Strong Motion Characteristics and Their Damage Impact to Structures During **the Off the Pacific Coast of Tohoku Earthquake of March 11, 2011**; How Extraordinary Was This M9.0 Earthquake?

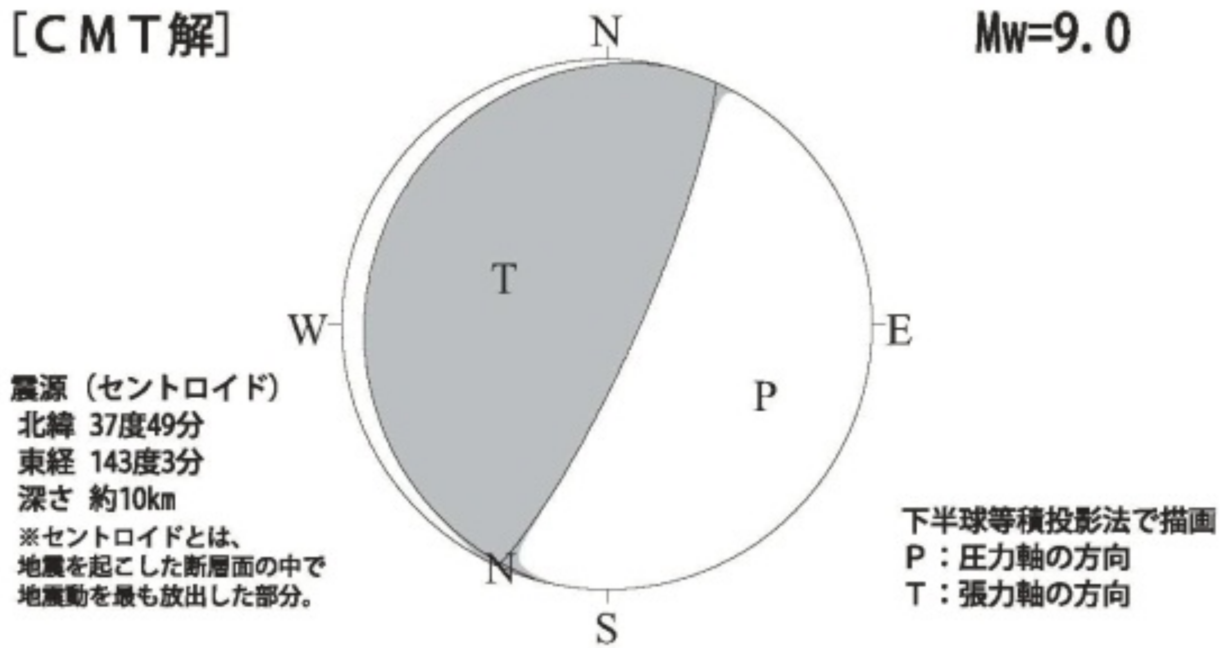
H. Kawase
(DPRI, Kyoto University)

What kind of the earthquake?

- A typical "plate boundary (subduction-zone) earthquake" between the Pacific plate and the North American plate of Japan Island.
- It started from the Miyagi-ken Oki area, where the highest probability of occurrence (99% in 30 years) was predicted.
- Two foreshocks occurred on 2005/08/16 (M7.3) and on 2011/03/09 (M7.3).
- No historical corresponding earthquake of this size was recorded.

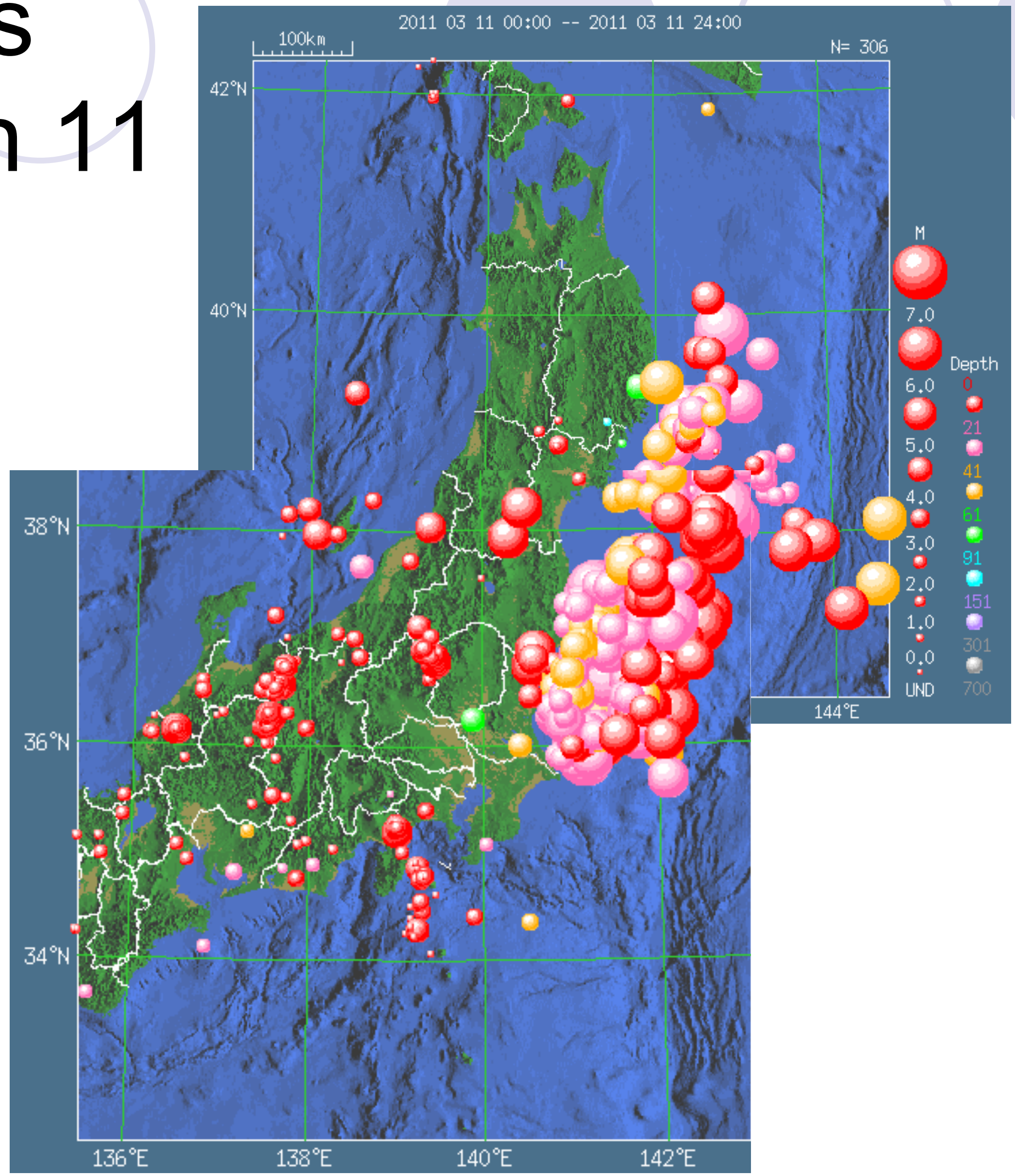
CMT Solution by JMA:M_0=4.22×10^{22}

Strike=193°, dip=10°, rake=79°, depth=10km



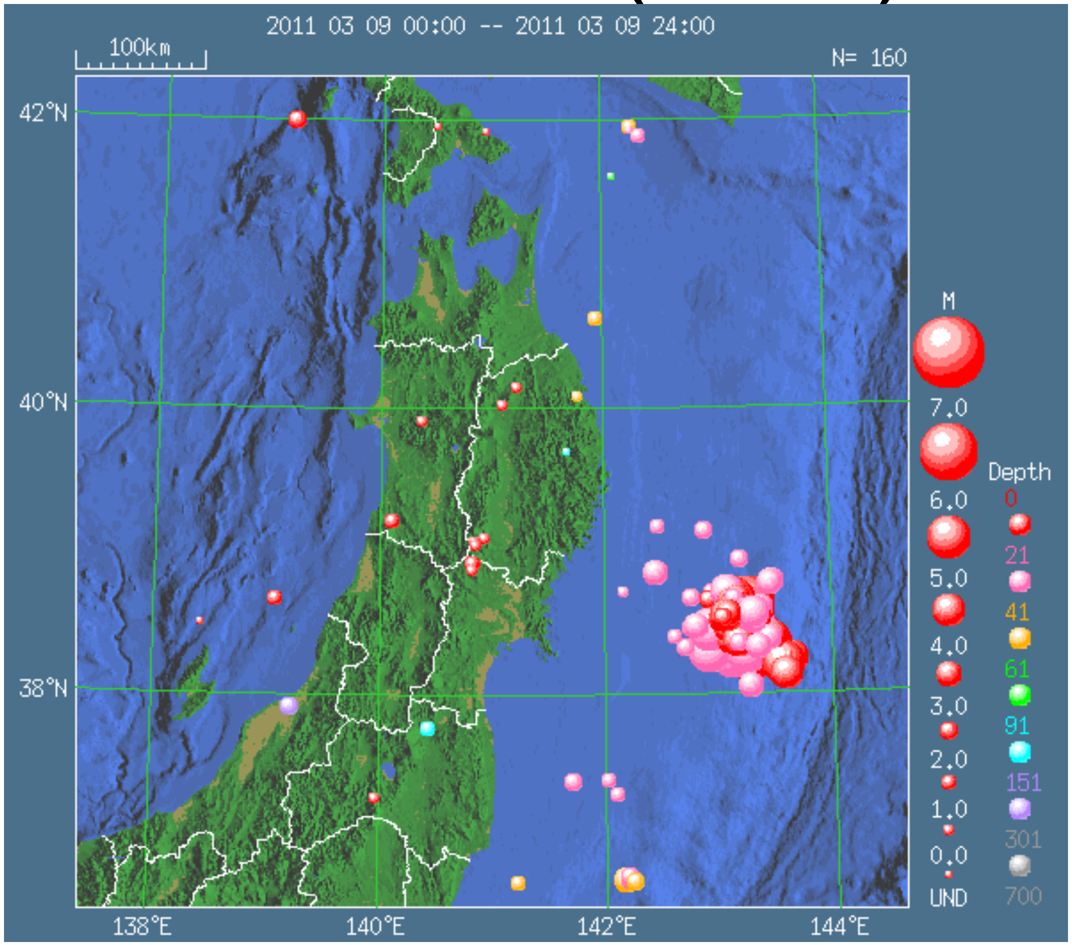
By JMA from http://www.seisvol.kishou.go.jp/eq/mech/cmt/fig/cmt20110311144618.html

