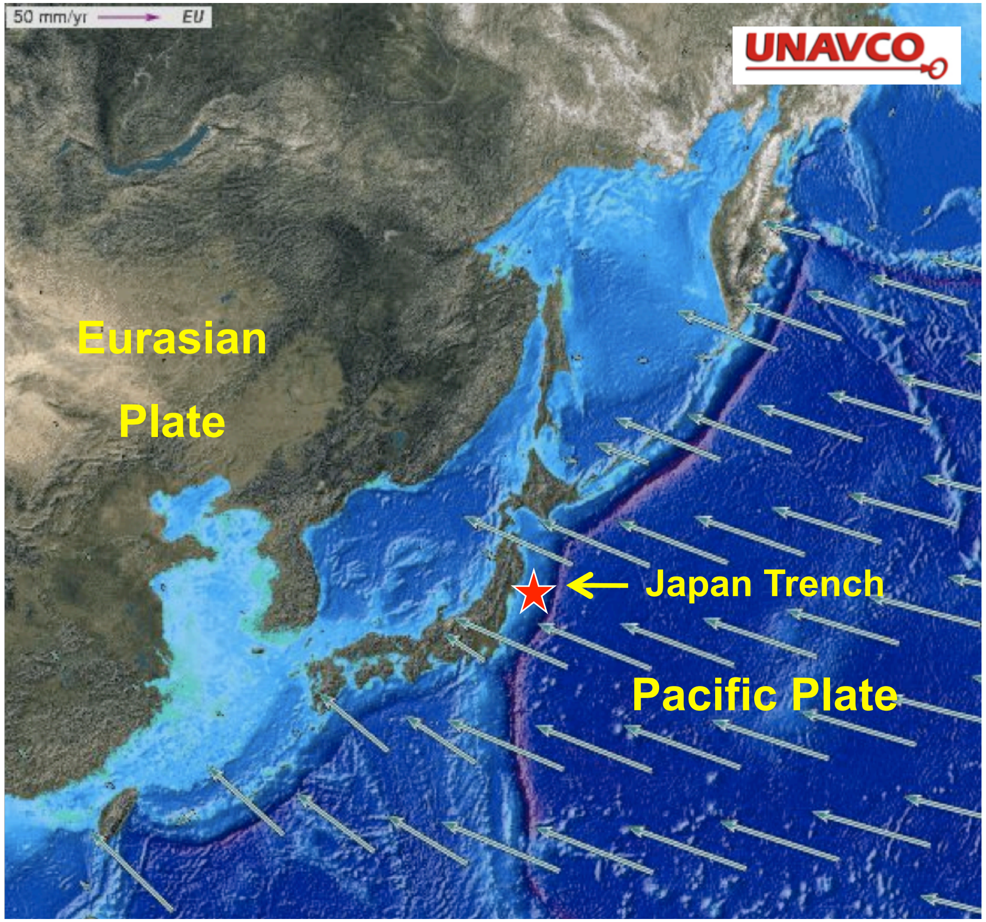
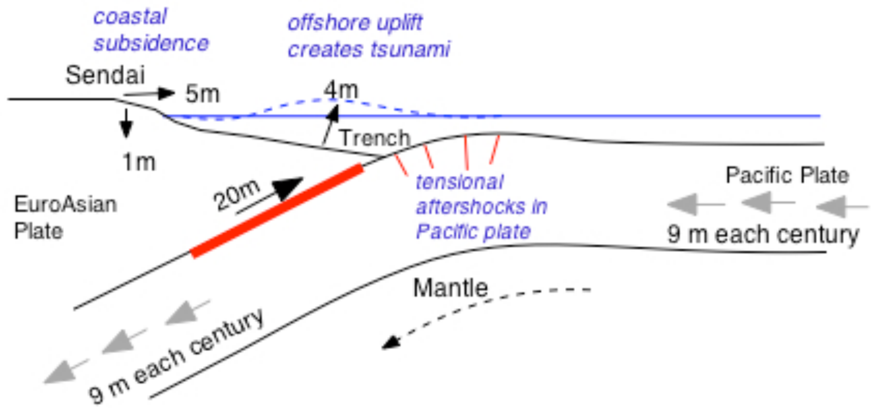
Tohoku-oki event: Tectonic setting

This earthquake was the result of thrust faulting along or near the convergent plate boundary where the Pacific Plate subducts beneath Japan.

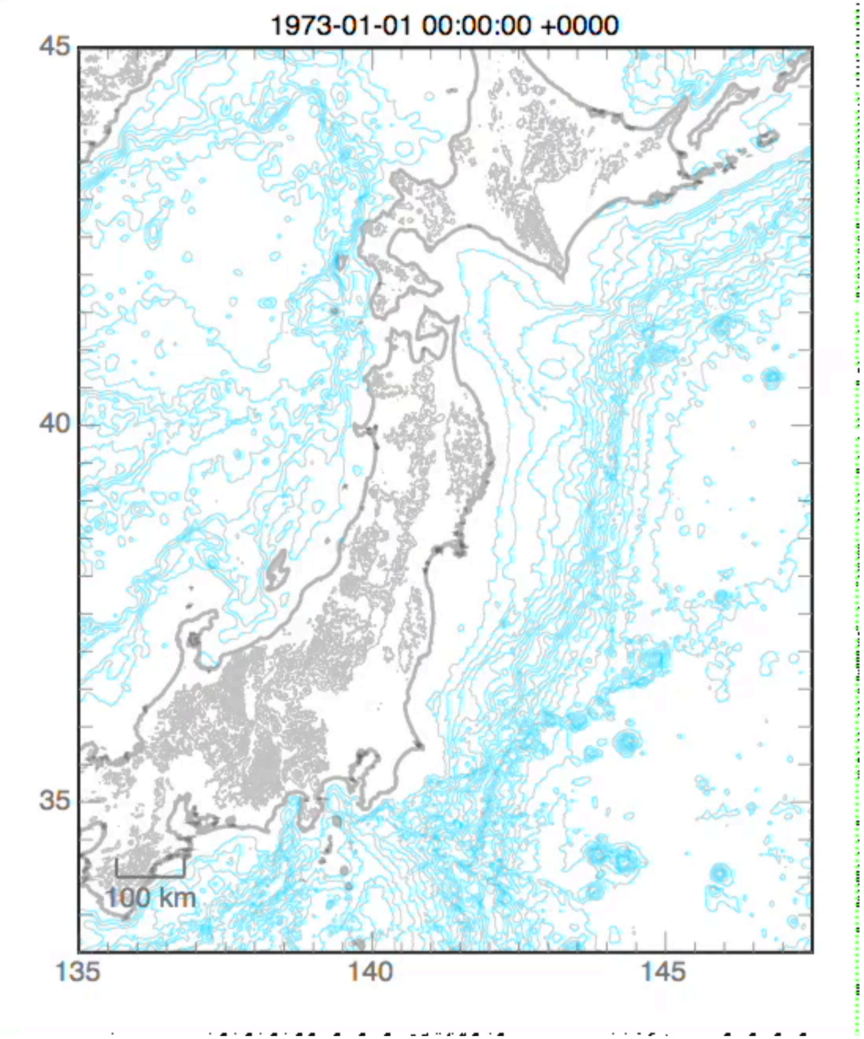
This map also shows the rate and direction of motion of the Pacific Plate with respect to the Eurasian Plate near the Japan Trench. The rate of convergence at this plate boundary is about 100 mm/yr (9 cm/year).

This is a fairly high convergence rate and this subduction zone is very seismically active.





Historical seismicity and aftershocks



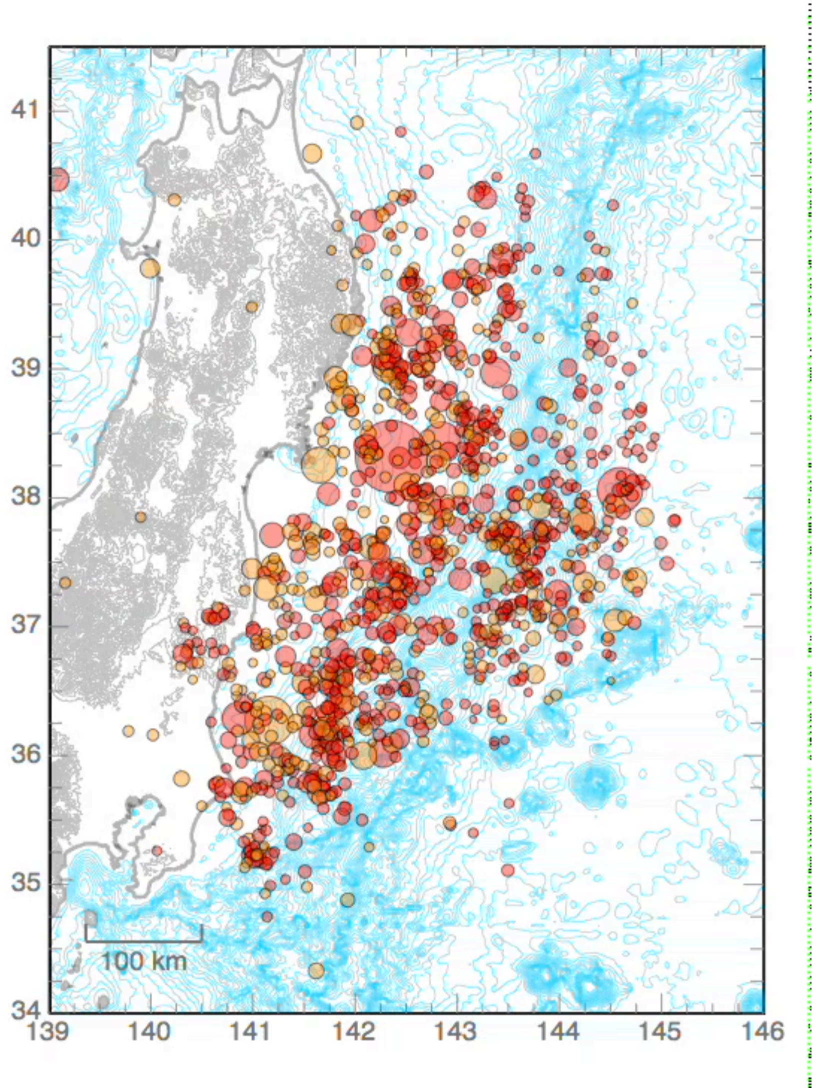
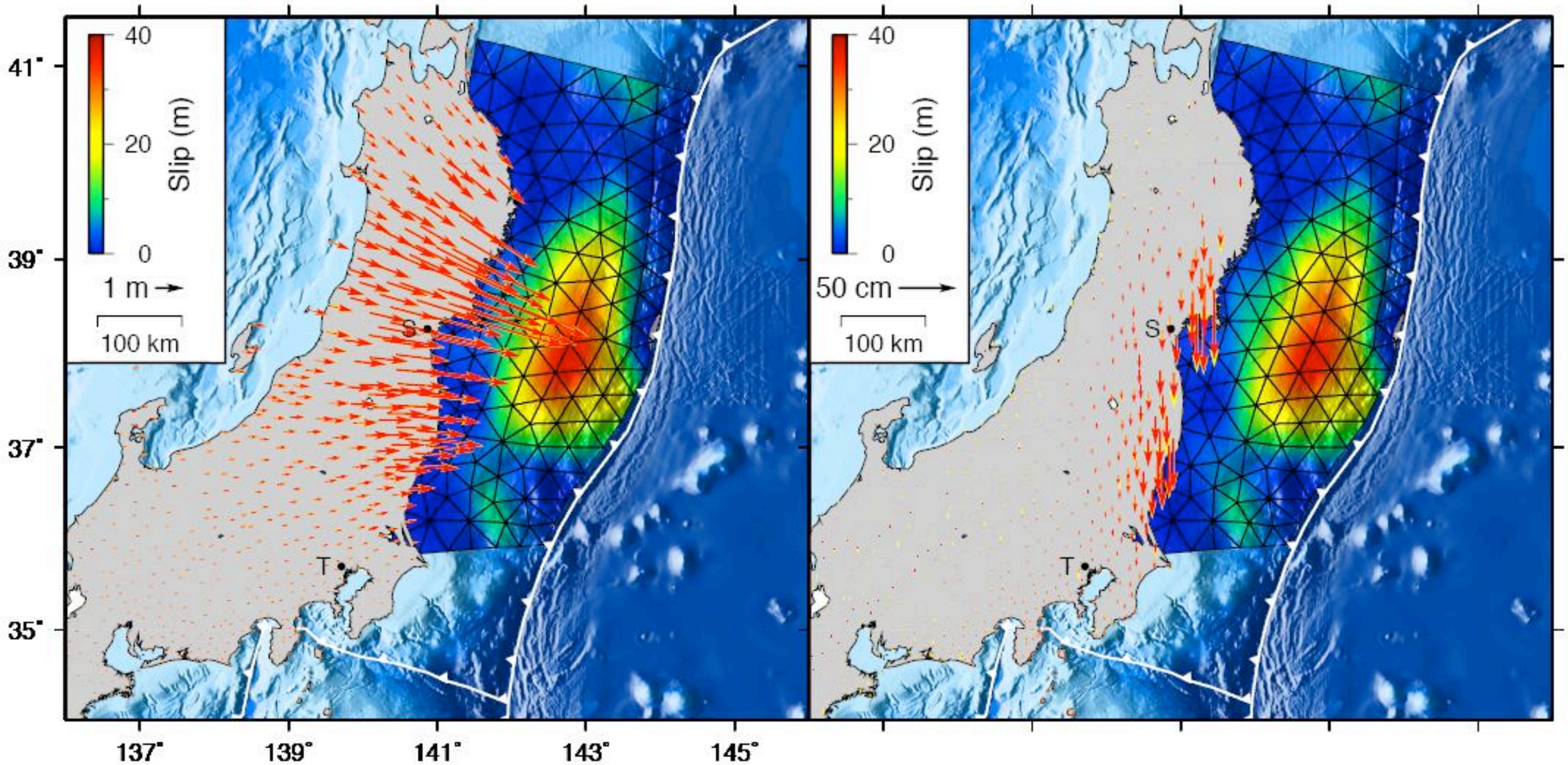


