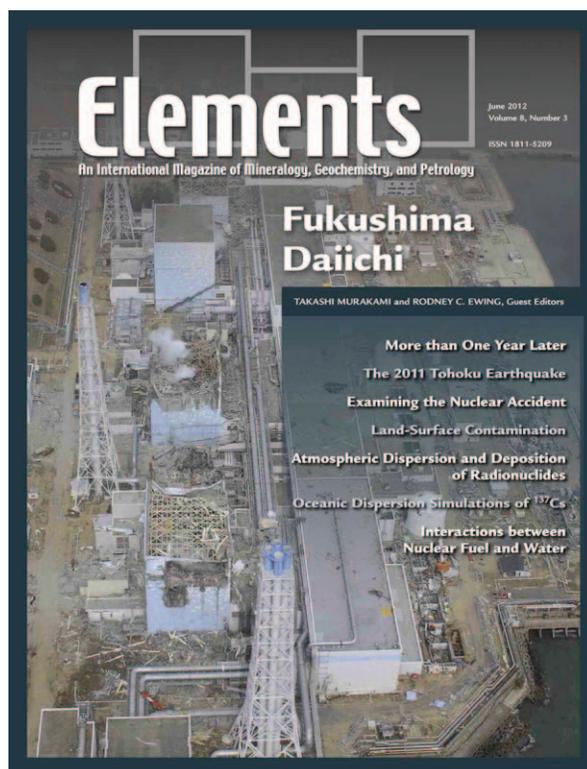


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The 2011 Tohoku Earthquake



The Tohoku earthquake in Iwate ©YOSHIYUKI KANEKO | DREAMSTIME.COM

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Rapid seismological analyses, carried out within minutes of the March 11, 2011, Tohoku earthquake, were crucial in providing an earthquake ground shaking and tsunami early warning and in hastening the evacuation of the population along Japan's northeastern coast. By 20 to 30 minutes after fault rupture began, these analyses had established that the event had a moment magnitude of $M_w = 9$ and involved shallow thrust faulting on the plate boundary megathrust. Preparation for future large earthquakes on megathrusts in Japan and elsewhere should include onshore and offshore geodetic monitoring of strain accumulation, implementation of rapid earthquake and tsunami warning systems, and public training and education for shaking and tsunami response.

KEYWORDS: Japan earthquake, megathrust, tsunami, earthquake early warning, rupture process

INTRODUCTION

The March 11, 2011, earthquake offshore from the Tohoku region of Japan ruptured a 300 km long by 200 km wide portion of the subduction zone megathrust fault at the boundary of the Pacific plate (Fig. 1). It was the fourth-largest recorded earthquake. The seafloor movement caused by the faulting generated a huge tsunami that devastated communities along the entire northeastern coast of Japan. Unprecedented video footage documented the imposing power of the ocean waves as they overtopped tsunami walls and coastal barriers, sweeping away entire towns. Flooding of the Fukushima Daiichi nuclear power plant led to a nuclear crisis that is still unfolding. The Tohoku earthquake and tsunami claimed some 20,000 lives. Many more lost their homes and livelihood, and economic losses are expected to reach \$300 billion.

While devastating, the Tohoku earthquake resulted in societal impacts and a scientific response that were much different from those of the 2004 Sumatra-Andaman earthquake. The Sumatra-Andaman earthquake had a moment magnitude, M_w , of 9.2 and was due to the rupture of the subduction zone megathrust in southeastern Asia. It generated a massive tsunami that struck Sumatra, Sri Lanka, India, and Thailand, taking over ten times more lives than the Tohoku tsunami. No country around the Indian Ocean

was prepared for such a large tsunami, and few warnings were issued, even for regions where the tsunami did not arrive until several hours after the earthquake. In contrast, seismological analysis of the 2011 Tohoku event commenced only seconds after the first ground vibrations were recorded at stations in Japan and around the world. While the rupture was still expanding (it took about 150 seconds for fault motions to complete), preliminary seismic wave analyses in an early warning system had established that a great earthquake of magnitude ~ 8 had occurred offshore from Honshu. Much of the well-

prepared population began to evacuate after the initial tsunami warnings were issued. Predictions of potential tsunami run-up height (the maximum onshore water height) along the coast ranged up to 6 m, much lower than the actual values of up to 40 m, but the early tsunami warning broadcasts likely saved many lives.

By the time the tsunami hit the shores of northern Honshu about 15–30 minutes after the faulting began, the earthquake size had been estimated at $M_w = 8.8$ by the National Oceanographic and Atmospheric Administration (NOAA) Pacific Tsunami Warning Center (PTWC) and $M_w = 9.0$ by the U.S. Geological Survey (USGS) National Earthquake Information Center (NEIC) from analysis of seismic recordings in the western Pacific region. The fault geometry solutions clearly indicated that the Tohoku earthquake had occurred on the plate boundary megathrust and that a potentially devastating tsunami had likely formed. On the basis of rapid earthquake quantification, the PTWC issued accurate warnings for Pacific nations to be alert for significant tsunami waves over the next 24 hours.