Aftershocks
Only March 11



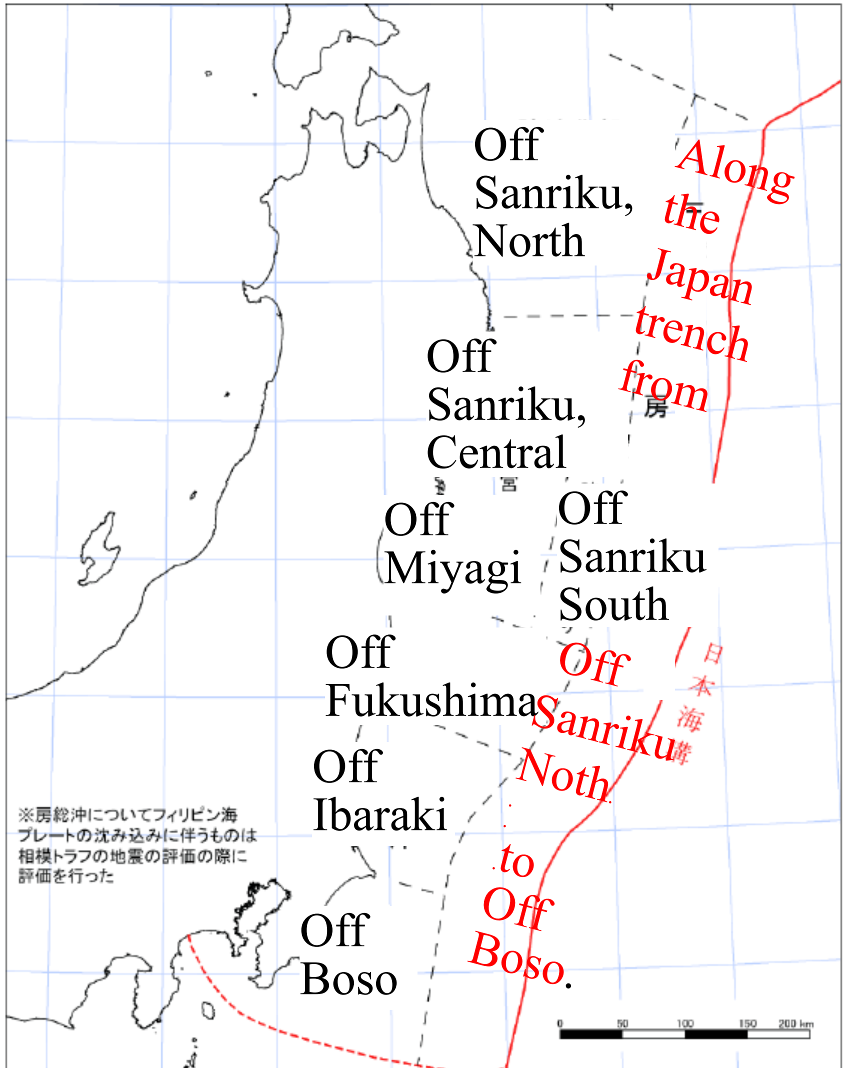
From JMA site http://www.seisvol.kishou.go.jp/eq/daily_map/sendai/ 20110311.shtml

Aftershocks of the Miyagi-Oki earthquake on March 9 (M7.3)

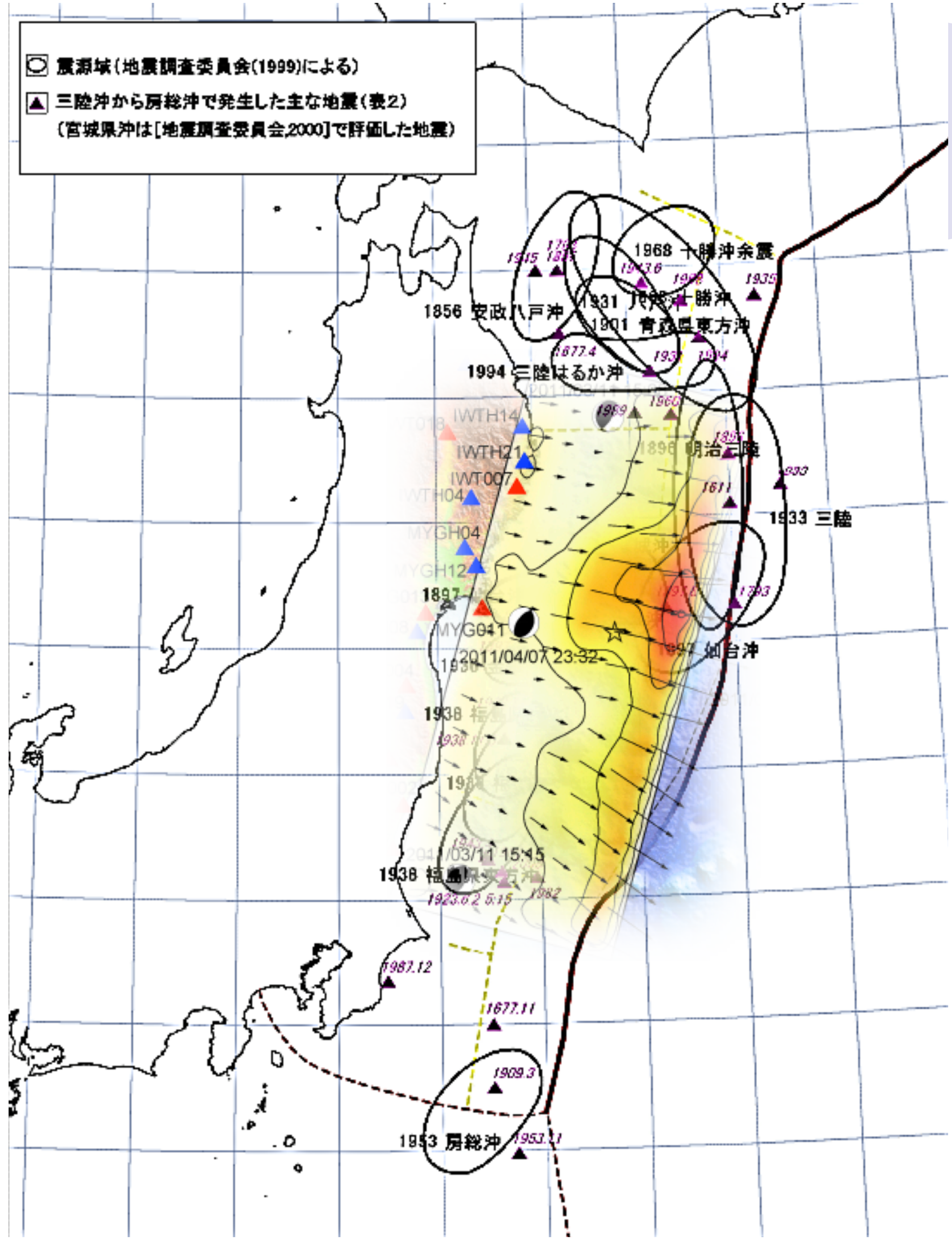


From JMA site http://www.seisvol.kishou.go.jp/eq/daily map/sendai/ 20110311.shtml

Assumed segments of earthquake occurrence along the Pacific Coast of the Tohoku Region (HERP, 2009).