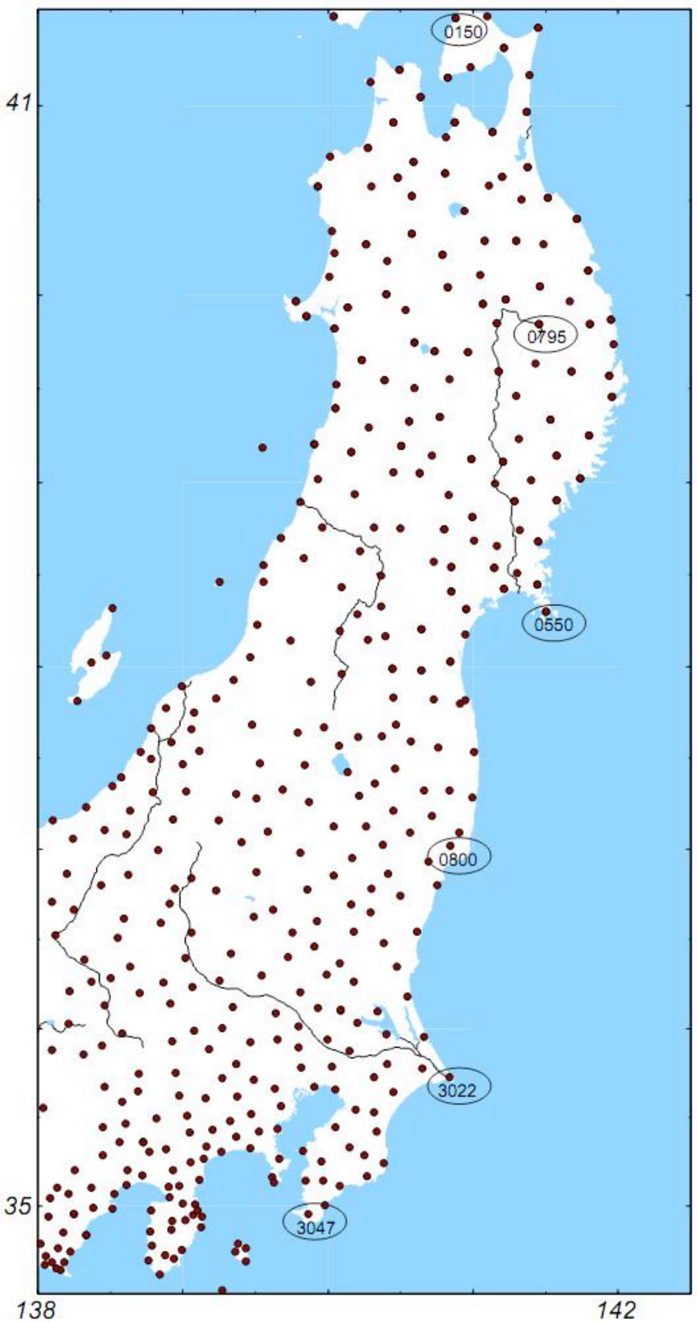
Image courtesy of Charles Ammon

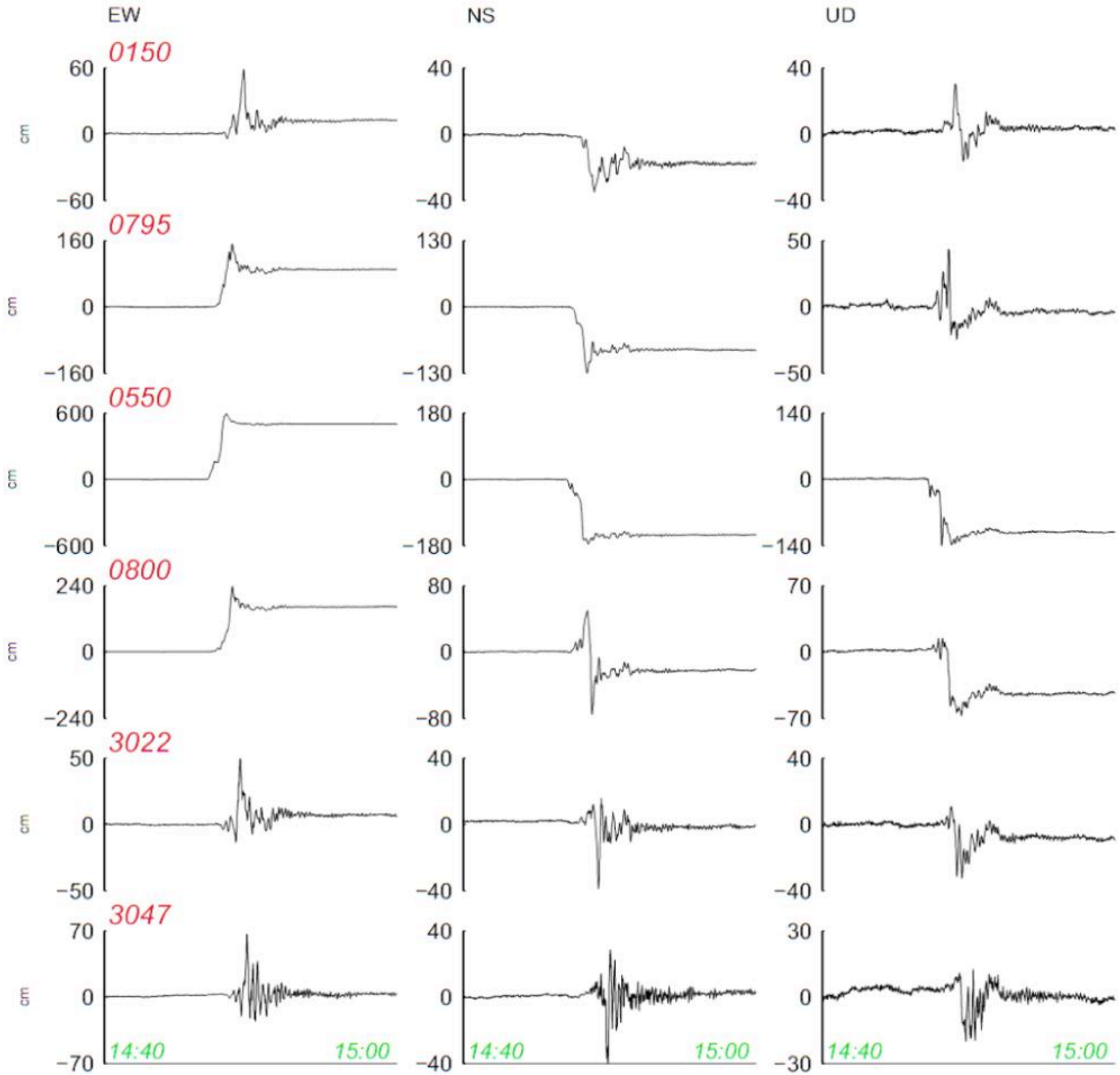
Co-seismic slip



M. Simons, F. Ortega, J. Jiang, A. Sladen, and S. Minson at Caltech as part of the ARIA project.
All orginal GEONET RINEX data provided to Caltech by the Geospatial Information Authority (GSI) of Japan.

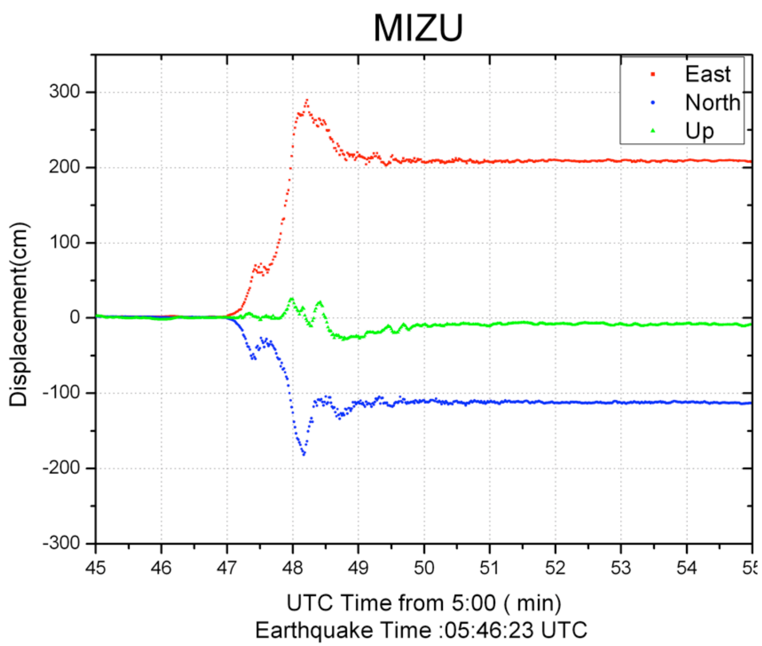
GPS waveforms





Analysis by Dr.Yokota using the GEONET data of Geographical Survey Institute

Co-seismic slip



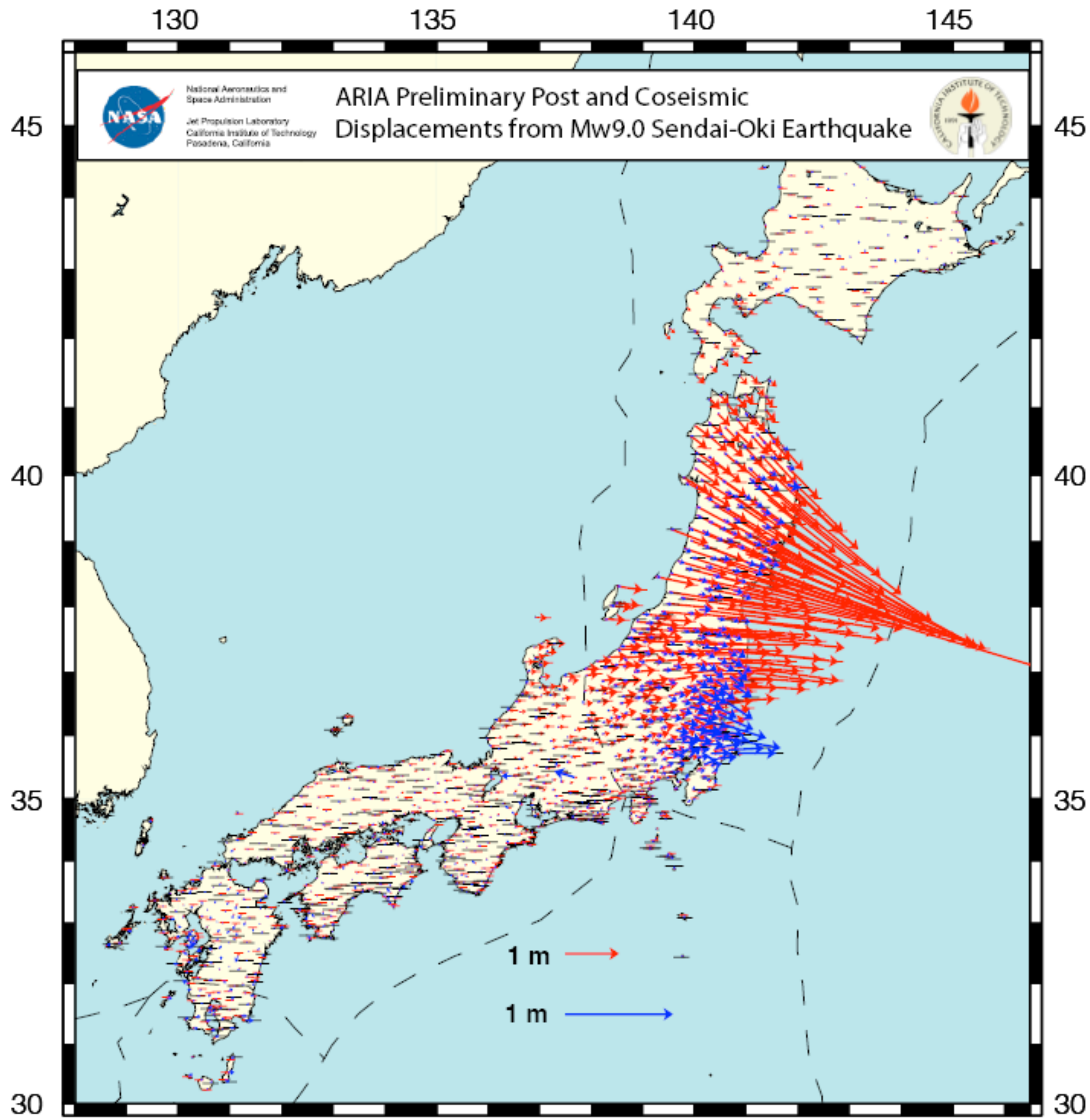
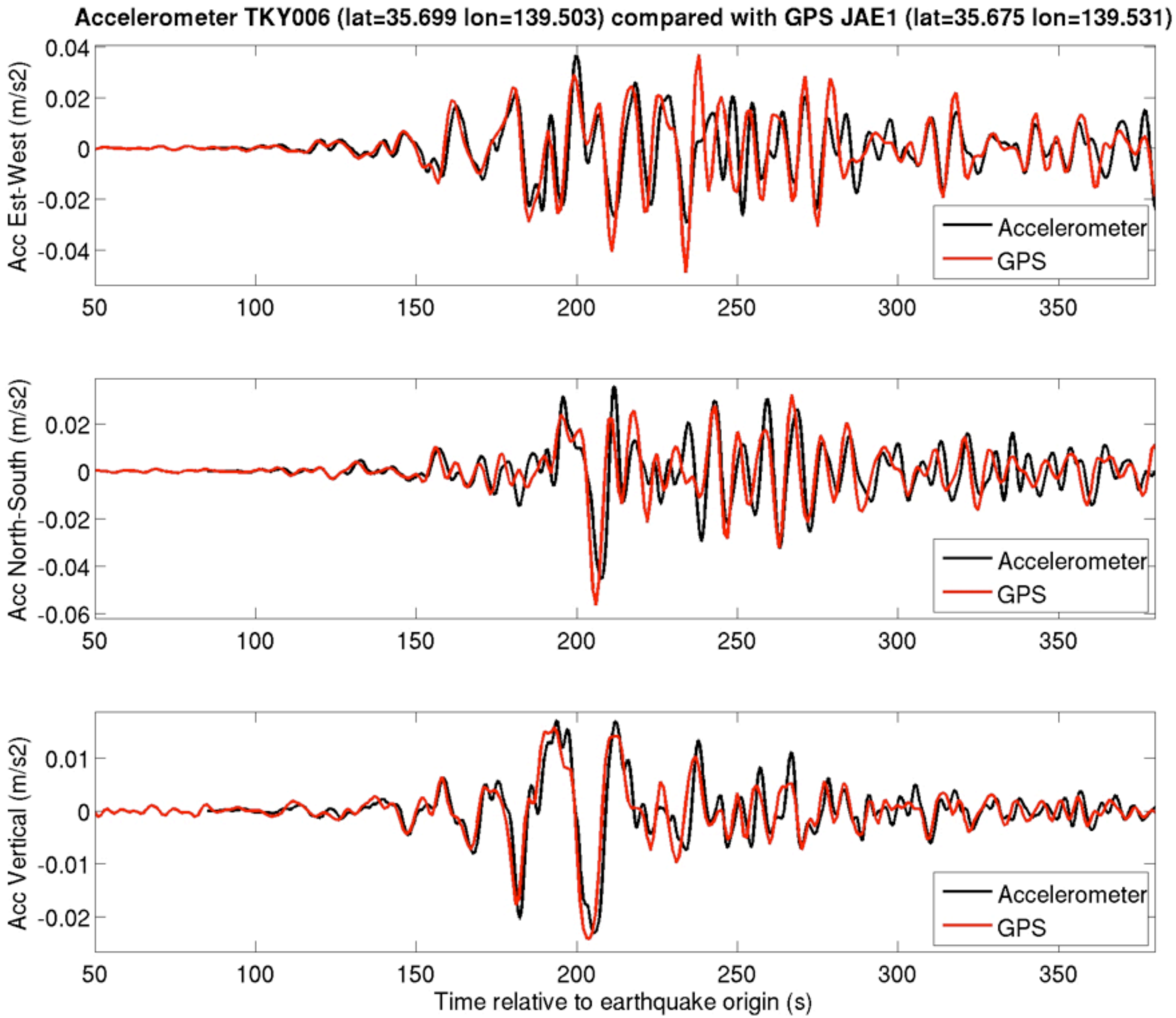