The rapid earthquake analyses in Japan were enabled by the substantial investments in infrastructure for earthquake monitoring that followed the destructive 1995 Kobe earthquake. An extensive network of recently deployed geophysical instruments recorded the Tohoku earthquake both onshore and offshore. This network includes 1200 continuously recording GPS sensors in Japan (Sagiya et al. 2000; Ozawa et al. 2011), several dozen tide gauges and seafloor pressure sensors around Japan (Sato et al. 2011), NOAA's DART buoy network in the Pacific (expanded after the 2004 tsunami), and thousands of seismometers in regional and global seismic networks. Near real-time telemetry of the seismic and ocean-wave data was essential for the rapid determination of the location and magnitude of the Tohoku earthquake and for direct measurements of the

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tsunami amplitudes near Japan and across the Pacific. Indeed, the Tohoku earthquake is by far the best scientifically recorded great earthquake to date, and it will be the best studied. A number of expert reports and over 100 reviewed scientific publications on the Tohoku earthquake have already appeared in major journals, including special issues of *Earth, Planets and Space* and *Geophysical Research Letters*.

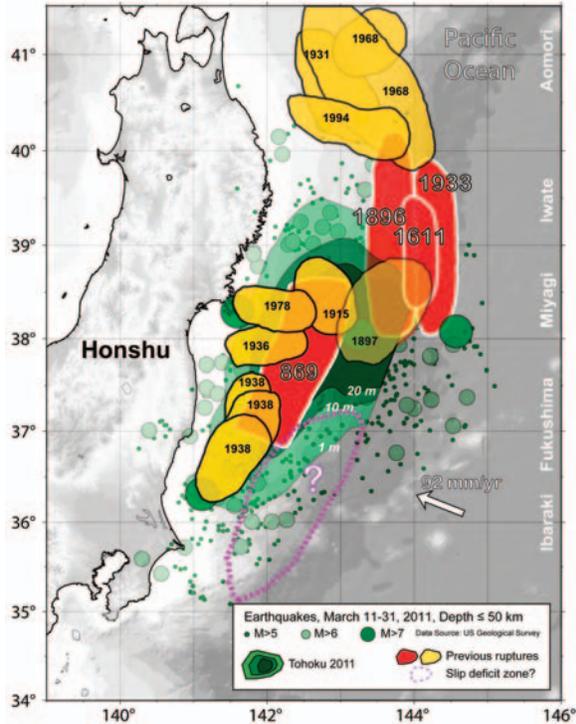


FIGURE 1 Map of the 2011 Tohoku earthquake region. The map shows aftershocks from the NEIC catalog, with depth less than 50 km, that occurred between March 11, 2011, and March 31, 2011. The three green contours indicate the 2011 rupture zone, with fault slip exceeding 1 m, 10 m, and 20 m, respectively (Yue and Lay 2011). The yellow and red patches indicate rupture zones related to previous large earthquakes. There is uncertain earthquake potential in the region outlined by purple dots (the possible “slip deficit zone”). The arrow indicates the direction of movement of the Pacific plate. Prefecture names are shown along the right side of the map, opposite their actual locations. M = magnitude

GEOPHYSICAL INVESTIGATIONS OF THE TOHOKU EARTHQUAKE

Analyses of the Tohoku earthquake had two key stages: (1) near real-time analysis of seismograms for first-order earthquake parameters and (2) integrated investigations of all geophysical recordings of the Tohoku earthquake and tsunami, foreshock and aftershock sequences, and field reconnaissance of ground shaking and tsunami impacts.

Real-Time Analysis and Earthquake Warning

Rapid seismic analysis is primarily based on automated procedures that estimate the location of rupture initiation, the earthquake magnitude, and the faulting mechanism. The near real-time processing of information evolves as the rupture grows, and frequent revisions are made as recordings lengthen and new seismic data become available. Very rapid analysis of the earliest seismic arrivals is crucial for immediate response to strong ground shaking and tsunami danger.

Several agencies conduct seismological analysis to report earthquake epicenters, depths, and magnitudes in near real-time. In Japan, earthquake early warning (EEW) is one of the main responsibilities of the Japan Meteorological Agency (JMA). The aim of EEW is to rapidly locate earthquakes and estimate magnitudes using 1100 stations in the JMA seismic network and stations from the Hi-net network of the Japan National Research Institute for Earth Science and Disaster Prevention. On the basis of the analysis, the JMA is mandated to warn the public of the potential for strong ground shaking and tsunami.

The USGS NEIC is mandated to rapidly evaluate all significant global earthquakes (Hayes et al. 2011). The PTWC is responsible for issuing tsunami warnings after major earthquakes have occurred in the Pacific Ocean. Coordination among the JMA, PTWC, and NEIC is intended to ensure that consistent information is released to emergency responders. A timeline of the response to the Tohoku earthquake by these agencies is summarized in TABLE 1.