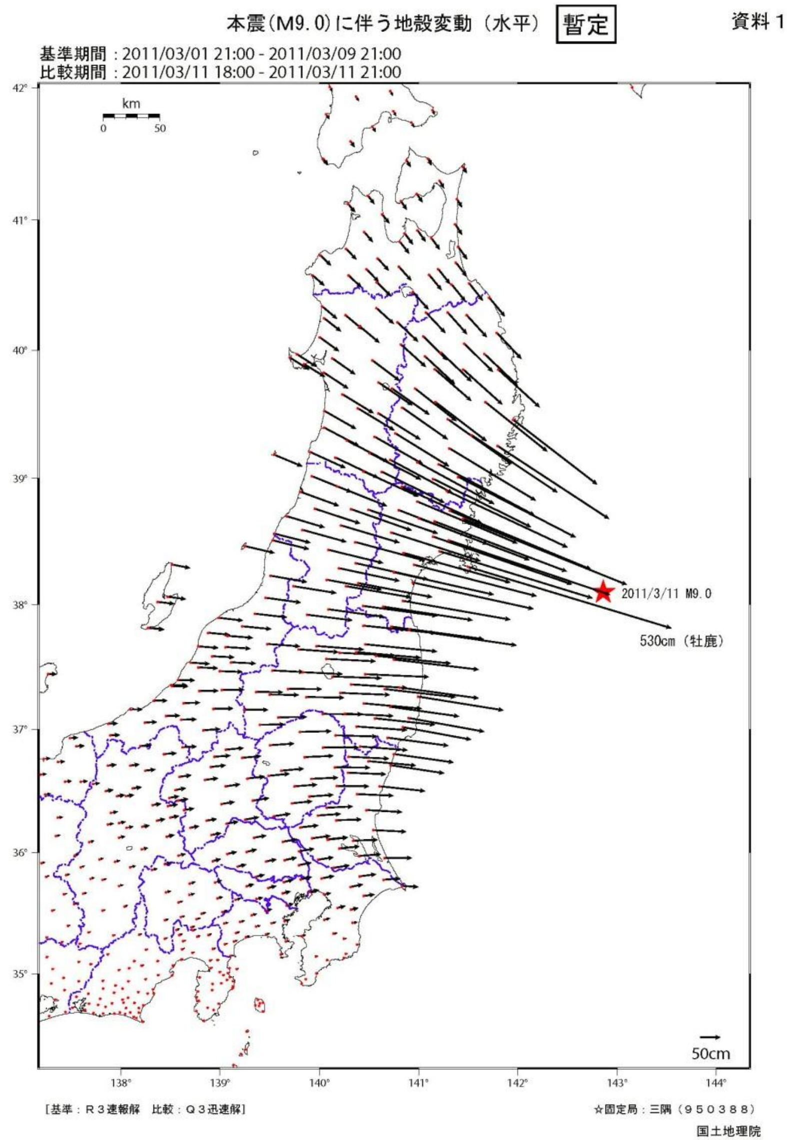


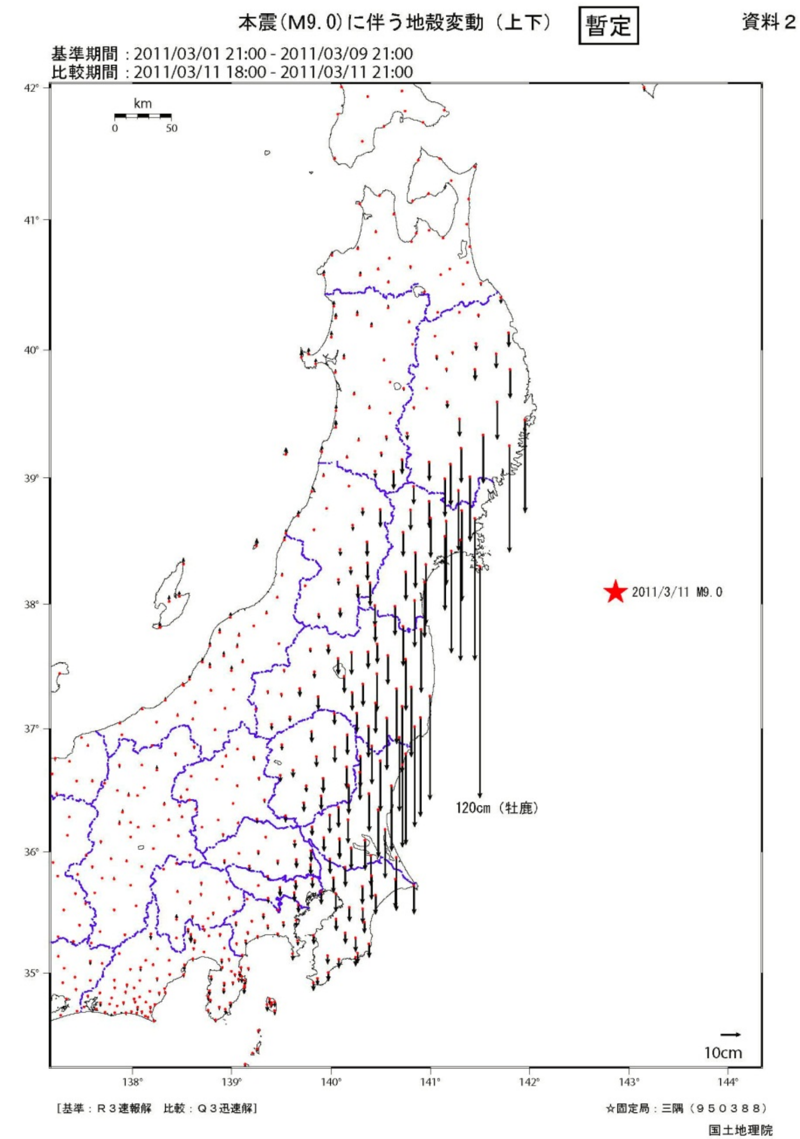
Source areas of earthquakes in Tohoku from 1923 to 2008 and inverted slip distribution by NIED.



From http://www.jishin.go.jp/main/chousa/ 09mar_sanriku/f01.htm

Crustal deformation by GPS network

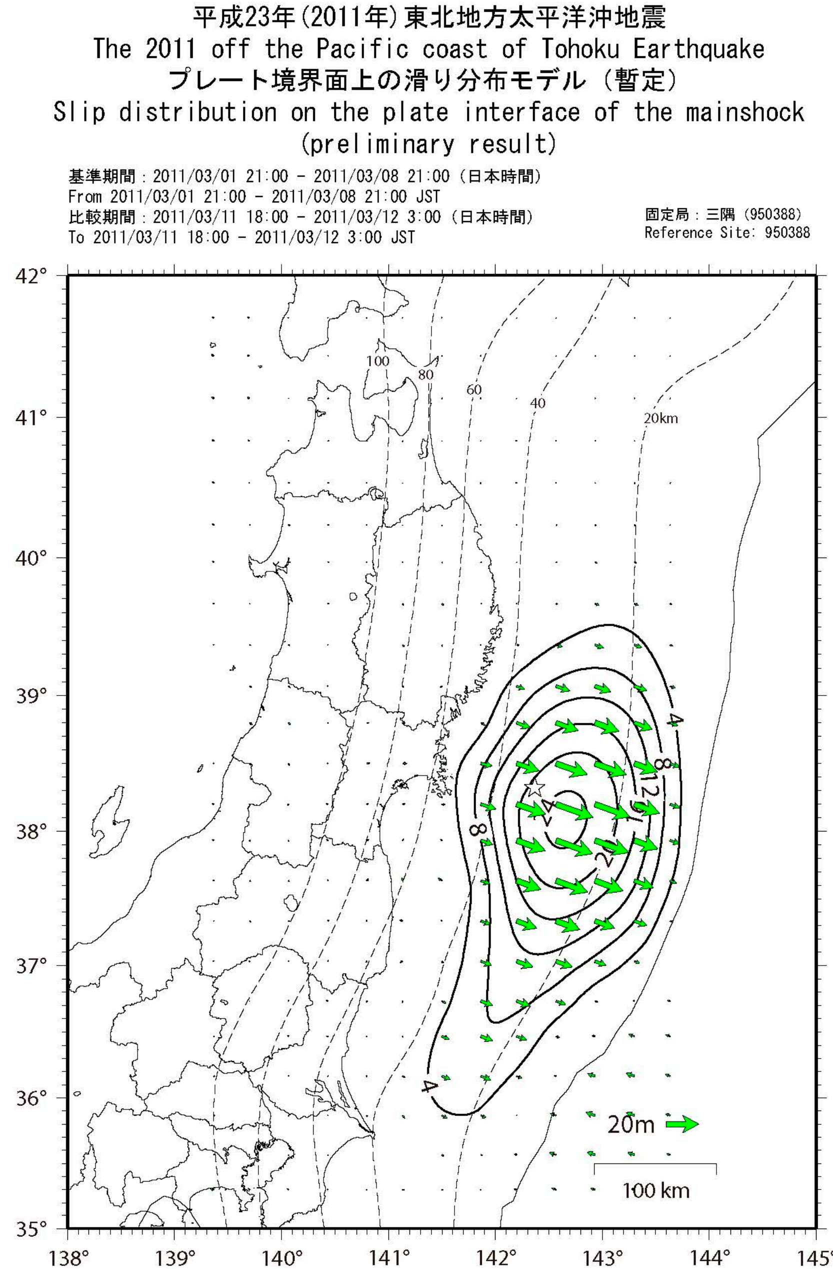




By G.S.J. from http://www.jishin.go.jp/main/chousa/ 09mar_sanriku/f01.htm

Slip distribution along the fault inverted from GPS crustal deformation only.