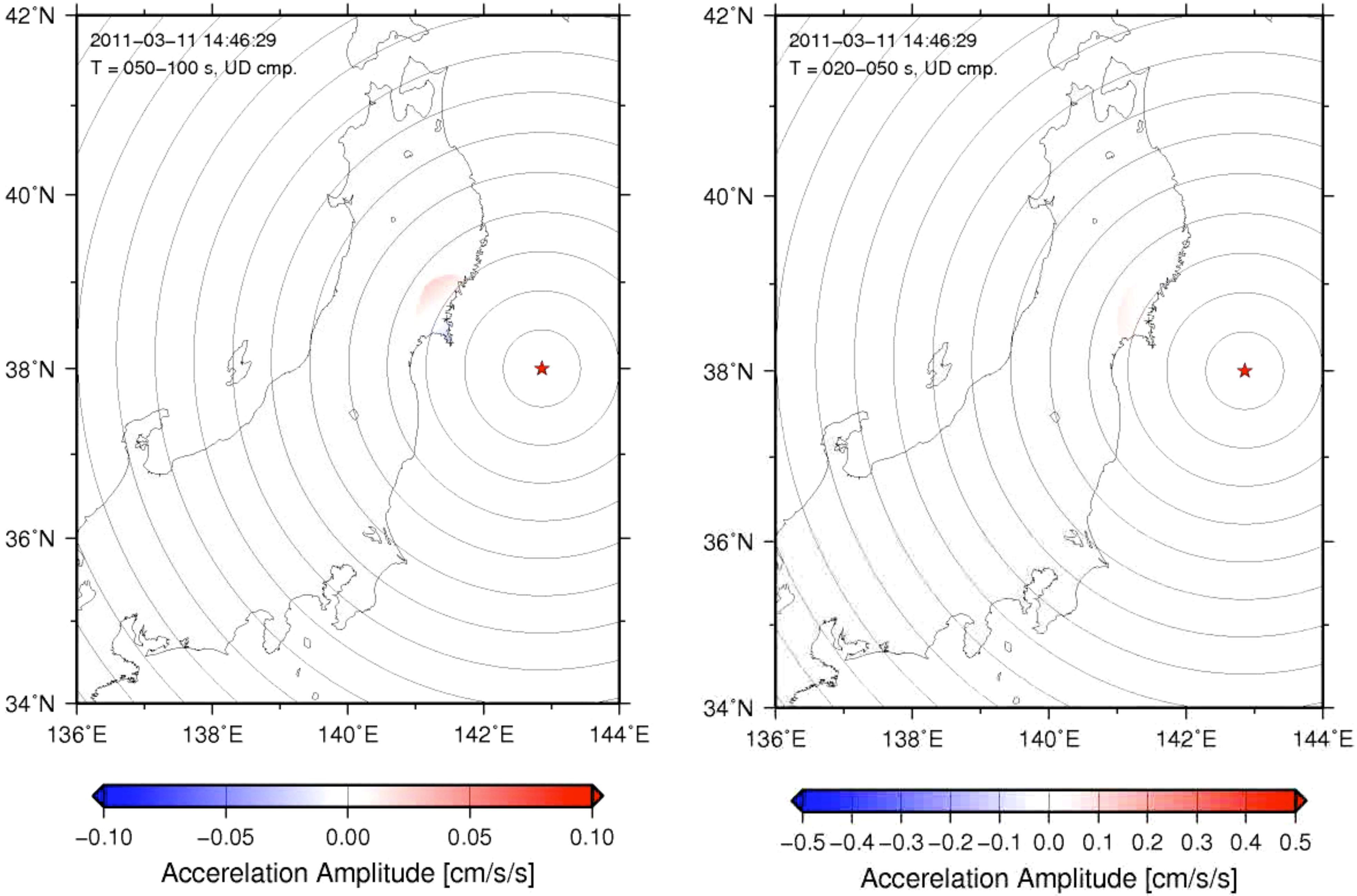
Figure shows horizontal displacements based on ARIA verion 0.3 position estimates for GEONET stations. Coseismic displacement is shown in red, and first 8 hours of postseismic motion is shown in blue, including motion caused by aftershocks. Bars at end of vector show 95% error estimate. Solutions courtesy of ARIA team at JPL and Caltech (email aria@jpl.nasa.gov or aria@caltech.edu). All original GEONET RINEX data provided to Caltech by the Geospatial Information Authority (GSI) of Japan.

GPS and GM signals



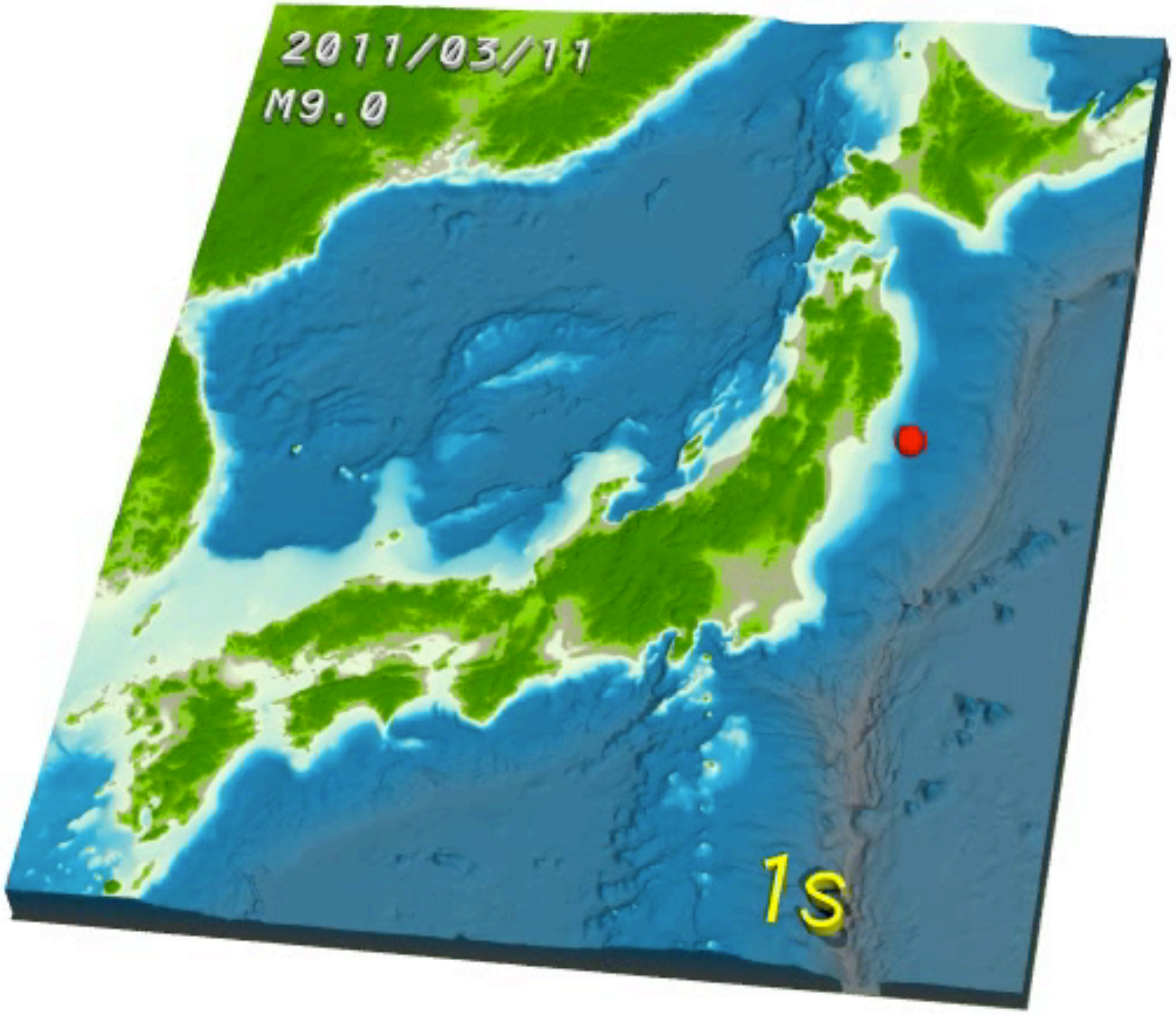
The figure shows the comparison between this GPS signal - twice differentiated - and the accelerometric signal, in the [0.005Hz - 0.125Hz] range.

Long period GM



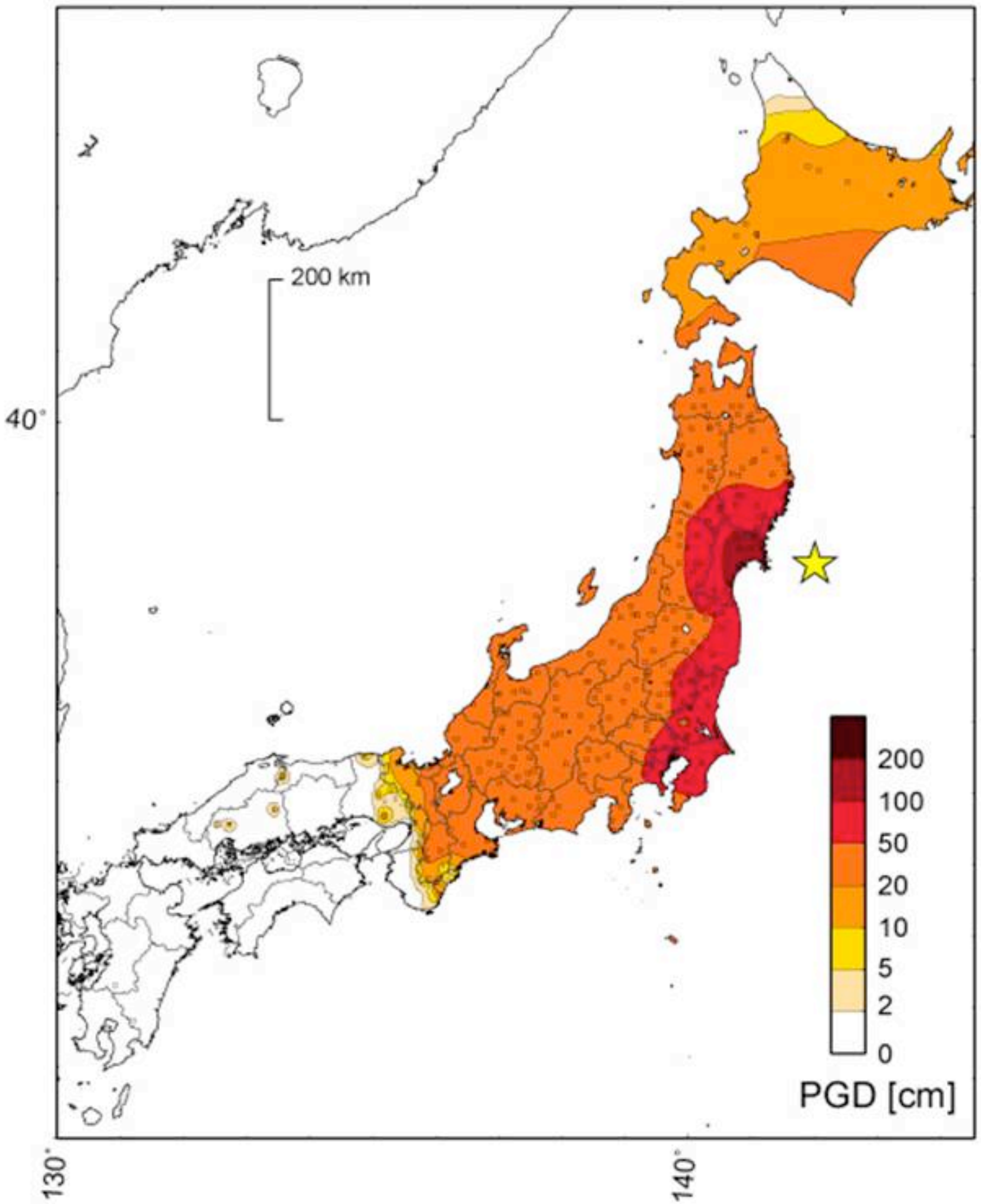
"Earthquake Research Institute, University of Tokyo: Dr. Furumura and Project Researcher Maeda

Ground motion animation: time scales...