Hoshiya et al. (2011) and Ozaki (2011) describe the EEW sequence following the Tohoku earthquake. The EEW system was triggered at 14:46:40.2 Japan Standard Time when the primary (P) wave was recorded by the closest seismograph. Fifteen “forecasts” followed with updated information. After 5.4 seconds, the magnitude was estimated to be only 4.3, which is consistent with later determinations that the Tohoku earthquake began as a small, magnitude 4.9 earthquake (Chu et al. 2011). About 8 seconds after the trigger, the magnitude was updated to 7.2, and seismic intensity was predicted to be “5-lower” for the central Miyagi prefecture. In the fifteenth update, 116.8 seconds after the trigger, the EEW magnitude was estimated to be 8.1. This magnitude is at the upper limit of the JMA EEW magnitude scale because the short-period seismic instrumentation that the JMA relies on had gone off-scale. Nevertheless, within two minutes after the main trigger, it was clear that a major earthquake had occurred off the Pacific coast of Tohoku. Intensities of “6-upper” and “6-lower,” which are equivalent to ground accelerations of

TABLE 1 THE FIRST HOUR

Time after detection	Source	Magnitude	Remarks
5.4 sec	JMA/EEW	4.3	The first estimate
8.6 sec	JMA/EEW	7.2	
116.8 sec	JMA/EEW	8.1	Final update and tsunami bulletin
2½ min	JMA (M_f)	7.9	The rapid JMA magnitude
9 min	PTWC	8.1	First tsunami bulletin
19 min	NEIC	7.9	Coordinated with JMA and PTWC
20 min	NEIC W-phase	9.0	Internal release only, limited data
22 min	PTWC W-phase	8.8	First internal release; assumed event depth of 84 km
33 min	rCMT (Polet and Thio 2011)	9.0	Internal release only
38 min	NEIC/PTWC	8.8	Coordinated update, public release
62 min	NEIC W-phase	8.9	Final automatic solution

JMA = Japan Meteorological Agency, EEW = earthquake early warning, PTWC = Pacific Tsunami Warning Centre, NEIC = National Earthquake Information Center, rCMT = rapid centroid-moment tensor

0.25–0.40 g, were observed over a $400 \times 100 \text{ km}^2$ area in the Tohoku and Kanto districts. The JMA warned of possible tsunami with run-up heights of 6 m in Miyagi and 3 m in Fukushima and Iwate prefectures. Due to the high background noise from scattered waves and numerous aftershocks, the EEW system did not perform well for the next several hours.

Accurate estimates of long-period seismic magnitude and characterization of overall earthquake faulting require analysis of on-scale ground-motion recordings with relatively low-frequency content. Several agencies and universities routinely analyze the magnitude and faulting mechanisms of global earthquakes using seismograms from the Federation of Digital Seismic Networks, which includes the NSF/USGS Global Seismic Network real-time data openly available online from the Incorporated Research Institutions for Seismology data center. A variety of waveform analyses are routinely conducted for all earthquakes larger than M_w 5.0. Many of these analyses involve variations of the centroid-moment tensor (CMT) method developed in the early 1980s (Dziewonski et al. 1981) and differ primarily in the types of waveform data that are analyzed.

The CMT method relies on an initial estimate of the earthquake origin time, location, and depth obtained from, for example, the NEIC, PTWC, or JMA. The CMT analysis yields a point-source moment tensor. Moment tensor solutions for most earthquakes (including the solution for the Tohoku earthquake) are consistent with “double-couple faulting” in which the earthquake represents shear sliding along a planar fault. The moment tensor indicates the orientation of the fault and the strength and direction of shearing motion on the fault. The Tohoku moment tensor solution (Fig. 2) is consistent with slip on the interface between the subducting Pacific plate and the Okhotsk plate. The size of the earthquake is quantified by the seismic moment, M_0 , and the moment magnitude, M_w [$M_w = 2/3 (\log_{10} M_0 - 9.1)$]. The seismic moment, M_0 , of the Tohoku earthquake is estimated to be $4.3 \times 10^{22} \text{ N}\cdot\text{m}$ (newton meter), which gives $M_w = 9.0$. The seismic moment is indicative of the spatial extent and the amount of slip on the fault plane (and hence the deformation of the seafloor).

The most rapidly produced long-period solution for the 2011 Japan event was based on analysis of the W phase (Fig. 3), the earliest very long-period signal in a seismogram (Kanamori 1993). Typically, the W phase has lower amplitude than the later surface-wave signals, but it is well recorded for moderate and large ($M_w > 6.5$) earthquakes. W phase analysis is particularly suited for rapid determination of the earthquake moment tensor because only a few minutes of recording are needed. Moreover, the analysis can be conducted automatically because the propagation of the W phase is accurately modeled using standard seismic models (Kanamori and Rivera 2008).

Automated W phase analysis was running at three institutions: (1) the USGS NEIC, (2) the NOAA PTWC, and (3) the Institut de Physique du Globe de Strasbourg. A robust W phase moment tensor for the Tohoku earthquake was computed 22 minutes after the earthquake origin time using the initial PTWC earthquake depth estimate and waveform data for 29 channels (Duputel et al. 2011) (TABLE 1). This solution provided an estimate of the moment magnitude, $M_w = 8.8$. This was upgraded to $M_w = 9.0$ after the source depth estimate was revised from 84 km to 24 km and additional waveform channels became available.