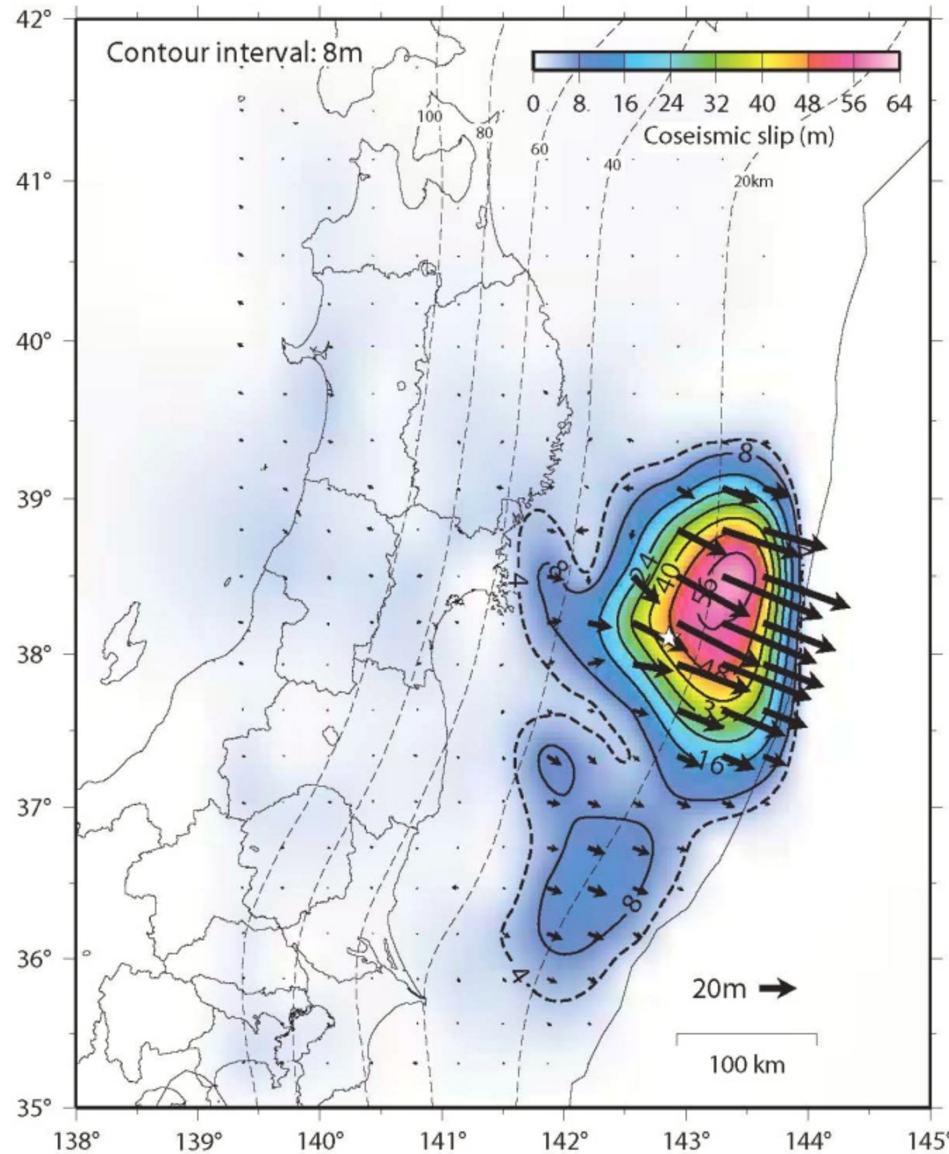
Near the hypocenter they obtained 25m slip, while to the south they did only 4 m～8m.



From GSJ site

Slip distribution along the fault inverted from GPS crustal deformation and ocean bottom deformation sensors.

Near the hypocenter they obtained 60 m slip, while to the south they found another robe with maximum slip of 10m.



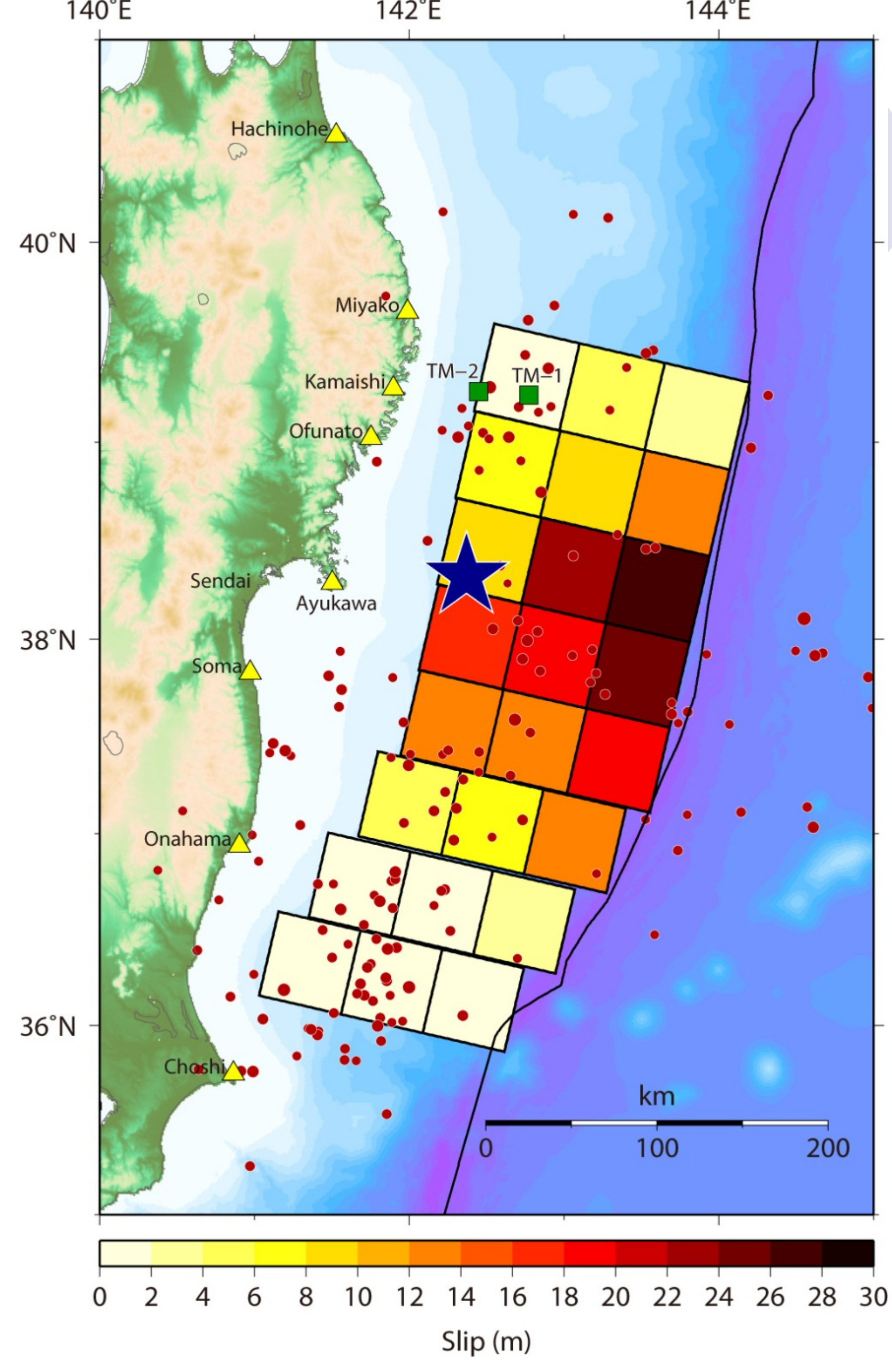
星印は本震の震央.
地震時の滑りのモーメントマグニチュードは 9.0（剛性率 40GPa ）
点線はプレート境界面の深さを示す

※図のベクトル（矢印）は、地表や海底の変動ではなく、
計算によって求めた地下のプレート境界面上でのすべりを示したものです

From GSJ site

Slip distribution by BRI based on the Tunami waveforms.

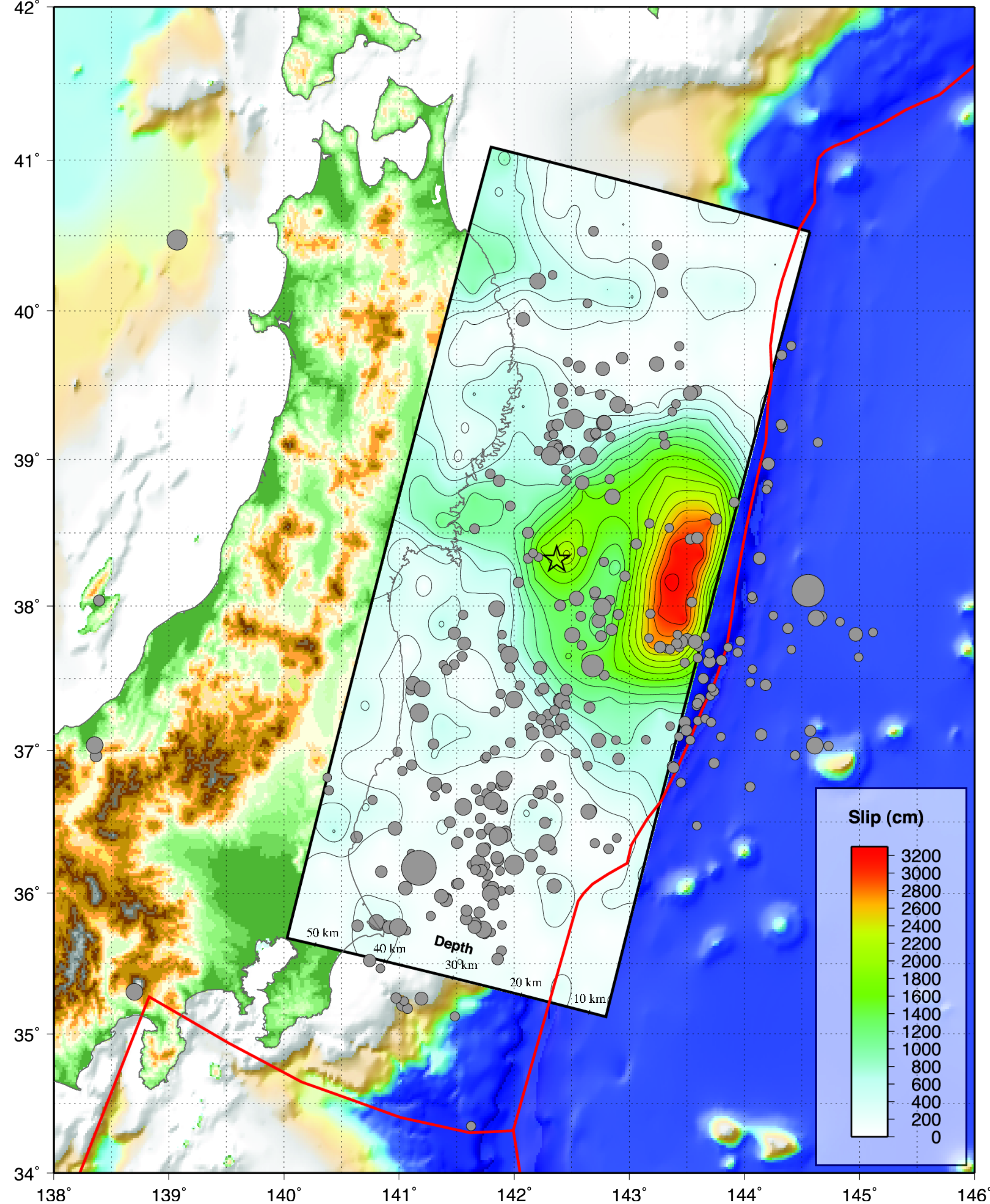
Near the hypocenter they obtained 30m slip, while to the south they did only 4 m～8m.