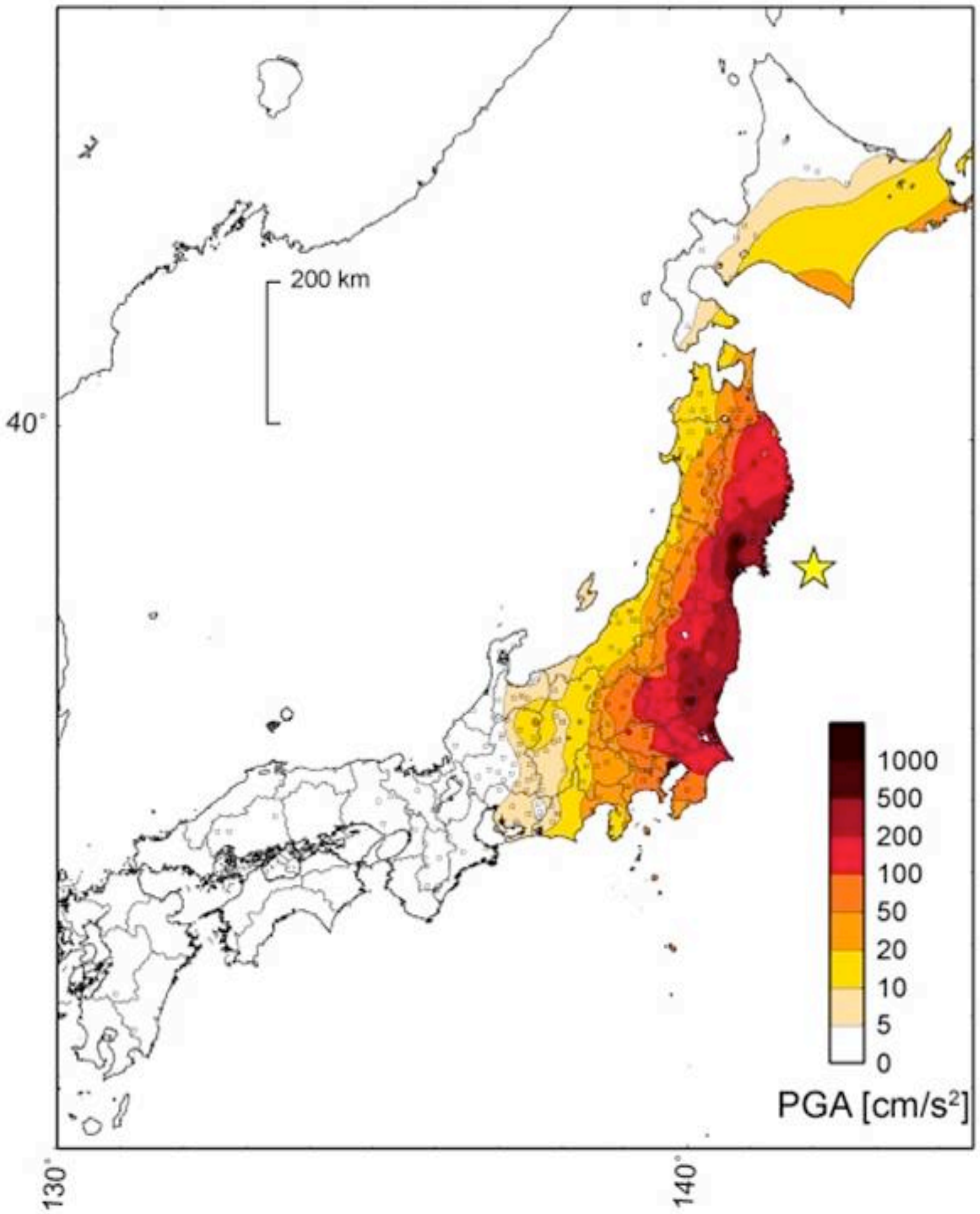


Courtesy of Takashi Furumura

PGD



PGA



A strong ground acceleration of over 2933 cm/s/s was observed in K-NET Tsukidate observation station (Miyagi pref.) near the hypocenter, and a strong ground acceleration propagated in broad area from Ibaraki to southern Iwate.

The distribution of strong ground acceleration is extending to three areas: between Iwate and Miyagi prefecture, Fukushima pref., between Tochigi and Ibaraki pref.

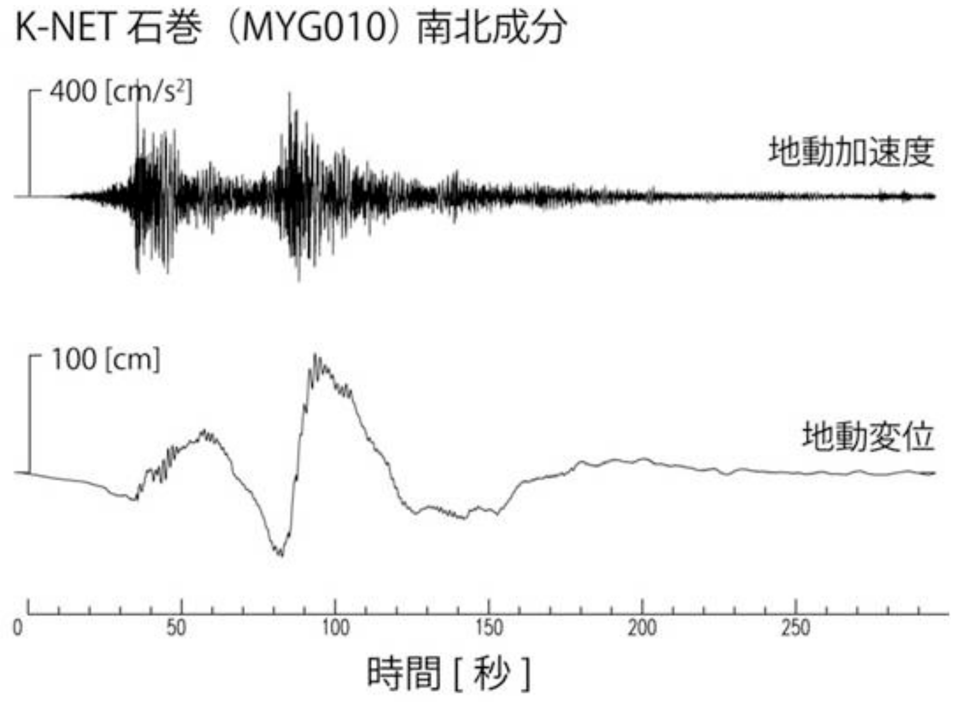
Therefore, it is assumed that a huge fault slip have occurred on the east of these areas.

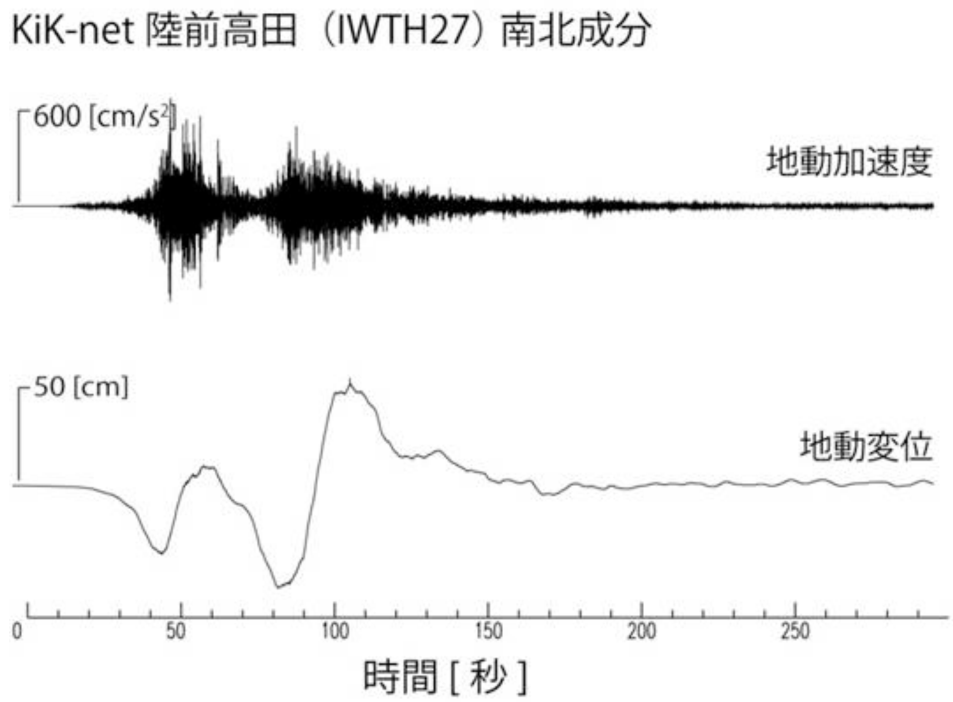
The ground acceleration is decaying drastically just after the border of Itoigawa-Shizuoka Tectonic Line, and it suggests that the wave attenuated at around this area.

Waveforms

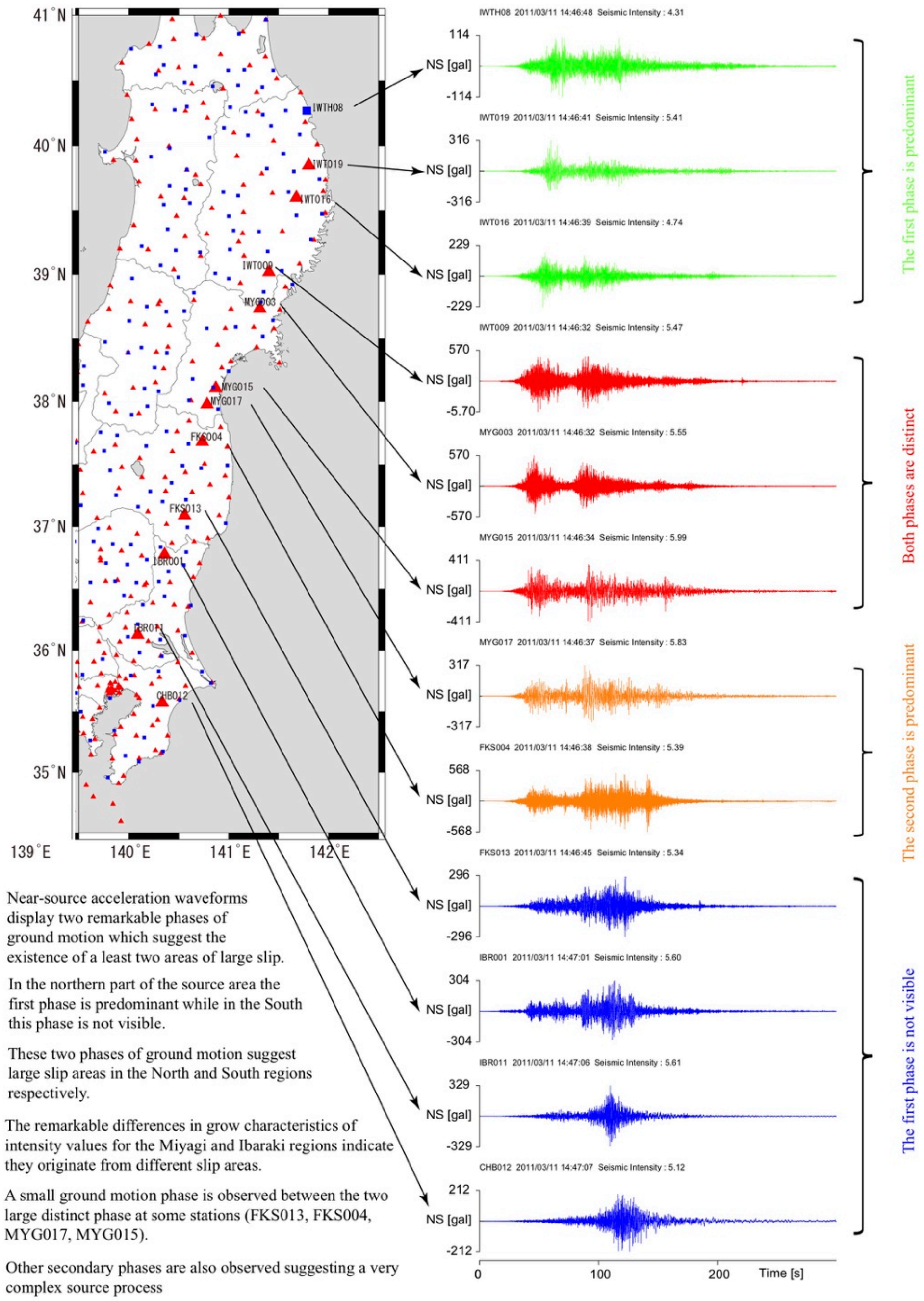
- Maximum acceleration and maximum displacement of ground motion in Ishinomaki and Rikuzentakata where ground motion was strong. The arrival of 2 strong seismic wave groups is seen after about 50 seconds. They suggest that a strong seismic wave was radiated from the 2 major asperities of the Miyagi coast and Iwate coast.