Other rapidly available long-period solutions include the rCMT solution (Polet and Thio 2011), which was determined 33 minutes after the Tohoku earthquake and was

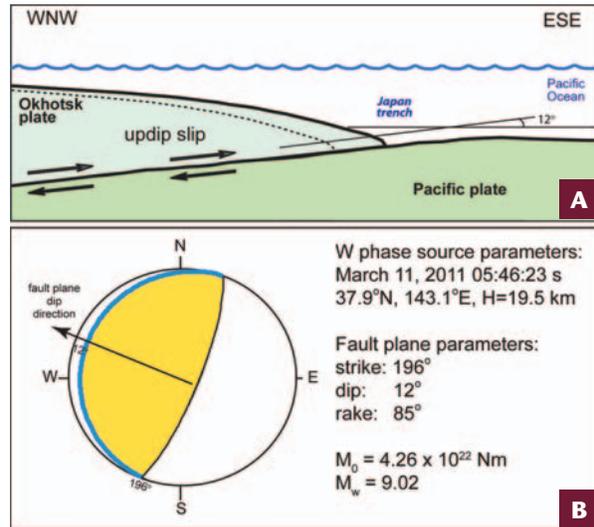


FIGURE 2 (A) Sketch of the Japan–Pacific subduction zone and the relative up-dip motion of the Okhotsk plate (in which Japan is located) over the Pacific plate along a plate-boundary fault plane (the megathrust) dipping $\sim 12^\circ$ to the WNW. Note that the sketch is not to scale. Maximum slip near the Japan trench was about 40–60 m, and the rupture extended down-dip about 200 km. Towards the west, the dip angle of the subducting Pacific plate increases; the fault is about 50 km deep beneath the coast of Japan. The dotted line indicates the pre-earthquake, flexed position of the upper plate, which abruptly shifted eastward and upward during the earthquake to its final position. The displacement of ocean water generated the tsunami that spread away from the region of ocean uplift. (B) Source mechanism from the W phase analysis. The “beachball” graph on the left is a lower-hemisphere projection of the compressional (yellow) and tensional (white) quadrants of the focal sphere. The blue line corresponds to the megathrust fault plane, which strikes at 196° and dips to the WNW at an angle of 12° .

based on the analysis of slightly longer segments of long-period seismograms. The Global CMT (gCMT) solution (www.globalcmt.org) was published after analysis of 9-hour-long recordings of multiple-orbit surface waves.

The long-period seismic wave solutions indicated that the Tohoku earthquake was a thrust earthquake at shallow depth, with $M_w = 8.8$ to 9.1. Differences in estimated moment magnitude are due to differences in the types of seismic signals analyzed, the assumed earthquake depth, and estimates of the fault dip angle (Kanamori and Given 1981). Nevertheless, all solutions are consistent with the very first W phase solution, which had clearly established the potential for a large tsunami.

Spatial Extent and Complexity of the Tohoku Earthquake Rupture

In the days and weeks following the earthquake, geophysicists further used a variety of available data to develop models of space–time slip on the fault plane that could be compared to previous large earthquakes in the region. This type of detailed earthquake rupture analysis advances our understanding of earthquake processes and the influence of prior ruptures. This contributes to the long-term assessment of the earthquake hazard in northeastern Japan and to preparations for future large events.

Finite-fault analysis resolves the spatial extent of the earthquake rupture and the variable slip distribution on the fault plane. Rapid analysis of finite faulting using seismic and geodetic data is now common and was applied by several groups to the Tohoku event (e.g. Hayes 2011; Lay et al. 2011; Shao et al. 2011; Simons et al. 2011). Quickly determined solutions are usually rather variable from

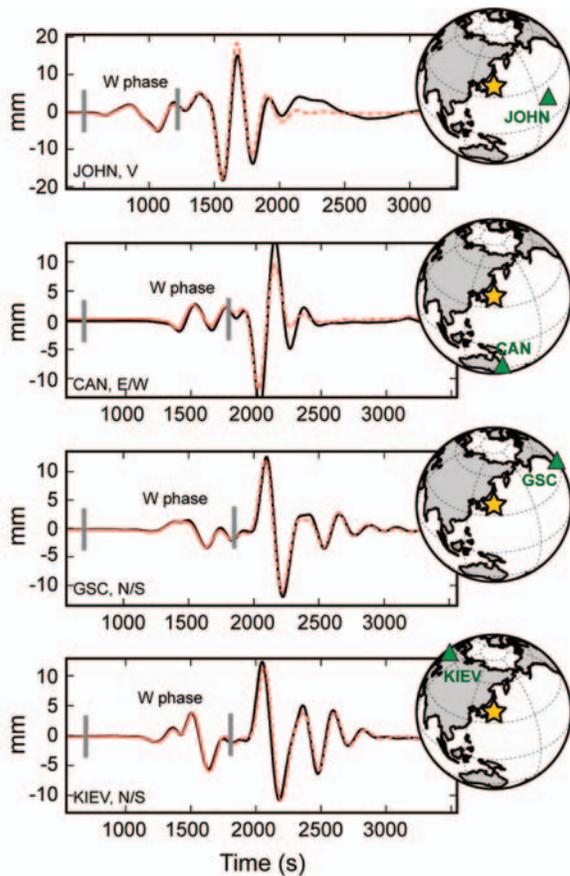


FIGURE 3 Examples of well-matching recorded (black) and predicted (red) W phase signals for the optimal source mechanism at stations JOHN (Johnston Island, USA), CAN (Canberra, Australia), GSC (Goldstone, USA), and KIEV (Kiev, Ukraine). The signals are filtered between 1 and 5 mHz. The analysis is applied to the W phase, which is the waveform segment between the vertical bars. Subsequent arrivals (surface waves) are also matched well. Station locations (triangles) are indicated on the globes, shown on the right, with the star indicating the Tohoku epicenter.

model to model, as they depend on data coverage and modeling assumptions, and it often takes some time for a consensus to develop on the best representation of the rupture process of a great earthquake.