From BRI web site

Slip distribution by USGS based on the teleseismic seismic waveforms.

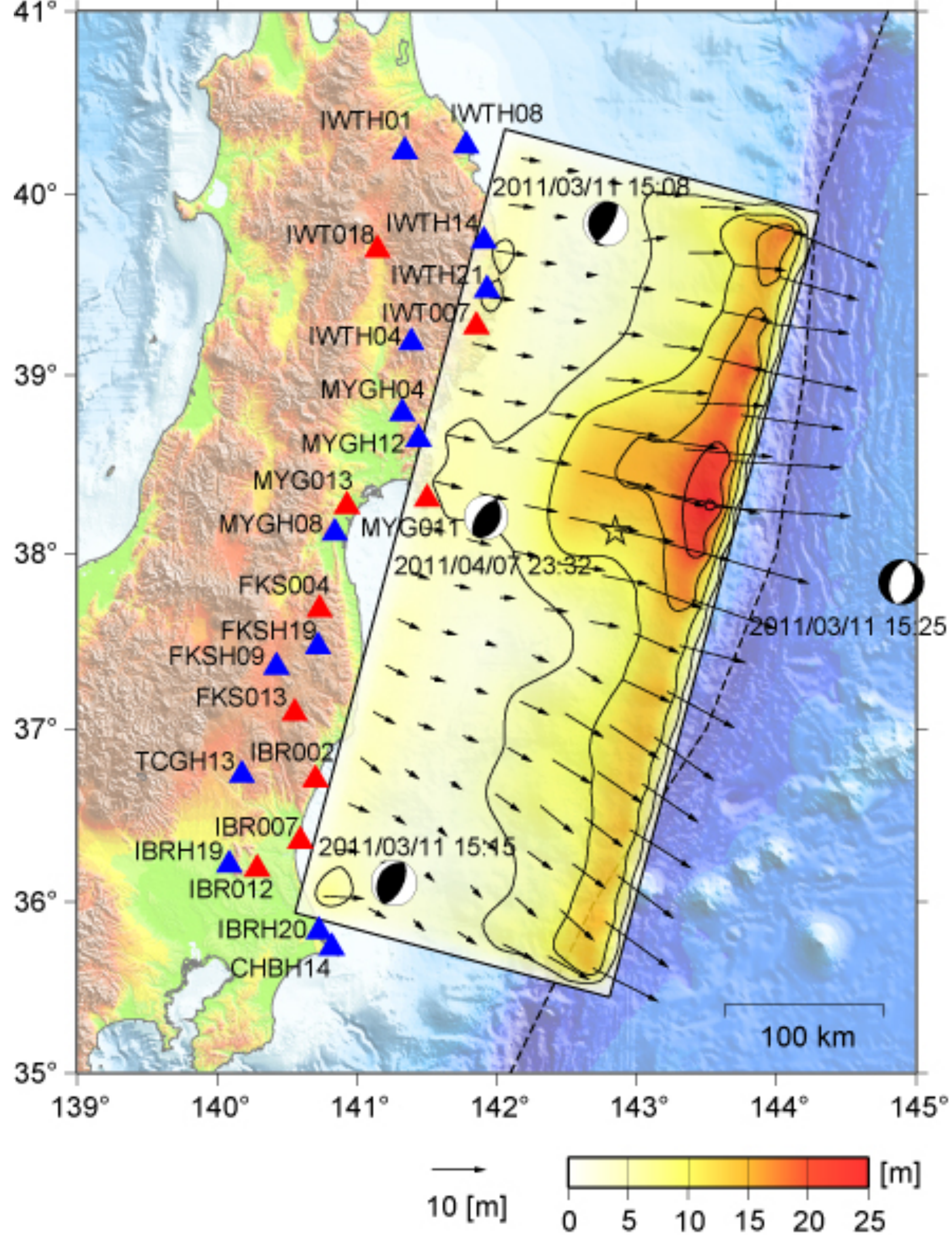
East of the hypocenter they obtained 30m slip, while to the south they did only less than 10m.



From USGS web site

Slip distribution by NIED based on the strong motion waveforms (>8sec.)

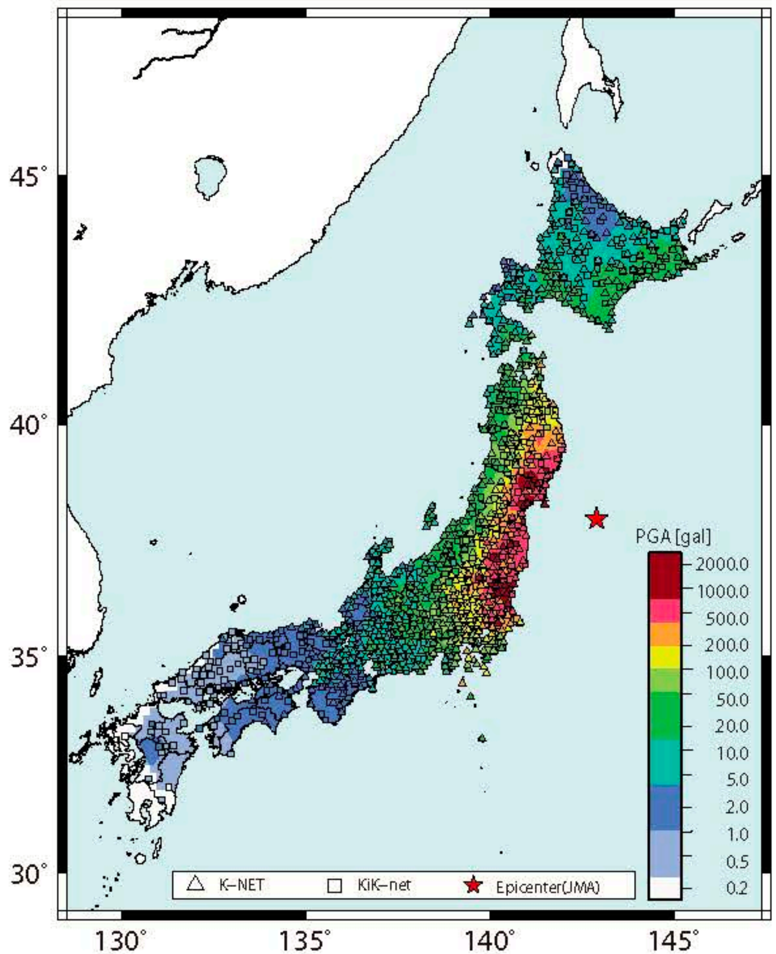
Near the hypocenter they obtained 25m slip, while to the south they did only 5m～10m.