- Two long-period pulses (40-50 second) was found in ground displacement and its amplitude is more than 50 to 100cm. The long-period of ground motion that lasted for 100 and several tens of seconds, indicates the long time rupture process of the fault in this massive earthquake.

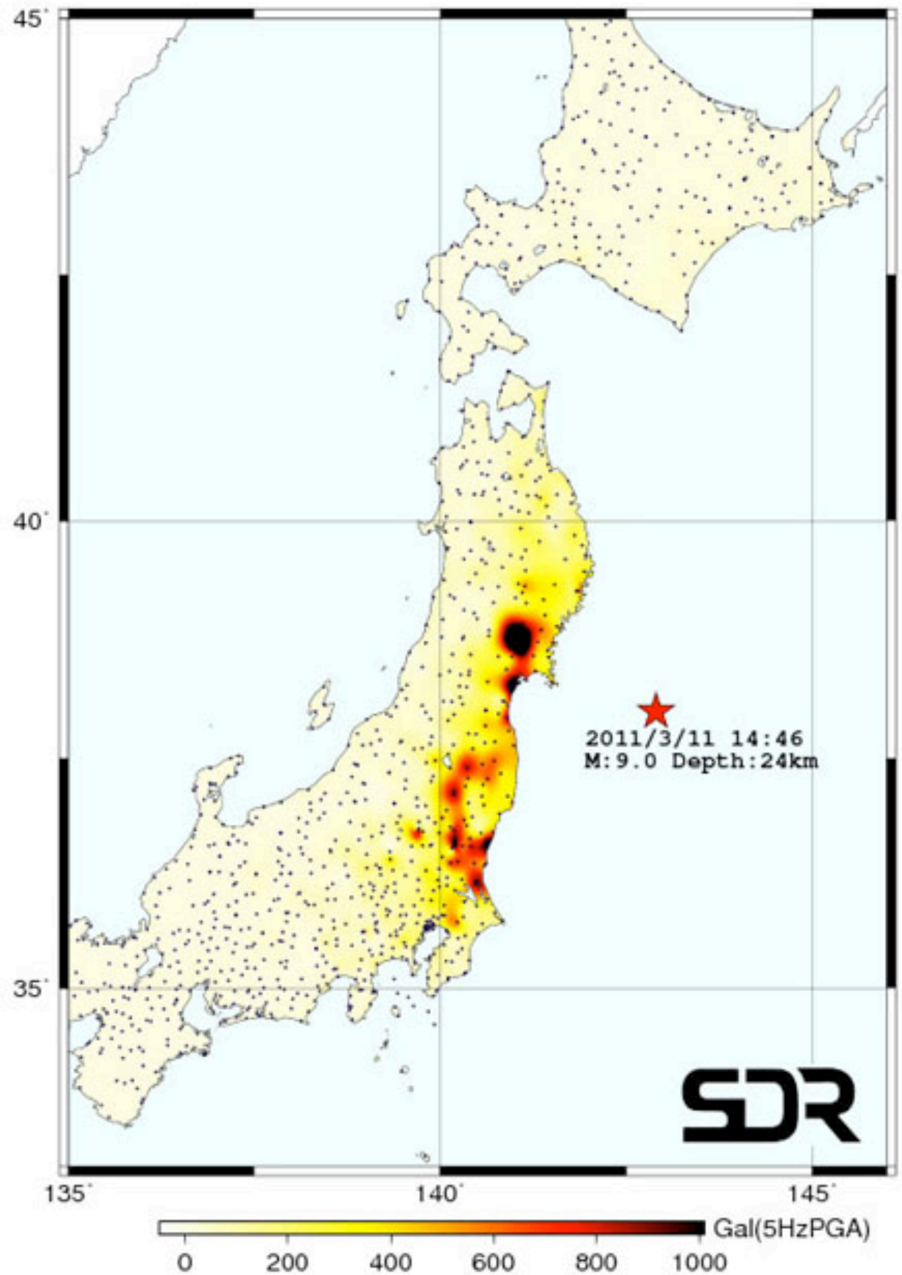




Rupture from ground motion



Source: Knet-NIED



Strong motion distribution at Eastern Japan (5HzPGA)
This PGA is commonly used as an index for the alarm to stop the train operation.

EEW - Japan

- Japan's Earthquake Early Warning System is managed by the Japan Meteorological Agency (JMA), and was first launched on October 1st, 2007. JMA's EEWS is a type of front-detection system in which seismometers near the hypocenter, or source of the earthquake, send warnings to more distant urban areas.

- The EEWS is split into two phases: earthquake detection and warning dissemination. In order to determine when and where an earthquake has occurred, ground movement data is collected using Japan's dense seismic network.

- This information is then analyzed by monitoring stations to determine whether it is necessary to issue an earthquake warning. If a warning is justified, this earthquake information is broadcasted to nearby residents through various media such as television, radio, and cellular networks.

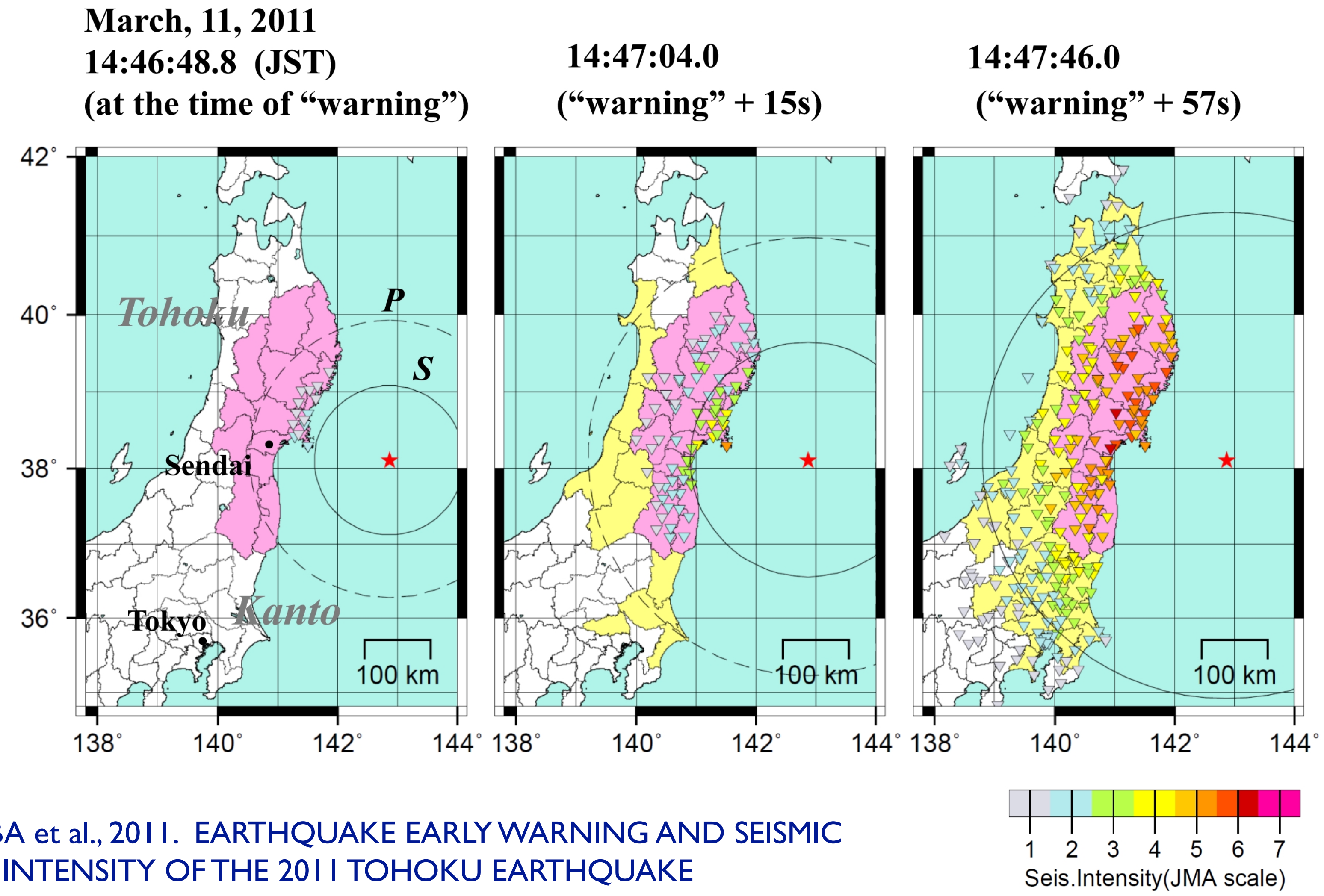
- Specialized alerts are also sent to business operators and facilities in order to deploy necessary countermeasures such as the shutdown of dangerous facilities or the slowing down of commuter trains in order to mitigate any earthquake-related damage

EEW - Japan (Tohoku-oki March 11)

Update number	Notes	Time in JST (hh:mm:ss.s)	Time since first P-wave detection (sec)	Estimated magnitude	Estimated maximum seismic intensity (shindo)	Latitude	Longitude
-	Initial Seismic Detection Time of p-wave	14:46:40.2	-	-	-	-	-
1	**First forecast issued to advanced users**	**14:46:45.6**	**5.4**	**4.3**	**1**	**38.2**	**142.7**
2		14:46:46.7	6.5	5.9	3	38.2	142.7
3		14:46:47.7	7.5	6.8	4	38.2	142.7
4	**First warning issued to the general public**	**14:46:48.8**	**8.6**	**7.2**	**5-lower**	**38.2**	**142.7**
5		14:46:49.8	9.6	6.3	4	38.2	142.7
6		14:46:50.9	10.7	6.6	4	38.2	142.7
7		14:46:51.2	11.0	6.6	4	38.2	142.7
8		14:46:56.1	15.9	7.2	4	38.1	142.9
9		14:47:02.4	22.2	7.6	5-lower	38.1	142.9
10		14:47:10.2	30.0	7.7	5-lower	38.1	142.9
11		14:47:25.2	45.0	7.7	5-lower	38.1	142.9
12	First warning issued for Tokyo area	14:47:45.3	65.1	7.9	5-upper	38.1	142.9
13		14:48:05.2	85.0	8.0	5-upper	38.1	142.9
14		14:48:25.2	105.0	8.1	6-lower	38.1	142.9
15	Final warning update	14:48.37.0	116.8	8.1	6-lower	38.1	142.9

Table 1: Real-time estimates of the epicenter location, parameters and maximum seismic intensity generated by EEWS (translated and adapted from JMA, 2011a).

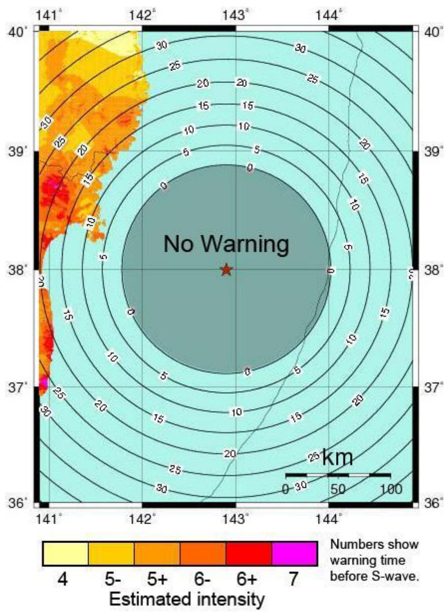
EEW - Japan (Tohoku-oki March 11)



M. HOSHIBA et al., 2011. EARTHQUAKE EARLY WARNING AND SEISMIC INTENSITY OF THE 2011 TOHOKU EARTHQUAKE

Fig. 2. Region of EEW "warning" and "forecast", and distribution of seismic intensities estimated in real time manner (Kunugi *et al.*, 2008) at 14:46:48.8 when the "warning" was issued (left), at 14:47:04.0 when intensity 5-lower or greater first appeared (center), and at 14:47:46.0 when the Tokyo region was first specified in the EEW "forecast" (right). Pink area indicates the region where the "warning" was issued, and the yellow areas are those specified in the "forecast". Wave fronts of *P* and *S* waves are shown by broken and solid circles, respectively. The seismic intensities (colored triangles) were measured using waveforms of the K-NET, KiK-net (NIED), and JMA networks. The animation of this figure is shown in the Meteorological Research Institute (2011). The distribution of the eventual seismic intensity, which means finally observed intensity, is shown in Fig. 3.