The main characteristics of the Tohoku rupture are now similar in most published finite-source models (Fig. 4). The rupture duration was about 150 s, which is relatively short for an M_w 9 earthquake. The earthquake nucleated offshore from the Miyagi-oki area and involved large slip in the up-dip region near the trench and smaller slip in the regions offshore from Fukushima, Ibaraki, and Sanriku. Slip exceeded 1 m over a $300 \times 200 \text{ km}^2$ region of the fault plane, with average values of 15–20 m. The largest slip is estimated to be 40–60 m, by far the largest earthquake slip ever reported.

The slip on the fault plane was variable and accompanied by differences in seismic radiation. Koper et al. (2011) showed that high-frequency seismic waves were generated in a region down-dip from the epicenter. Little-coherent, short-period radiation came from the regions of largest slip near the trench. The slip-distribution maps in FIGURE 4 provide a good match to the seismic, geodetic, and tsunami data. In particular, large, shallow slip near the trench is required by the arrival time and narrow pulse of the tsunami at nearby deep-ocean pressure sensors (Fujii et al. 2011; Yamazaki et al. 2011) and by the timing of the onset

of ground deformation in Japan as recorded by high-resolution GPS recordings (Yue and Lay 2011). The models also can account for large seafloor offsets measured by several independent procedures. Koketsu et al. (2011) demonstrate how many seismic and geodetic data can now be reconciled with similar models.

PERSPECTIVES

Although Japan has a long and well-documented history of large earthquakes and tsunamis, the 2011 Tohoku earthquake was much larger than any known earthquake during the past 1100 years. Given the lack of historical earthquakes of this size, the M_w 9 Tohoku earthquake caught most seismologists by surprise.

Earthquakes offshore from Honshu during the past century had estimated seismic magnitudes lower than 8.5 (Fig. 1). Among the largest earthquakes in the northern part of Japan are the 1968 Tokachi-oki (off the Tokachi coast) and 1994 Sanriku-Haruka-oki earthquakes. Off the Sanriku coast, the largest earthquakes occurred in 1896 and 1933 (Fig. 1). The 1896 Meiji-Sanriku earthquake (magnitude 8.2–8.5) was a thrust-faulting event at the northern end of the Tohoku earthquake zone that ruptured the shallow portion of the plate interface (Tanioka and Satake 1996). This was a “tsunami” earthquake according to the definition of Kanamori (1972), with strong tsunami generation as compared with the surface-wave seismic magnitude. The 1933 earthquake (magnitude ~8.3) involved extensional faulting in the bending oceanic lithosphere (Kanamori 1971). An earlier, large, tsunami-generating event, the 1611 Keicho earthquake, has poorly constrained magnitude and location, but appears to have been near the 1933 event.

Before the Tohoku earthquake, the seismic risk in Japan had been perceived as highest in the off-coast region of Miyagi, south of Sanriku. Here, a number of earthquakes with a magnitude of 7 or greater occurred in 1933, 1936, 1978, and 2005. The March 9, 2011, foreshock of the Tohoku earthquake occurred seaward of this zone. The roughly 30–40-year intervals separating these earthquakes formed the basis for the proposed relatively high seismic risk in the region, although it is not clear that these earthquakes are repeating events (Kanamori et al. 2006). The 869 Jogan earthquake is the oldest and largest earthquake in the region. It left a record of tsunami deposits on the Sendai Plain (Abe et al. 1990; Minoura et al. 2001; Sawai et al. 2008). Numerical simulations of tsunami run-up and inundation suggest that the 869 event had a magnitude of ~8.5 and that it was located up-dip from the Miyagi-oki events, but possibly not extending all the way to the trench (Satake et al. 2008). Known earthquakes with magnitudes between 7.1 and 7.8 that occurred in 1938 offshore from Fukushima and Ibaraki prefectures were studied by Abe (1977). There is no tsunami or seismic record of earthquakes in the region prior to the 1938 sequence.

The Tohoku earthquake ruptured across almost the entire width of the plate boundary megathrust, and the rupture extended from north of the Miyagi-oki ruptures to south of the Fukushima-oki region that ruptured in 1938 (Fig. 1). The rupture encompassed the likely area of the 869 event, but extended to the trench with large slip, similar to the 1896 rupture to the north. Thus it appears that the 2011 Tohoku event broke several adjacent portions of the megathrust that had previously failed in more localized ruptures (Lay and Kanamori 2011).

