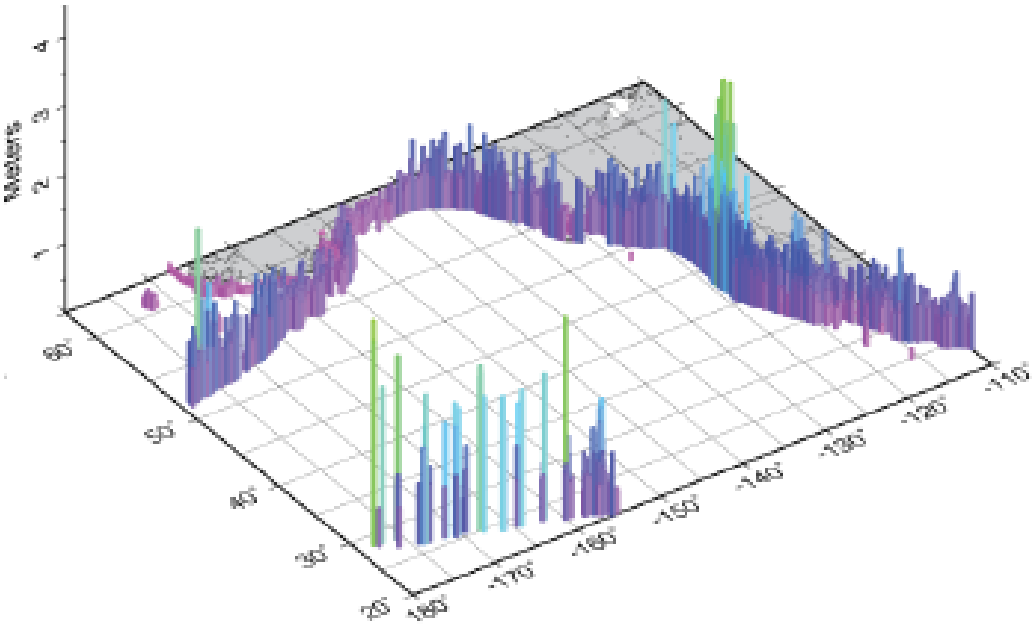


Figure 10. Predicted shoreline peak tsunami amplitudes in North America. Sourc