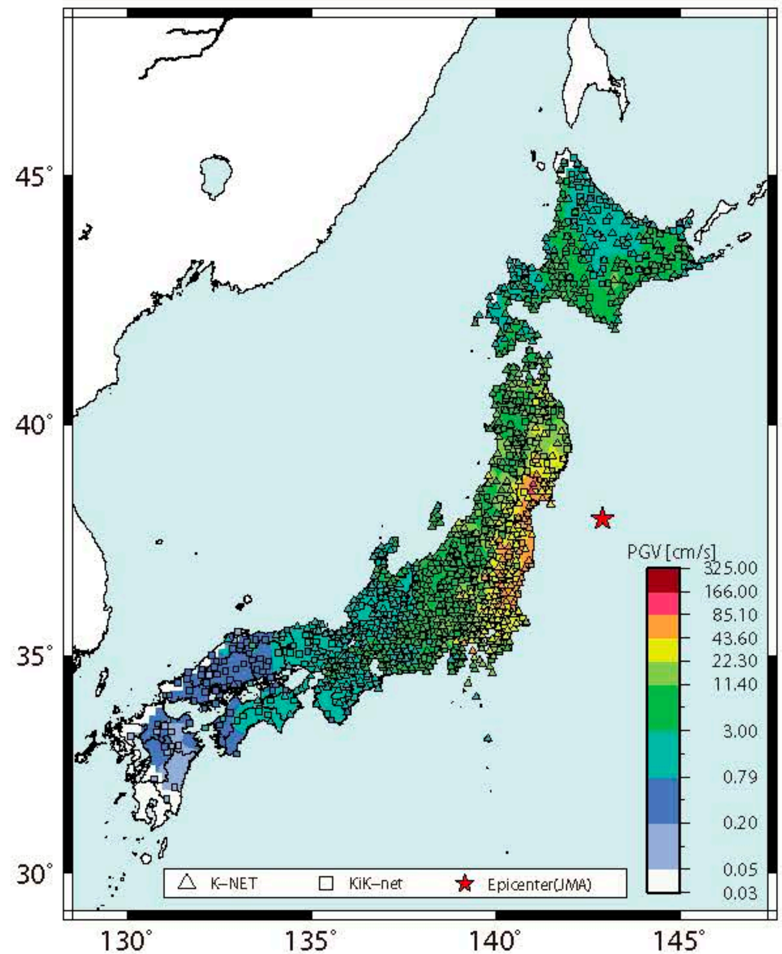
From NIED web site

PGA and PGV distribution by K-NET & KiK-net

Peak Ground Acceleration



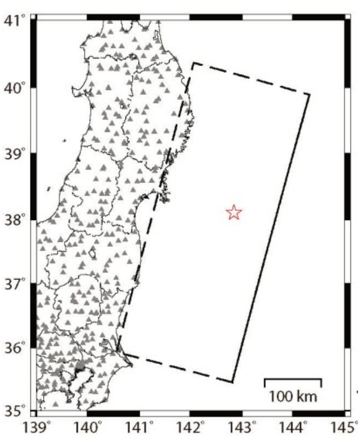
Peak Ground Velocity



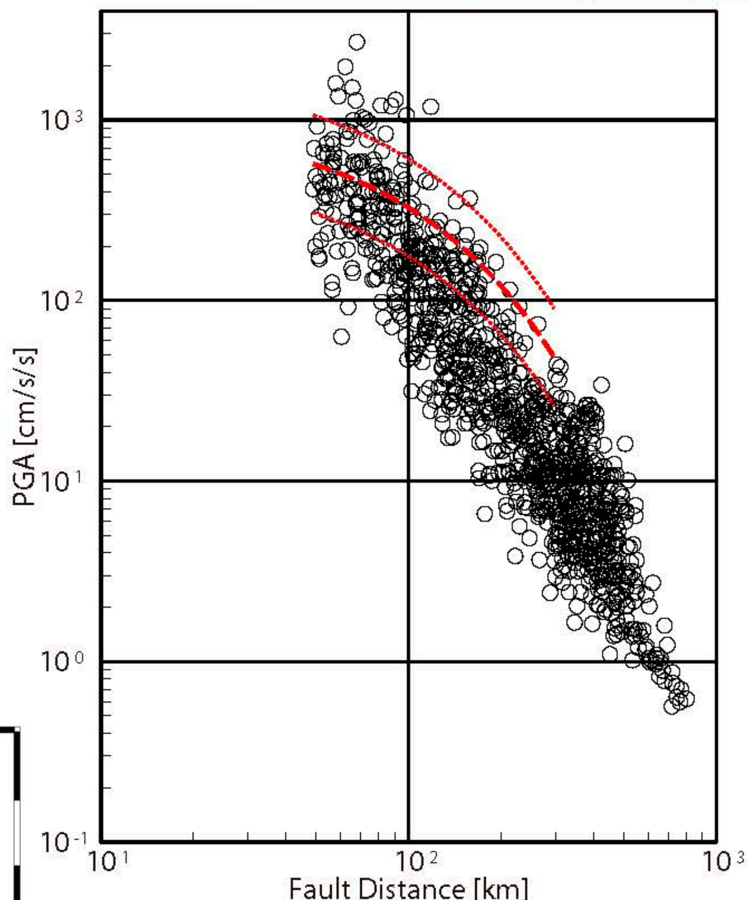
From NIED web site

Attenuation relationship by K-NET & KiK-net

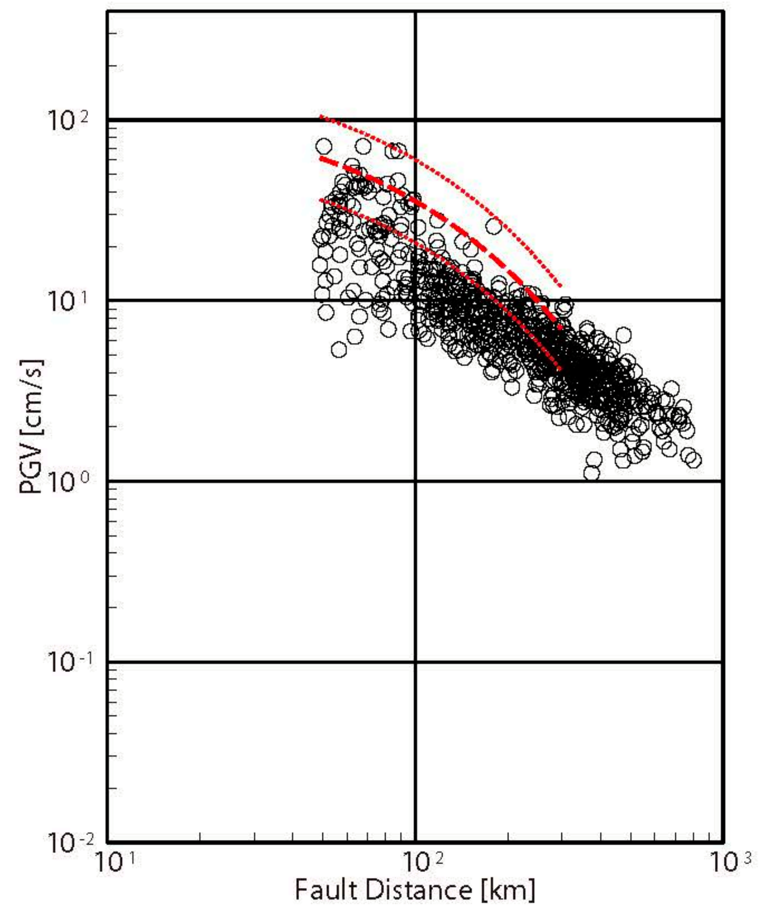
If we use shortest distance to the fault (below), PGAs in the far field look small