The study of older earthquakes off Honshu is primarily based on analyses of tsunami records and deposits. Such analyses are uncertain and have tended to play a secondary

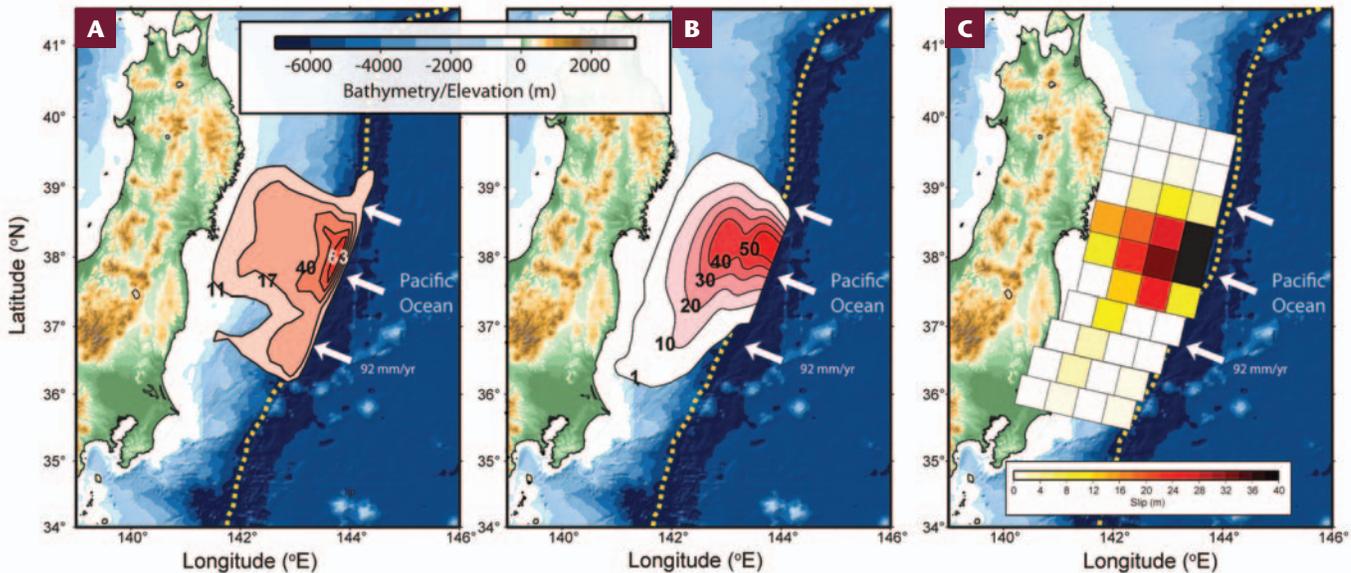


FIGURE 4 Maps of the total amount of slip on the fault plane (projected vertically on the surface) derived from the analysis of (A) teleseismic broadband P waves (Lay et al. 2011), (B) high-rate GPS waveforms in Japan (Yue and Lay 2011), and

(C) regional tsunami height observations (Fujii et al. 2011). The dotted line is the Japan trench. The numbered contours indicate the amount of slip in meters. The arrows indicate the direction of movement of the subducting Pacific plate.

role in assessing the seismic risk in the region. Nevertheless, tsunami heights related to previous large earthquakes provided valuable guidance on the potential inundation and tsunami height of the Tohoku earthquake (Mori et al. 2011; EERI 2011), although the high run-up of the Tohoku tsunami had a much wider spread (Fig. 5). The maximum run-up height of the Tohoku tsunami was 39.7 m at Miyako. The historical records of maximum run-up height are 38.2 m for the 1896 Meiji Sanriku tsunami and 28.7 m for the 1933 Showa Sanriku tsunami. Deposits of the Keicho tsunami of 1611 have mostly been erased by human activity, but Hatori (1975) suggested that 6 to 8 m high tsunamis devastated the Sendai Plain and northern Fukushima areas. Tsunami deposits in the Sendai Plain associated with the 869 Jogan earthquake extend 1–3 km inland (1 km from the present coast) (Abe et al. 1990; Minoura et al. 2001).

There is no evidence that large earthquakes had occurred prior to 1938 along the Japan Trench east of Fukushima and Ibaraki prefectures. This region slipped in 2011, but probably less than 10 m or so. Allowing for 8 cm/year of convergence, there could be a significant “slip deficit” in this region if no other earthquakes occurred in the past 1000 years (Fig. 1). There is thus some concern for another large event in the future. The potential for this depends on the nature of strain accumulation in the region. While Japan has an extensive network of GPS ground-motion instruments, and these revealed that strain was accumulating in the mainland in Fukushima, but less so near Boso to the south (e.g. Suwa et al. 2006; Hashimoto et al. 2009), it is unclear whether there is still earthquake potential in this region. Japan has led the world in developing technology to monitor offshore deformation, and this will be particularly valuable for assessing the nature of strain accumulation along the megathrust south of the region of large slip in 2011. This is a costly and technically challenging endeavor. However, the important observations of seafloor deformation after the Tohoku earthquake in the Miyagi region (Sato et al. 2011) motivate long-term data acquisition, as these would have helped to recognize the potential for an earthquake as large as the Tohoku event.