EEW - Japan (Tohoku-oki March 11)



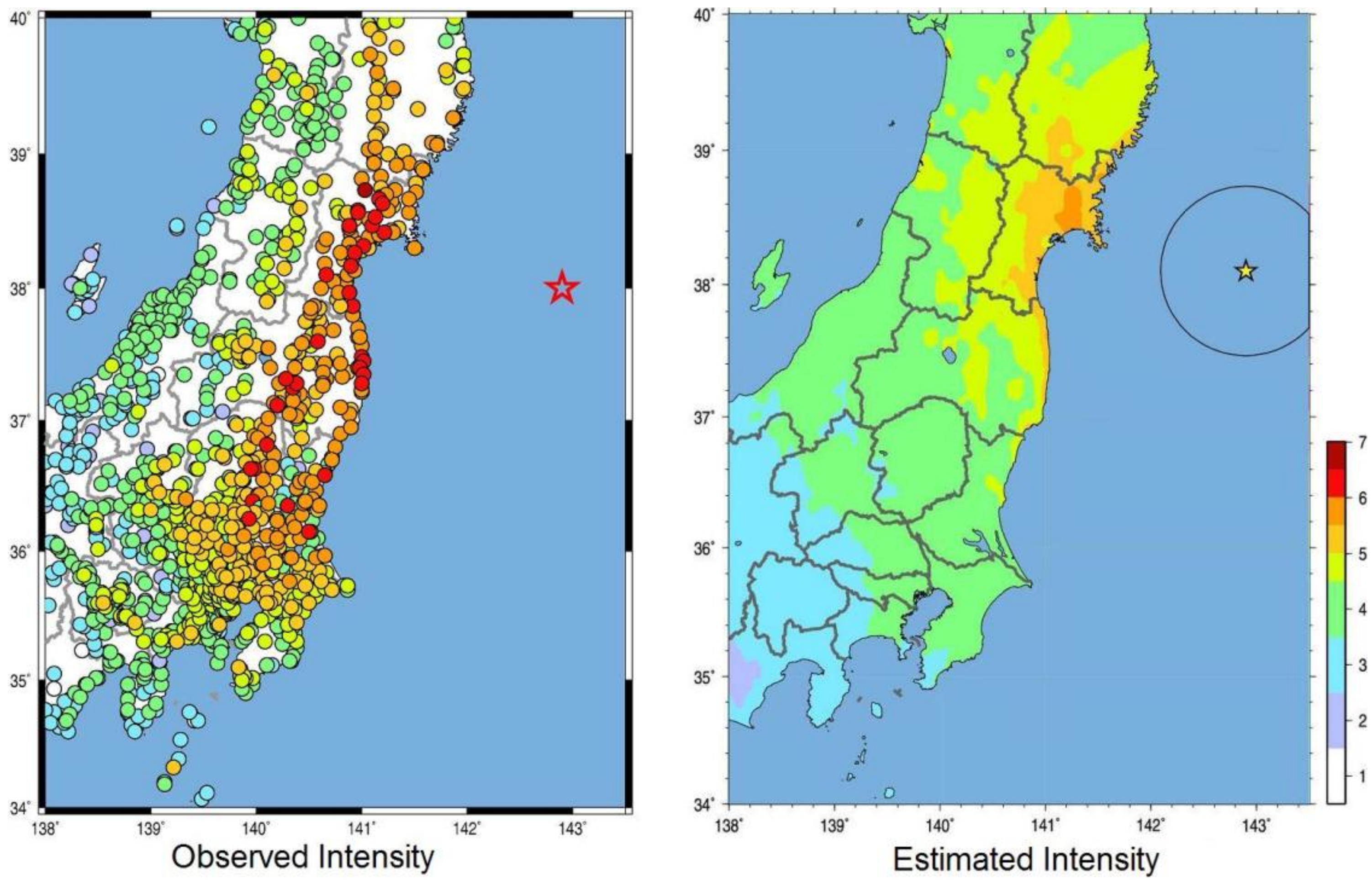


Figure 4: Japan Meteorological Agency's estimated seismic intensity computed based on the last warning issued by the EEWS (right); the actual observed seismic intensity (left)

EEW - Japan (Tohoku-oki March 11)

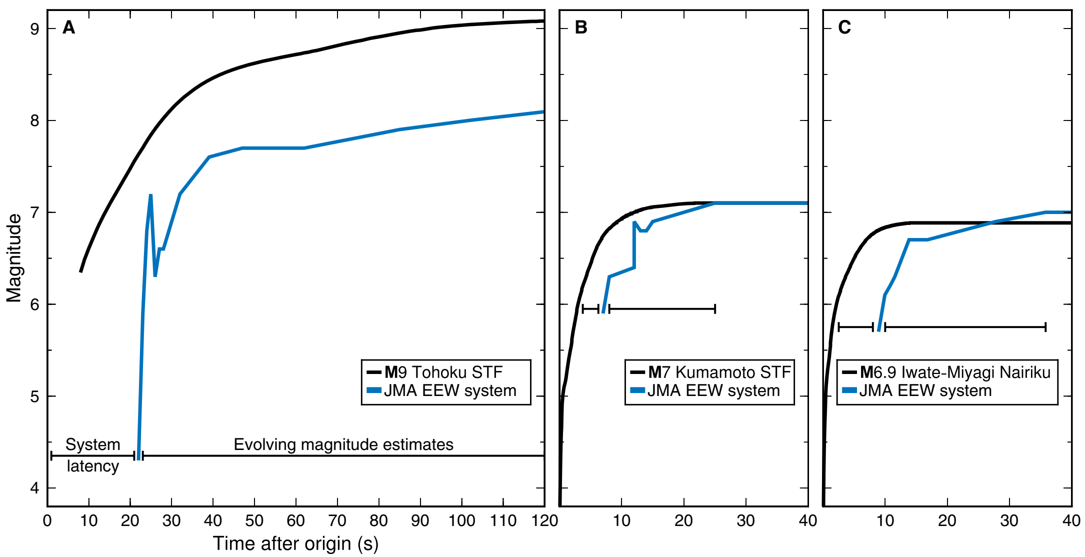
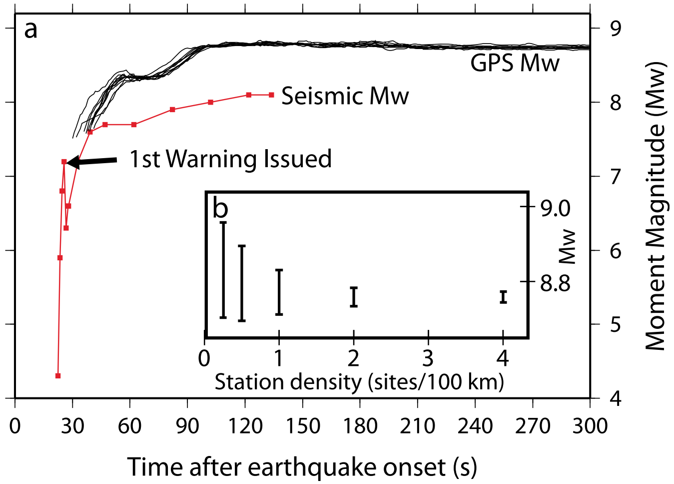
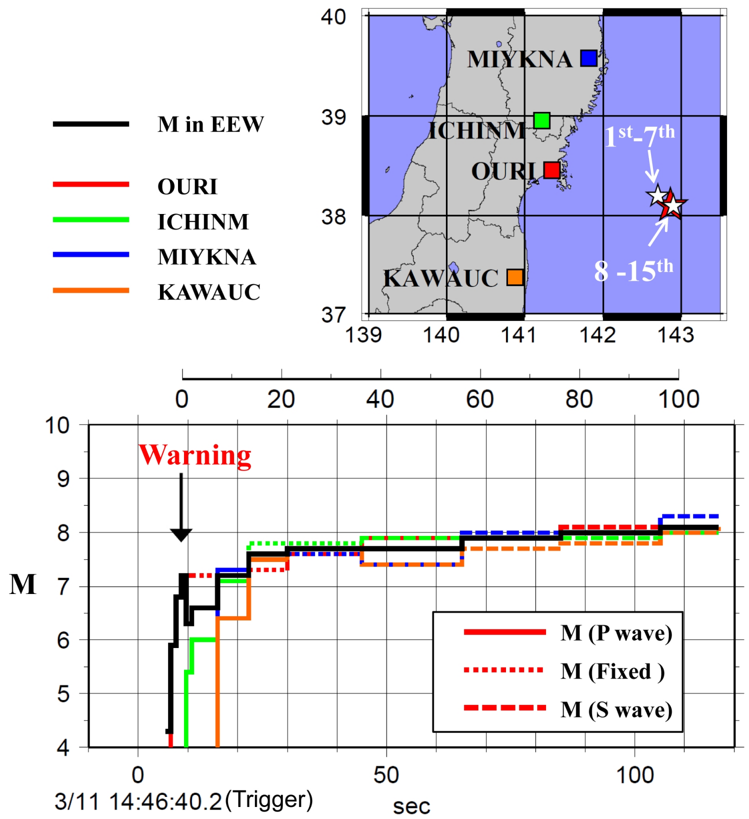


Fig. 1. Earthquake magnitude and alert evolution. Evolution of EEW magnitude estimates for the (**A**) 2011 **M**9.0 Tohoku, (**B**) 2016 **M**7.0 Kumamoto, and (**C**) 2008 **M**6.9 Iwate-Miyagi Nairiku, Japan earthquakes. We compare the time evolution of magnitude estimates from the JMA EEW system (blue) to the inferred actual magnitude evolution based on kinematic rupture modeling (black) (*35–37*). The JMA estimates have the same shape as the actual source time function (STF) but are time-shifted. This indicates that the EEW magnitude estimates are following the moment release of the earthquake as it evolves with time (with some delay due to system latency) rather than predicting the final magnitude. Note that the JMA EEW magnitude estimate for the Tohoku earthquake saturates near **M**8 because of limitations in the frequency band used (*38*).

Minson et al., Sci. Adv. 2018; 4:eaaq0504



Wright et al., 2015.



M. Hoshiba et al., 2011.

Fig. 1. Sequence of determinations of epicenter and magnitude in JMA EEW. Upper right panel: epicenters determined by the EEW system are shown as a white star for the first to seventh “forecast” (5.4–11.0 s after the first trigger) and another for the next eight (15.9–116.8 s). Focal depth was estimated to be 10 km for all 15 announcements. Red star indicates the epicenter location from the unified JMA catalog (focal depth is 24 km). The resolution of the JMA EEW system is 0.1 degree for latitude and longitude, and 10 km for focal depth for hypocenter determination. Lower panel: magnitudes estimated from maximum displacement amplitude at four stations. Color lines represent the different stations; the black line is the median value, which is used for JMA EEW. Bottom axis shows the elapsed time from the first trigger, and offset axis at top shows time elapsed from the EEW “warning” (the fourth “forecast”). The solid line indicates the magnitude of the P wave, broken line is that of S wave, and dotted line shows the period during which the magnitude is kept unchanged around the S wave arrival.

EEW - Japan (Tohoku-oki March 11)

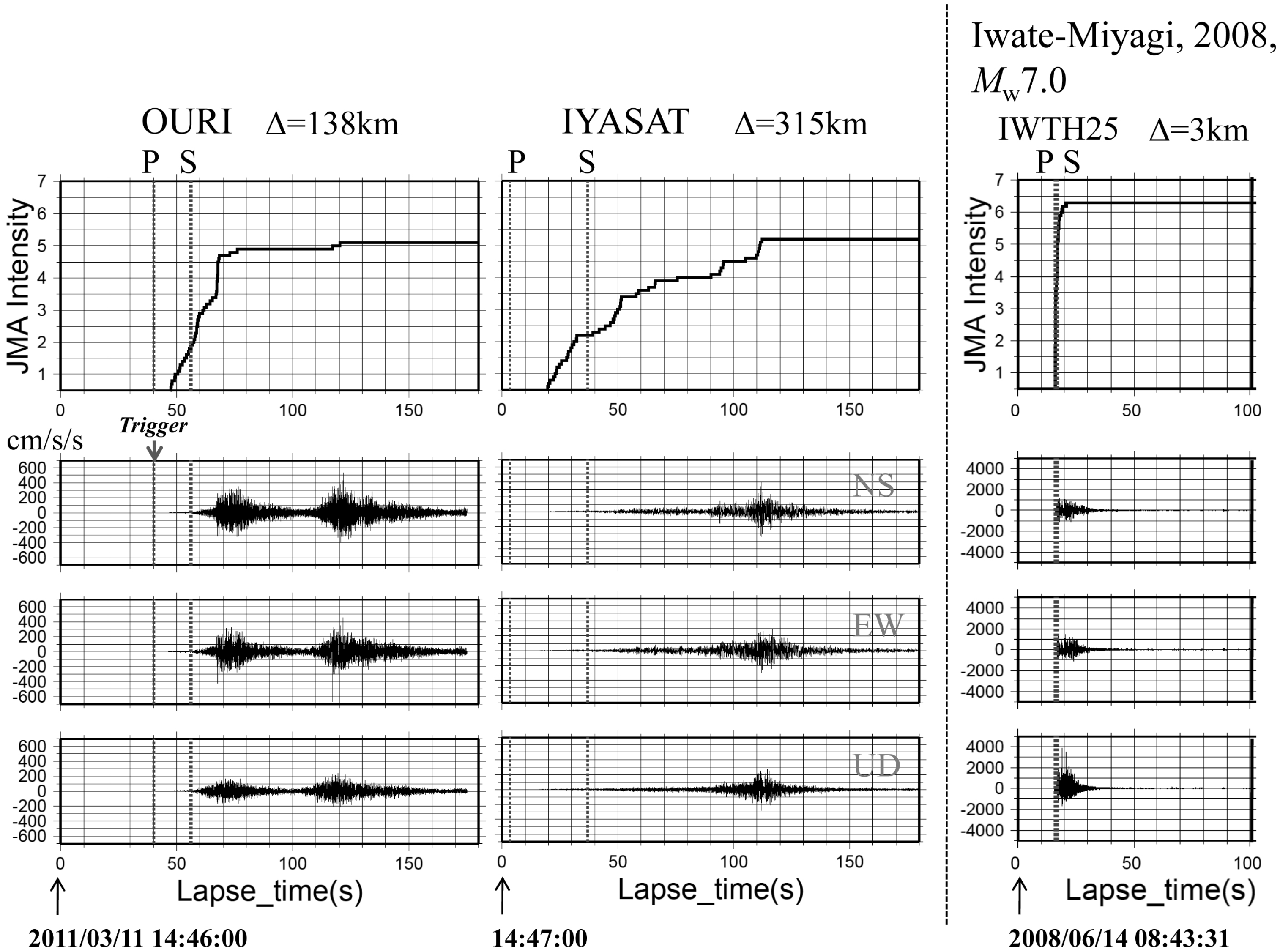
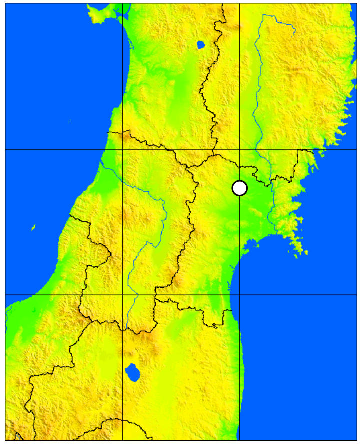


Fig. 4. Acceleration waveform and seismic intensity estimated in real-time manner at OURI and IYASAT. *P* and *S* wave arrival times are shown by dotted lines. The arrow labeled "Trigger" indicates 14:46:40.2, when station OURI triggered the EEW procedure. For comparison, acceleration and intensity at IWTH25 (KiK-net) are also shown at the time of the 2008 Iwate Miyagi Nairiku earthquake (June 14, 2008, focal depth is 8 km, M_w 7.0).