2011/03/11 14:46 Depth=24km(JMA), Mw=9.0
Si & Midorikawa (1999) inter-plate



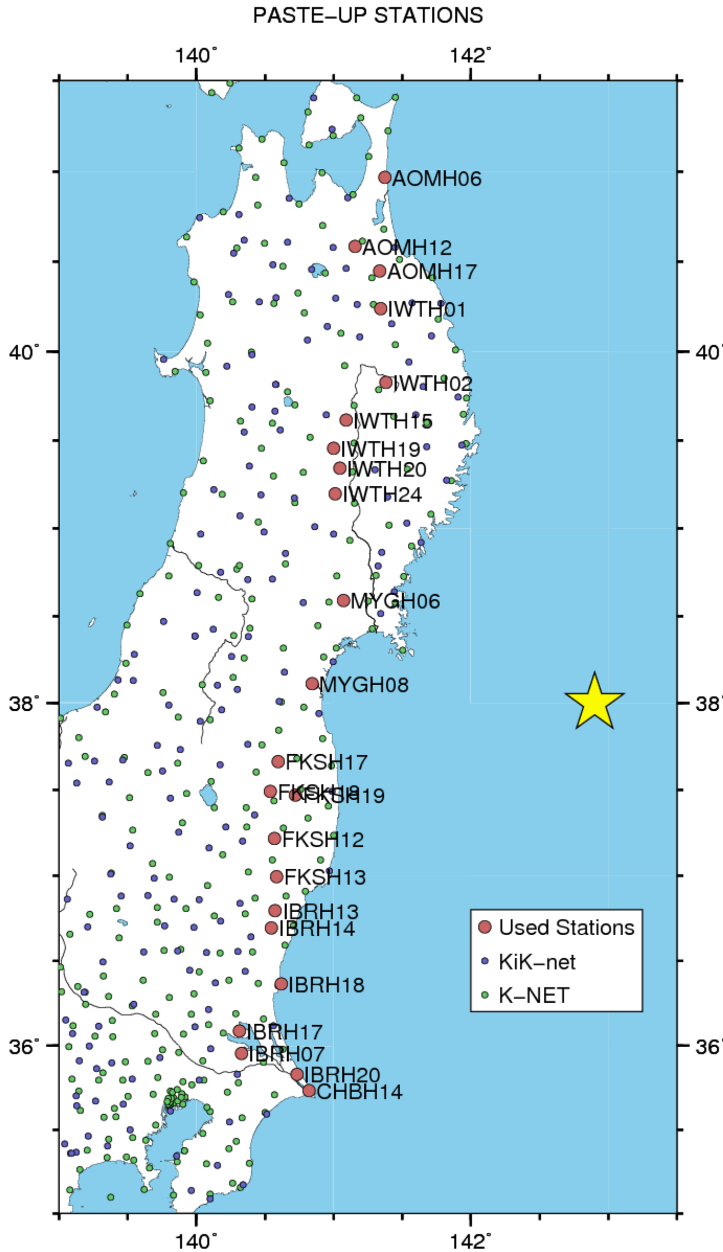
Peak Ground Acceleration
cm/s^2

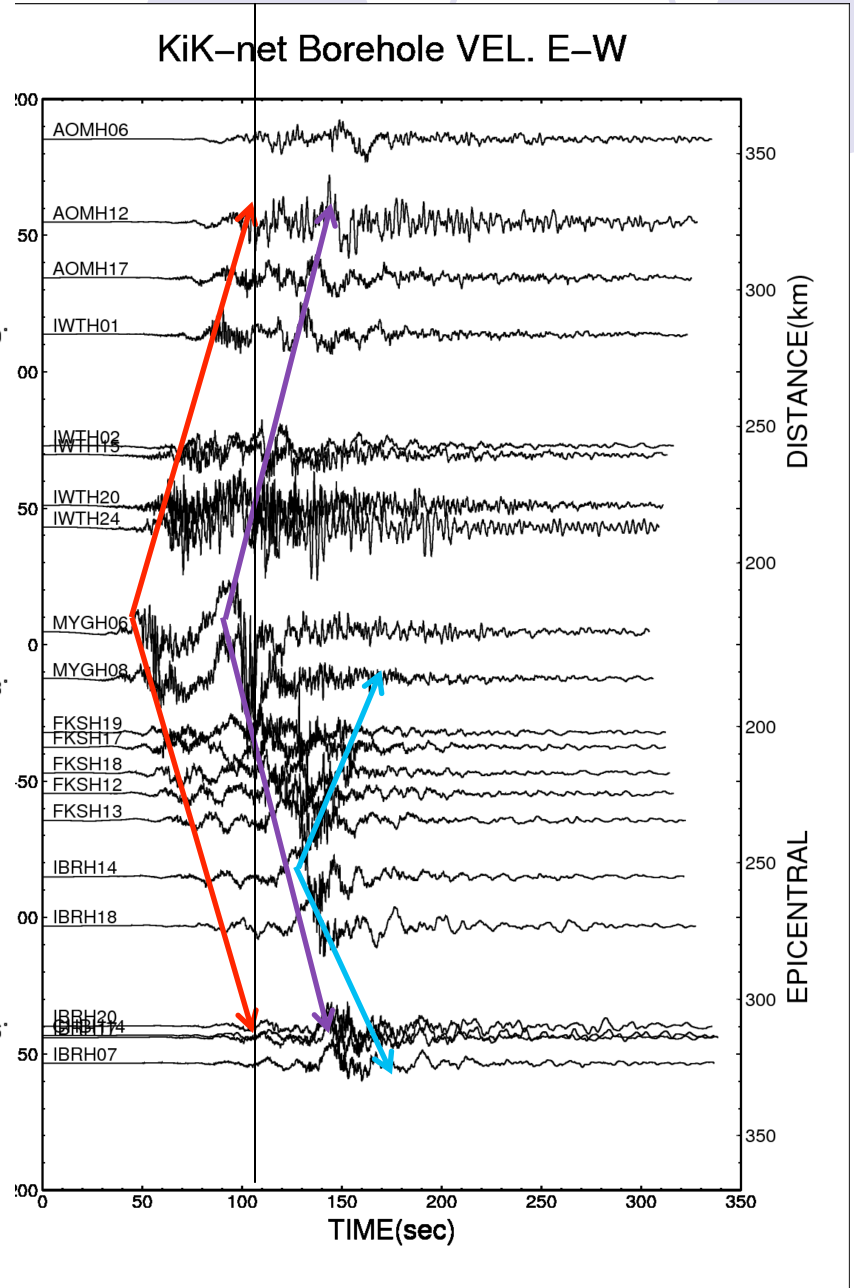


Peak Ground Velocity
cm/s

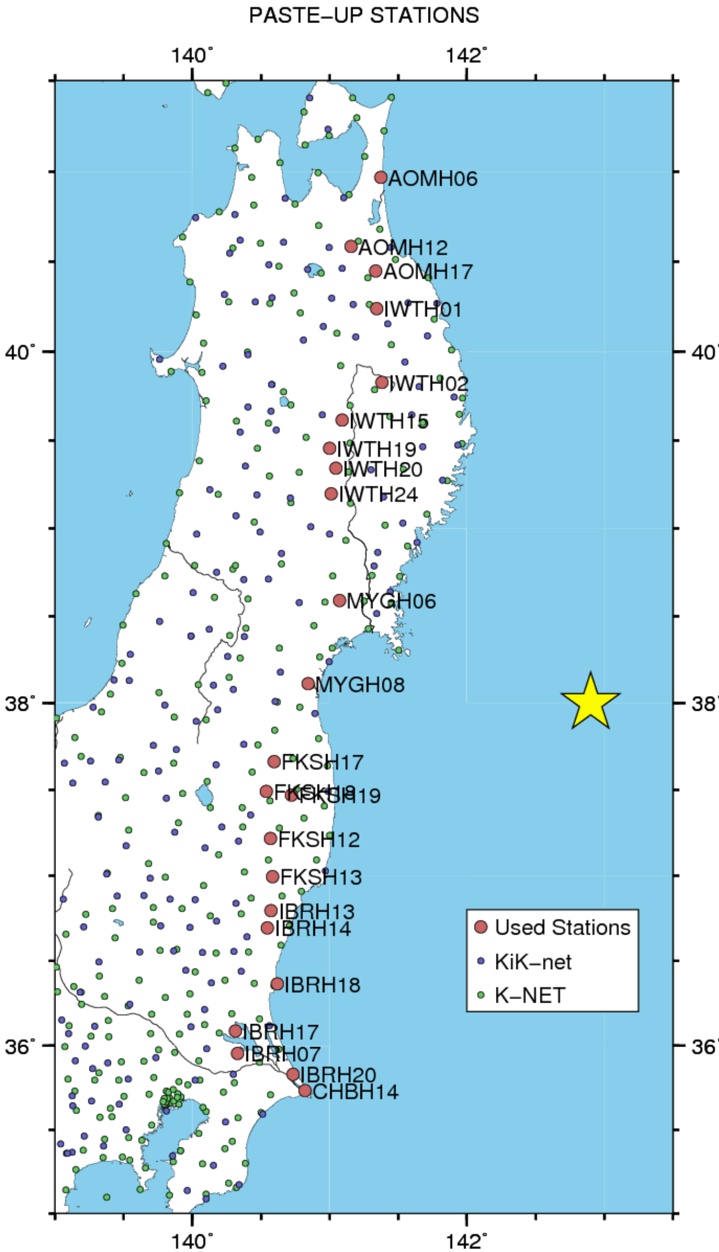
By NIED

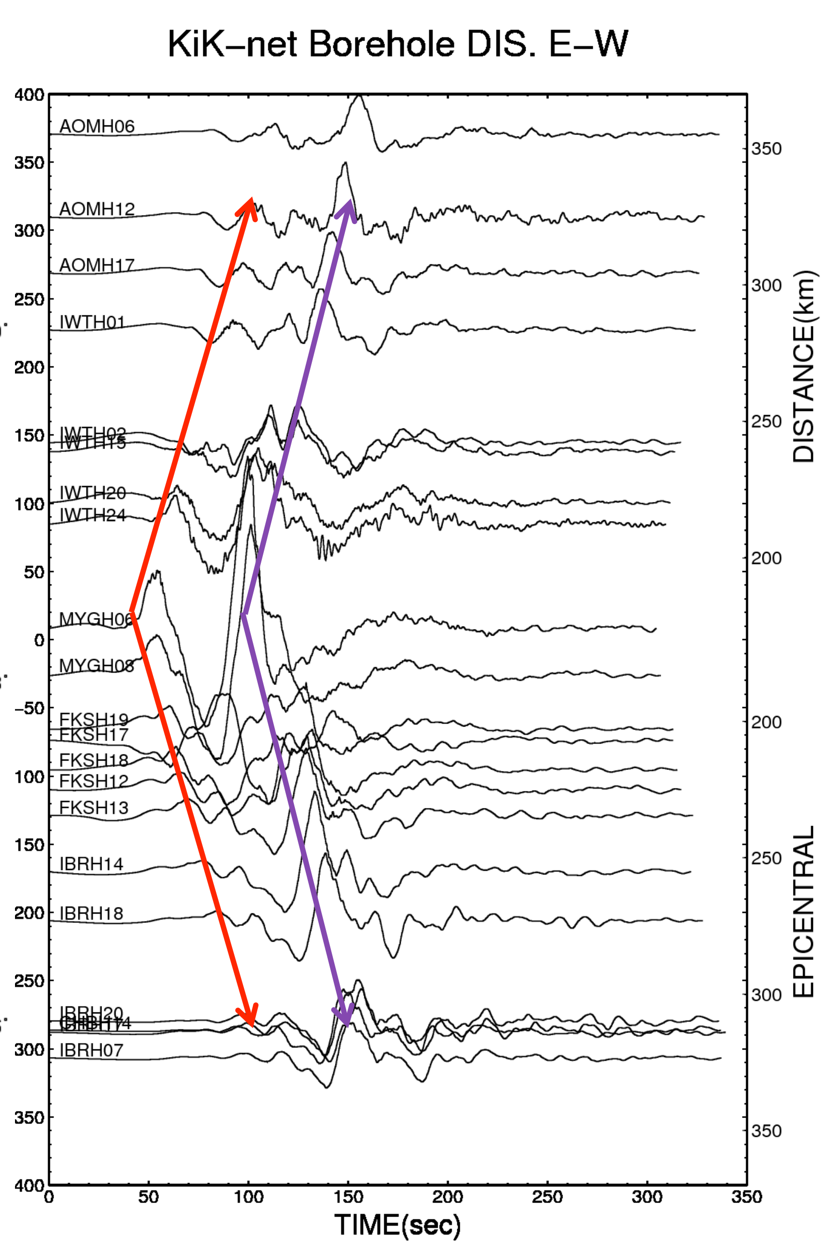
Velocity waveforms of KiK-net data (borehole)