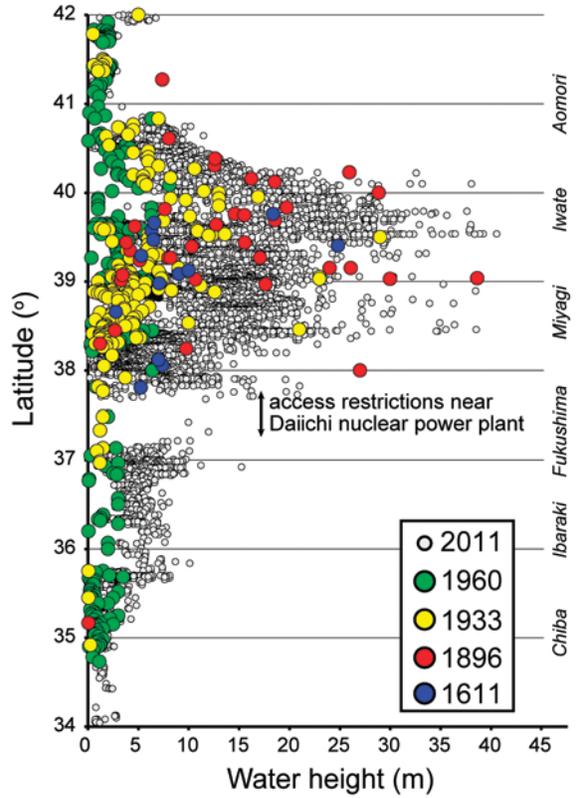


FIGURE 5 Tsunami run-up heights for the 2011 Tohoku (grey); 1960 Chile (green); and 1933 (yellow), 1896 (red), and 1611 (blue) Sanriku earthquakes as a function of latitude along Japan’s northeastern coast. Run-up measurements for the Tohoku tsunami were not available in the 30 km long restricted area around the Daiichi nuclear power plant, but direct observations indicate a 15 m run-up at the site. The names of prefectures are shown on the right.

Earthquake risk assessment is notoriously complicated because only a very short earthquake record is available. The Tohoku earthquake experience shows how difficult it is to anticipate infrequent, catastrophic events based on a short recorded history. However, the event also

demonstrated the value of efforts to mitigate the effects of earthquake shaking and tsunami; the high construction standards in Japan appear to have limited loss from shaking, and while the tsunami overtopped many tsunami walls, rapid warning and public preparation for response reduced the loss of lives, as compared with the 2004 Sumatra earthquake. The most promising technological approach is to extend rapid warning and faulting-quantification procedures, exploiting both onshore and, ideally, offshore measurements of ground motion to develop more precise early estimates of faulting displacements and tsunami heights. Duputel et al. (2011) have demonstrated

that a stable magnitude and fault-plane solution can be determined by W phase inversion within 7 minutes after the earthquake origin time using regional broadband seismic and geodetic signals. Widespread use of the most advanced capabilities to monitor the plate interface, with real-time analysis of the data, can certainly speed up robust tsunami warnings. To save lives, this technological capability needs to be coupled to emergency-response procedures and to societal awareness and preparation. Japan has learned this lesson; the rest of the world should do so as well. ■