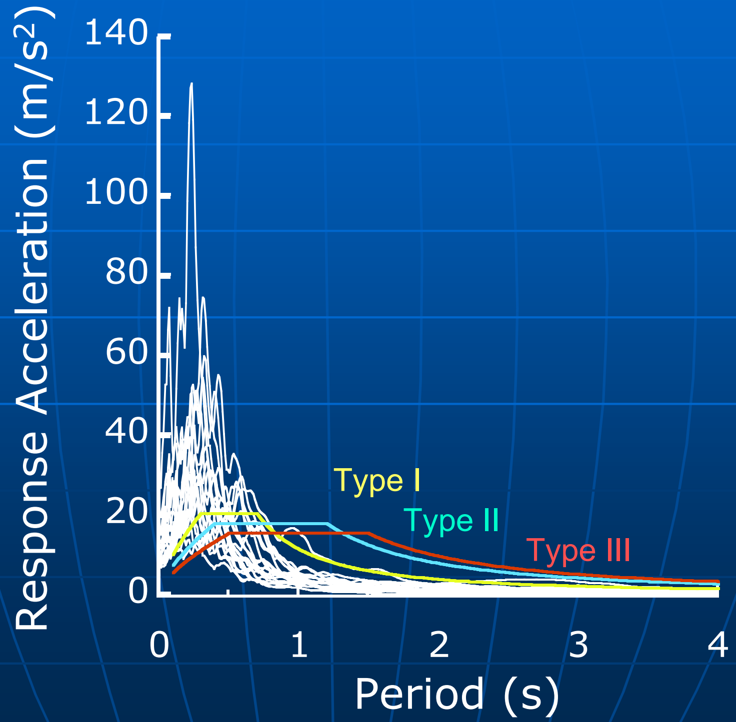
M. Hoshiba Et Al., 2011. EARTHQUAKE EARLY WARNING AND SEISMIC INTENSITY OF THE 2011 TOHOKU EARTHQUAKE

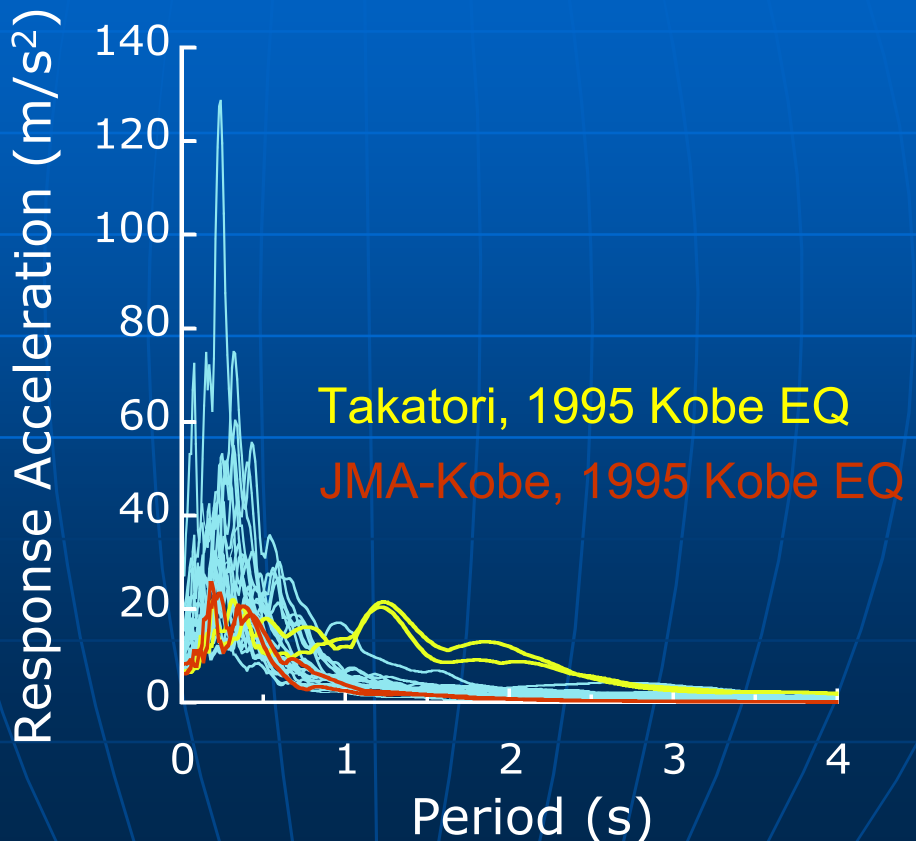
Tsukidate

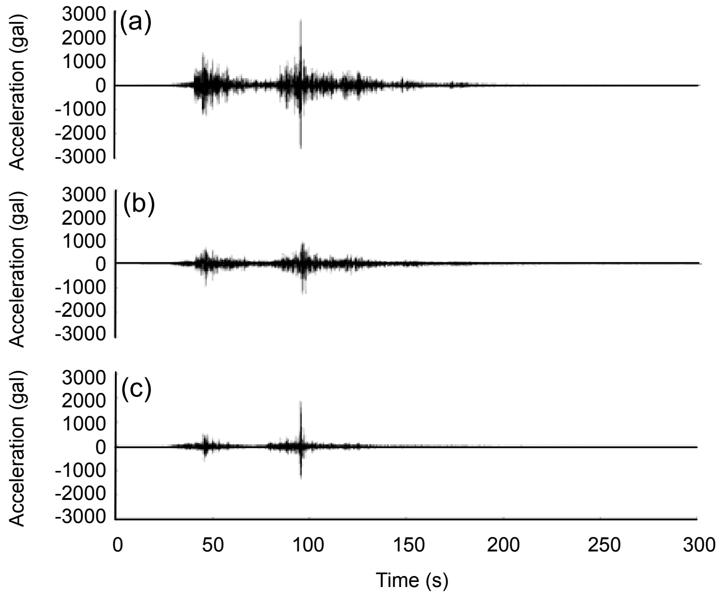


Courtesy of Kazuhiko Kawashima

Comparison with Type II Design Spectra, JRA Design Specifications of Bridges







Tsukidate

(a) Overall view of the Kurihara City Municipal Office Building

(b) Fall of ceiling of Municipal Assembly Hall (1)

(c) Fall of finishing tiles on a column

(d) Fall of ceiling of Municipal Assembly Hall (2)

Photo 1: Kurihara City Municipal Office Building and non-structural damage

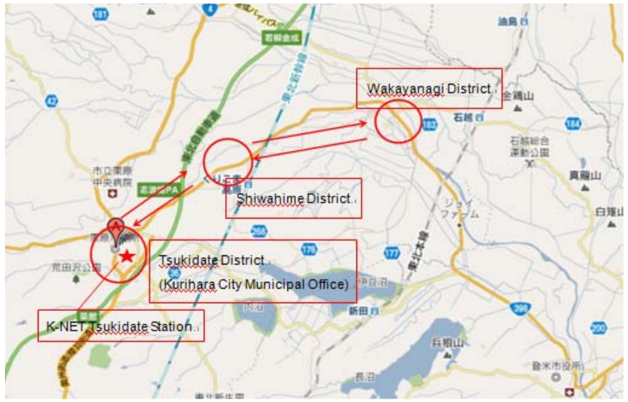
Photo 4: Lifting of a man hole due to soil liquefaction near Shiwahime

Photo 5: Fall of masonry walls

Photo 6: Undamaged concrete block walls and damaged masonry walls

The JMA seismic intensity was estimated to be 7, the highest intensity of the JMA scale.

Investigators studied the damage in Kurihara City to correlate the observed ground motion intensity and the damage in the area.



http://www.eqclearinghouse.org/2011-03-11-sendai/2011/04/04/tohoku-chapter-aij-reconnaissance-report-kurihara-city/

Tsukidate

Photo 8: Fall of exterior mud finishing of traditional ware house walls

Photo 7: Damage of houses in urban area of Wakayanagi-machi

Photo 10: Ground settlement at the elementary school

Photo 11: Fall of a statute

Photo 12: Fall down of two gateposts of the Kanro-ji temple to west

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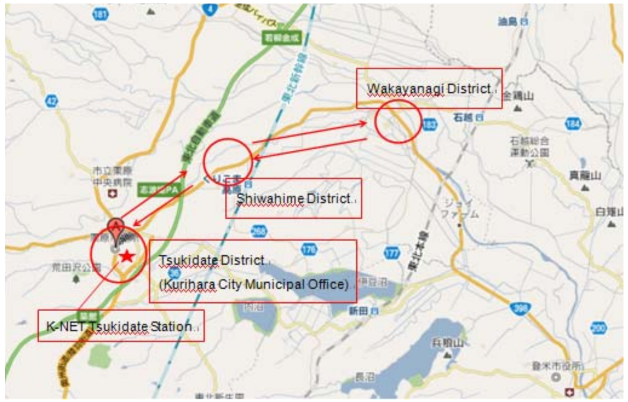
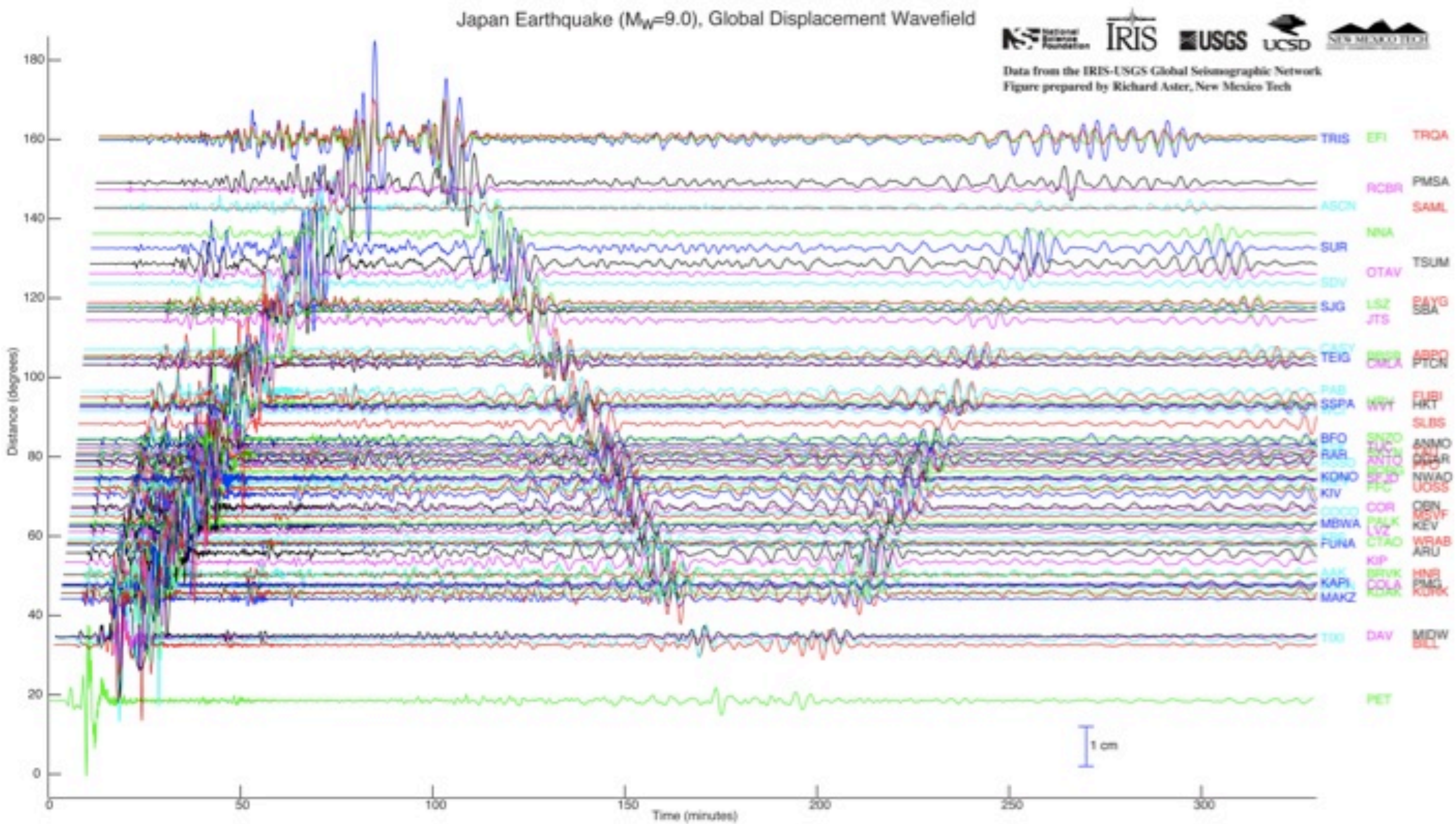