REFERENCES

- Abe K (1977) Tectonic implications of the large Shioya-oki earthquakes of 1938. *Tectonophysics* 41: 269-289
- Abe H, Sugeno Y, Chigama A (1990) Estimation of the height of the Sanriku Jogan 11 earthquake-tsunami (A.D. 869) in the Sendai Plain. *Journal of the Seismological Society of Japan (Zishin)* 43: 513-525
- Chu R, Wei S, Helmberger DV, Zhan Z, Zhu L, Kanamori H (2011) Initiation of the great M_w 9.0 Tohoku-Oki earthquake. *Earth and Planetary Science Letters* 308: 277-283
- Duputel Z, Rivera L, Kanamori H, Hayes GP, Hirshorn B, Weinstein S (2011) Real-time W phase inversion during the 2011 off the Pacific coast of Tohoku Earthquake. *Earth, Planets and Space* 63: 535-539
- Dziewonski AM, Chou T, Woodhouse JH (1981) Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *Journal of Geophysical Research* 86: 2825-2852
- ERI (2011) The Japan Tohoku tsunami of March 11, 2011. Special Earthquake Report November 2011. Earthquake Engineering Research Institute
- Fujii Y, Satake K, Sakai S, Shinohara M, Kanazawa T (2011) Tsunami source of the 2011 off the Pacific coast of Tohoku Earthquake. *Earth, Planets and Space* 63: 815-820
- Hashimoto C, Noda A, Sagiya T, Matsu'ura M (2009) Interplate seismogenic zones along the Kuril-Japan trench inferred from GPS data inversion. *Nature Geoscience* 2: 141-144
- Hatori T (1975) Scales and source areas of Sanriku-oki historical earthquakes. *Bulletin of the Earthquake Research Institute* 50: 397-414
- Hayes GP (2011) Rapid source characterization of the 2011 M_w 9.0 off the Pacific coast of Tohoku Earthquake. *Earth, Planets and Space* 63: 529-534
- Hayes GP, Earle PS, Benz HM, Wald DJ, Briggs RW, USGS/NEIC Earthquake Response Team (2011) 88 hours: The U.S. Geological Survey National Earthquake Information Center response to the 11 March 2011 M_w 9.0 Tohoku earthquake. *Seismological Research Letters* 82: 481-493
- Hoshihara M, Iwakiri K, Hayashimoto N, Shimoyama T, Hirano K, Yamada Y, Ishigaki Y, Kikuta H (2011) Outline of the 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0)—Earthquake Early Warning and observed seismic intensity. *Earth, Planets and Space* 63: 547-551
- Kanamori H (1971) Seismological evidence for a lithospheric normal faulting; the Sanriku earthquake of 1933. *Physics of the Earth and Planetary Interiors* 4: 289-300
- Kanamori H (1972) Mechanism of tsunami earthquakes. *Physics of the Earth and Planetary Interiors* 6: 346-359
- Kanamori H (1993) W phase. *Geophysical Research Letters* 20: 1691-1694
- Kanamori H, Given JW (1981) Use of long-period surface waves for rapid determination of earthquake-source parameters. *Physics of the Earth and Planetary Interiors* 27: 8-31
- Kanamori H, Rivera L (2008) Source inversion of W phase: speeding up tsunami warning. *Geophysical Journal International* 175: 222-238
- Kanamori H, Miyazawa M, Mori J (2006) Investigation of the earthquake sequence off Miyagi prefecture with historical seismograms. *Earth, Planets and Space* 58: 1533-1541
- Koketsu K and 10 coauthors (2011) A unified source model for the 2011 Tohoku earthquake. *Earth and Planetary Science Letters* 310: 480-487
- Koper KD, Hutko AR, Lay T, Ammon CJ, Kanamori H (2011) Frequency-dependent rupture process of the 2011 M_w 9.0 Tohoku Earthquake: Comparison of short-period P wave backprojection images and broadband seismic rupture models. *Earth, Planets and Space* 63: 599-602
- Lay T, Kanamori H (2011) Insights from the great 2011 Japan earthquake. *Physics Today* 64(12): 33-39
- Lay T, Ammon CJ, Kanamori H, Xue L, Kim MJ (2011) Possible large near-trench slip during the 2011 M_w 9.0 off the Pacific coast of Tohoku Earthquake. *Earth, Planets and Space* 63: 687-692
- Minoura K, Imamura F, Sugawara D, Kono Y, Iwashita T (2001) The 869 Jogan tsunami deposit and recurrence interval of large-scale tsunami on the Pacific coast of northeast Japan. *Journal of Natural Disaster Science*: 23: 83-88
- Mori N, Takahashi T, Yasuda T, Yanagisawa H (2011) Survey of 2011 Tohoku earthquake tsunami inundation and run-up. *Geophysical Research Letters* 38: doi:10.1029/2011GL049210
- Ozaki T (2011) Outline of the 2011 off the Pacific coast of Tohoku Earthquake (M_w 9.0)—Tsunami warnings/advisories and observations. *Earth, Planets and Space* 63: 827-830
- Ozawa S, Nishimura T, Suito H, Kobayashi T, Tobita M, Imakiire T (2011) Coseismic and postseismic slip of the 2011 magnitude-9 Tohoku-Oki earthquake. *Nature* 475: 373-376
- Polet J, Thio HK (2011) Rapid calculation of a Centroid Moment Tensor and wave-height predictions around the north Pacific for the 2011 off the Pacific coast of Tohoku Earthquake. *Earth, Planets and Space* 63: 541-545
- Sagiya T, Miyazaki S, Tada T (2000) Continuous GPS array and present-day crustal deformation of Japan. *Pure and Applied Geophysics* 157: 2303-2322
- Satake K, Namegaya Y, Yamaki S (2008) Numerical simulation of the AD 869 Jogan tsunami in Ishinomaki and Sendai plains. *Annual Report on Active Fault and Paleoseismicity Researches* 8: 71-89
- Sato M, Ishikawa T, Ujihara N, Yoshida S, Fujita M, Mochizuki M, Asada A (2011) Displacement above the hypocenter of the 2011 Tohoku-Oki earthquake. *Science* 332: 1395
- Sawai Y, Shishikura M, Komatsubara J (2008) A study on paleotsunami using hand corer in Sendai plain (Sendai City, Natori City, Iwanuma City, Watari Town, Yamamoto Town) Miyagi, Japan. *Geological Survey of Japan* 8: 17-70
- Shao G, Li X, Ji C, Maeda T (2011) Focal mechanism and slip history of the 2011 M_w 9.1 off the Pacific coast of Tohoku Earthquake, constrained with teleseismic body and surface waves. *Earth, Planets and Space* 63: 559-564
- Simons M and 14 coauthors (2011) The 2011 magnitude 9.0 Tohoku-Oki earthquake: mosaicking the megathrust from seconds to centuries. *Science* 332: 1421-1425
- Suwa Y, Miura S, Hasegawa A, Sato T, Tachibana K (2006) Interplate coupling beneath NE Japan inferred from three-dimensional displacement field. *Journal of Geophysical Research* 111: 1997-2002
- Tanioka Y, Satake K (1996) Fault parameters of the 1896 Sanriku tsunami earthquake estimated from tsunami numerical modeling. *Geophysical Research Letters* 23: 1549-1552
- Yamazaki Y, Lay T, Cheung KF, Yue H, Kanamori H (2011) Modeling near-field tsunami observations to improve finite-fault slip models for the 11 March 2011 Tohoku earthquake. *Geophysical Research Letters* 38: doi:10.1029/2011GL049130
- Yue H, Lay T (2011) Inversion of high-rate (1 sps) GPS data for rupture process of the 11 March 2011 Tohoku earthquake (M_w 9.1). *Geophysical Research Letters* 38: doi:10.1029/2011GL048700 ■