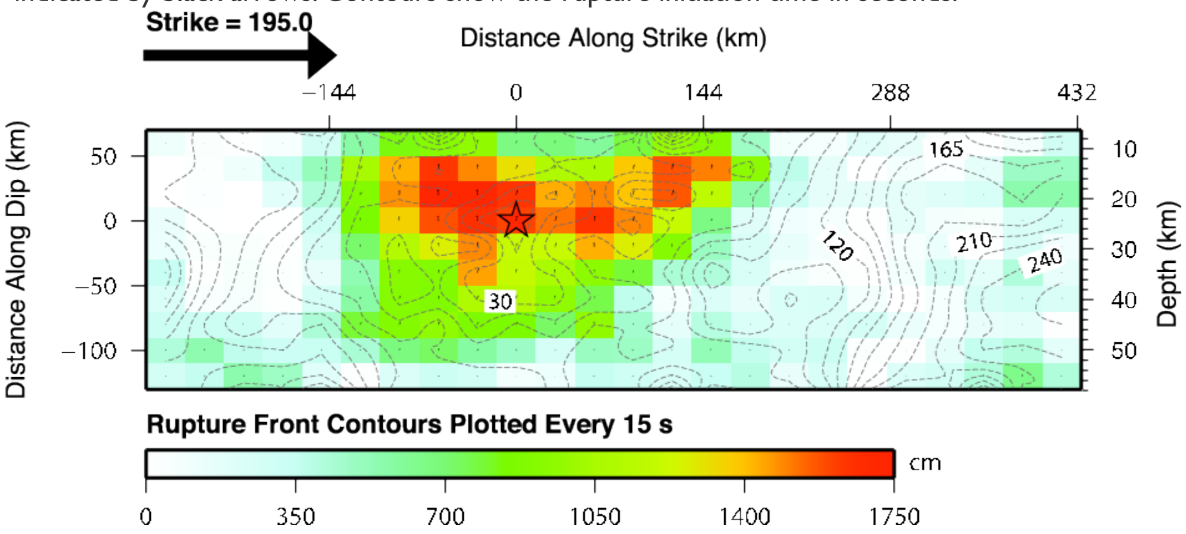
http://www.eqclearinghouse.org/2011-03-11-sendai/2011/04/04/tohoku-chapter-aij-reconnaissance-report-kurihara-city/

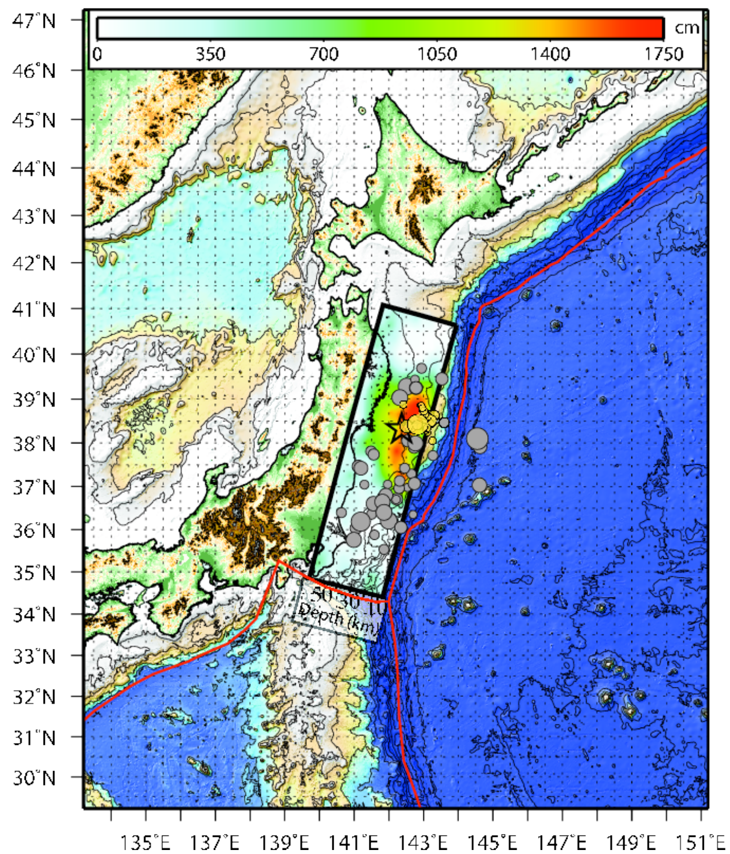
Ground motion - Worldwide

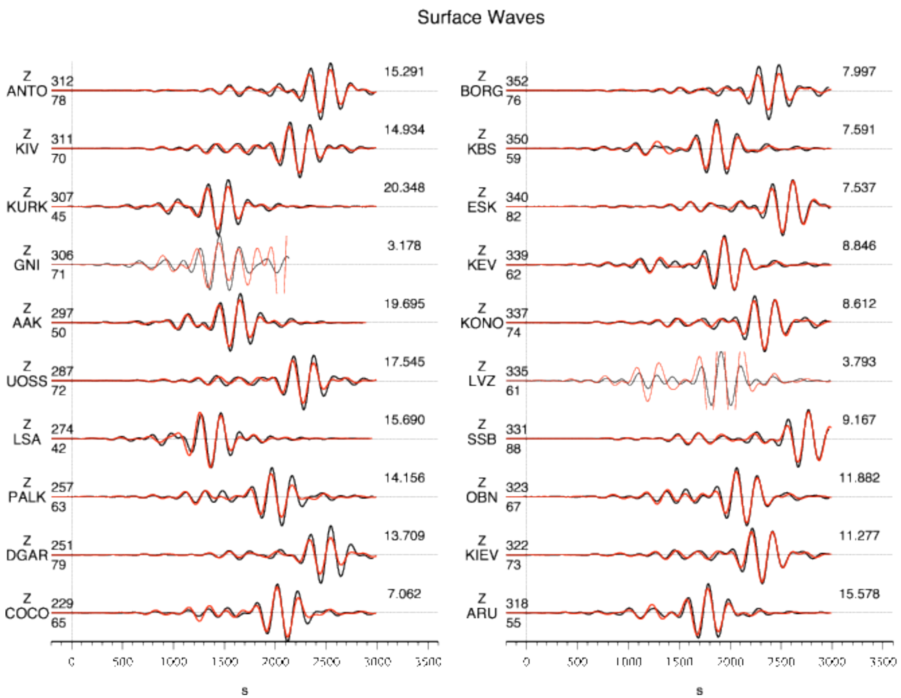


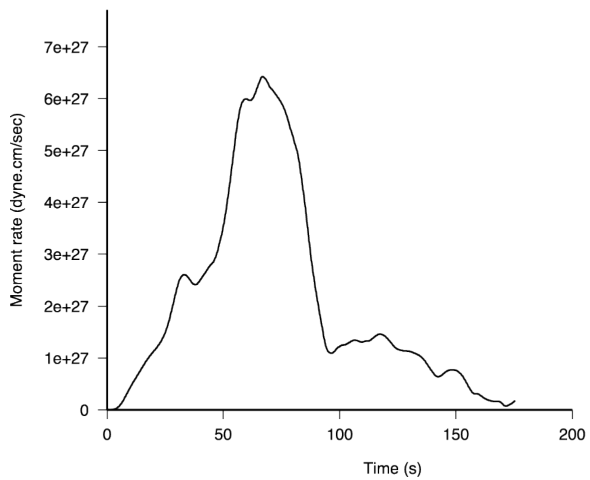
USGS - Finite fault model

Cross-section of slip distribution. The strike direction of the fault plane is indicated by the black arrow and the hypocenter location is denoted by the red star. The slip amplitude are showed in color and motion direction of the hanging wall relative to the footwall is indicated by black arrows. Contours show the rupture initiation time in seconds.

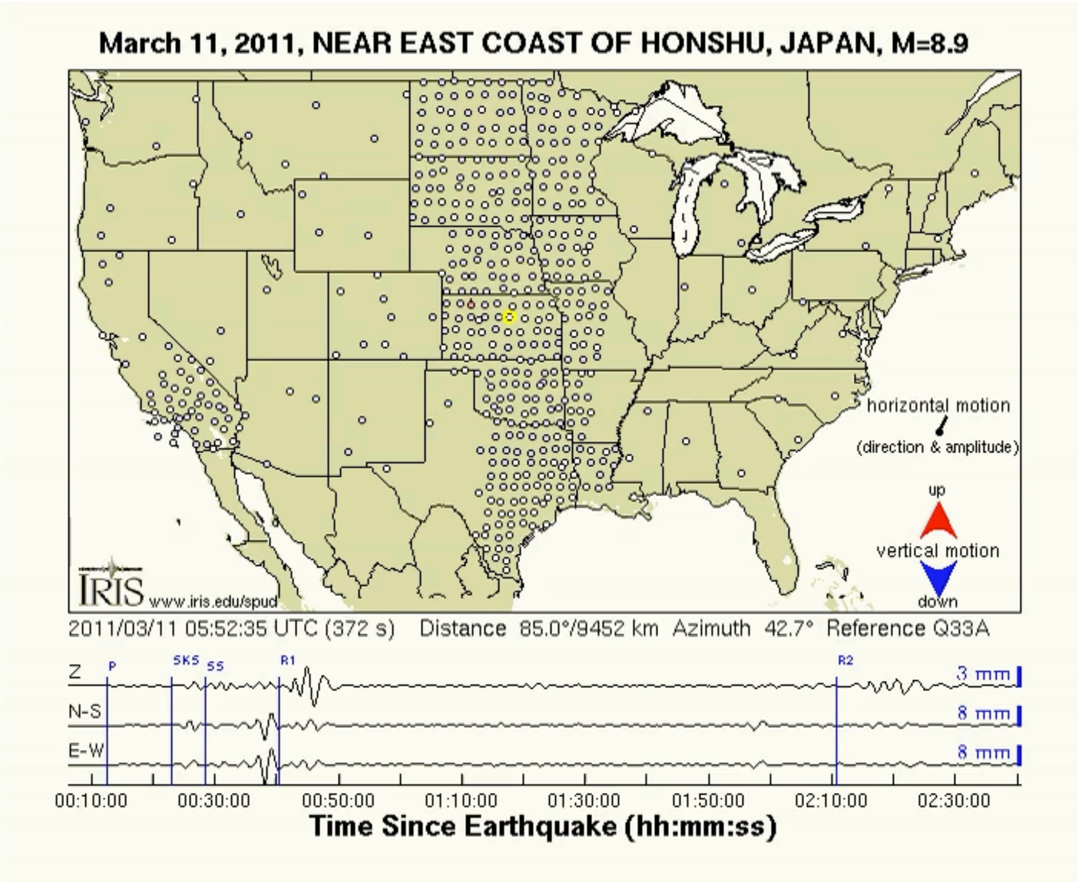


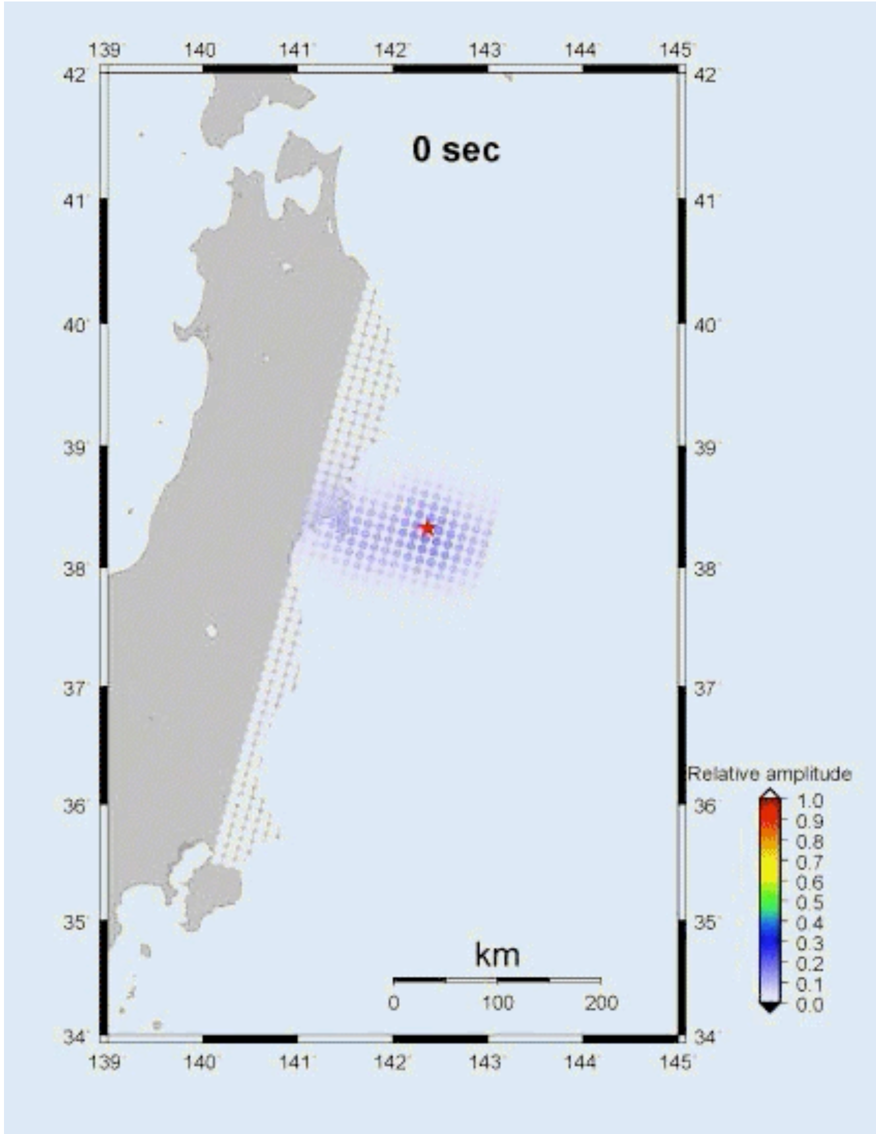






Ground motion - USA & backprojection





Courtesy of Dun Wang and Jim Mori