Displacement waveforms of KiK-net data (borehole)

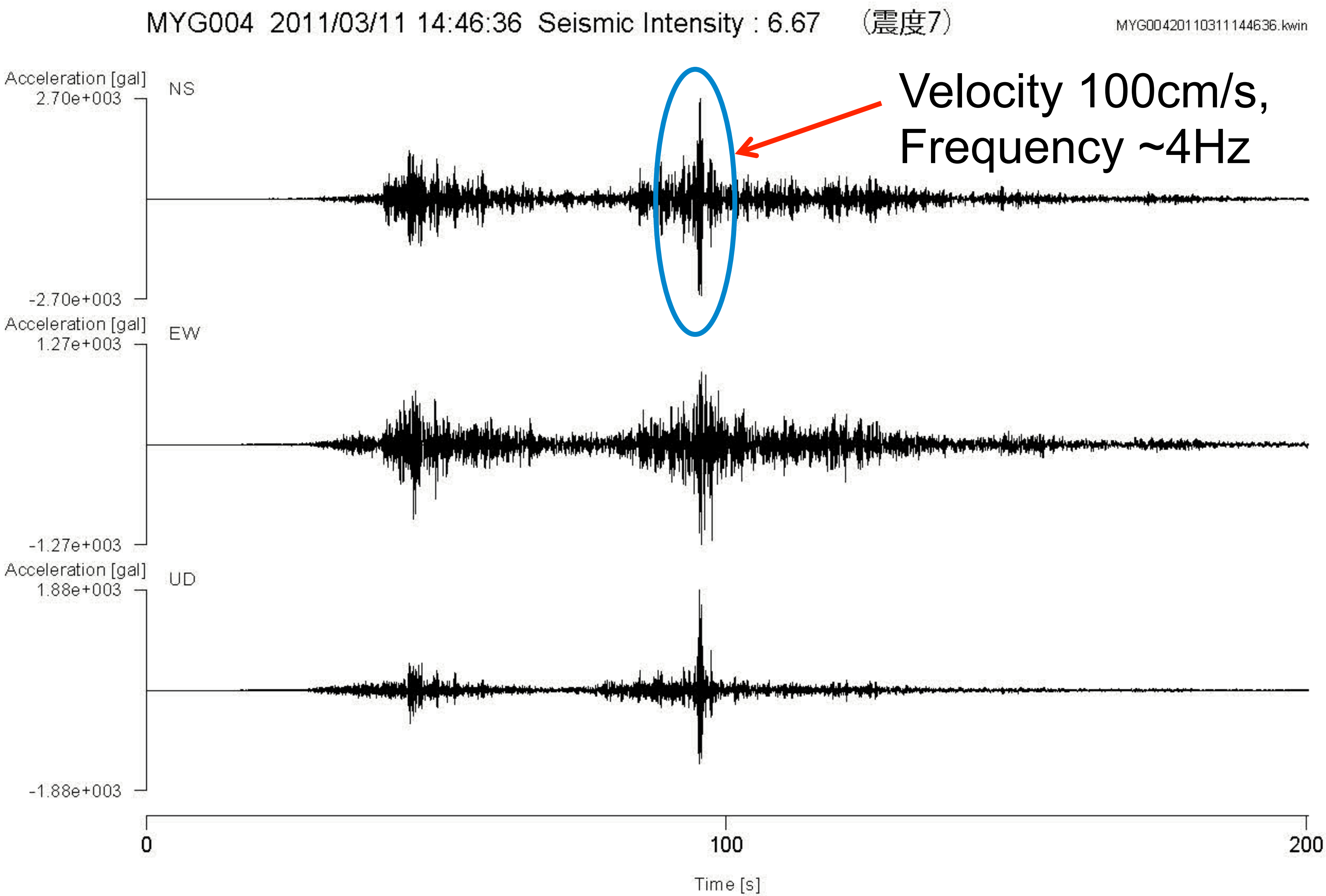




High PGA sites

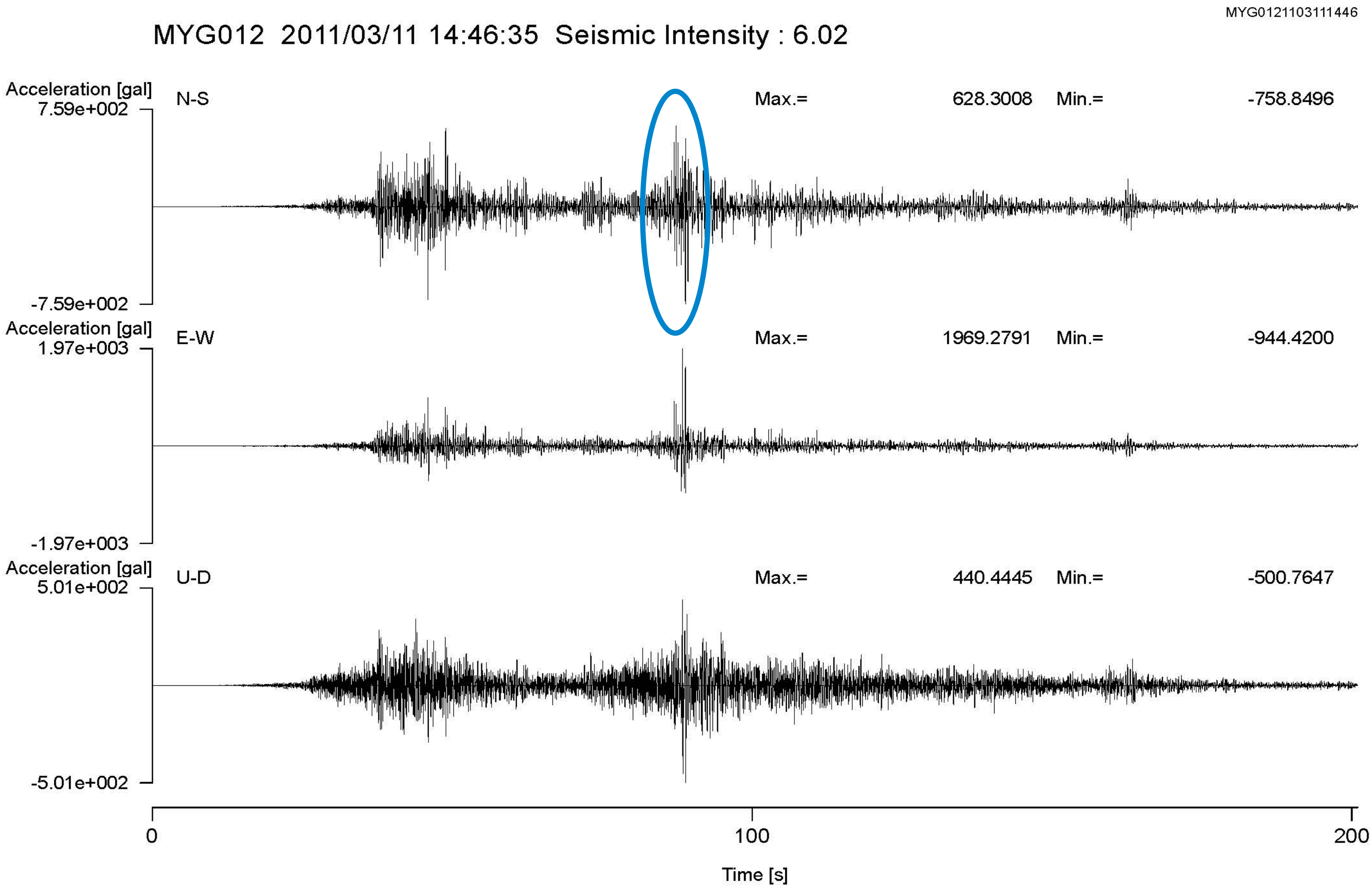
Site code	Name	PGA NS	PGA EW	PGA UD	Vector
MYG004	Tukidate	2,700	1,268	1,880	2,933
MYG012	Shoigama	758	1,969	501	2,019
IBR003	Hitachi	1,598	1,186	1,166	1,845
MYG013	Sendai	1,517	982	290	1,808
IBR013	Hokota	1,355	1,070	811	1,762
TCG009	Imaichi	1,017	1,186	493	1,444
FKS016	Shirakawa	1,295	949	441	1,425
FKSH10	Saigo	1,062	768	1,016	1,335
IBR004	Oomiya	1,283	1,007	775	1,312
TCGH16	Haga	799	1,197	808	1,305
TCG014	Mogi	711	1,205	494	1,291
IWT010	Ichinoseki	998	852	353	1,226
IBRH11	Iwase	815	827	815	1,224
MYGH10	Yamamoto	871	853	622	1,137
FKS018	Kooriyama	745	1,069	457	1,110
FKS008	Funabiki	1,012	736	327	1,069
IBRH15	Omaeyama	606	781	640	1,062
CHB007	Sakura	1,036	491	200	1,054

K-NET Tsukidate（MYG004) strong motion record



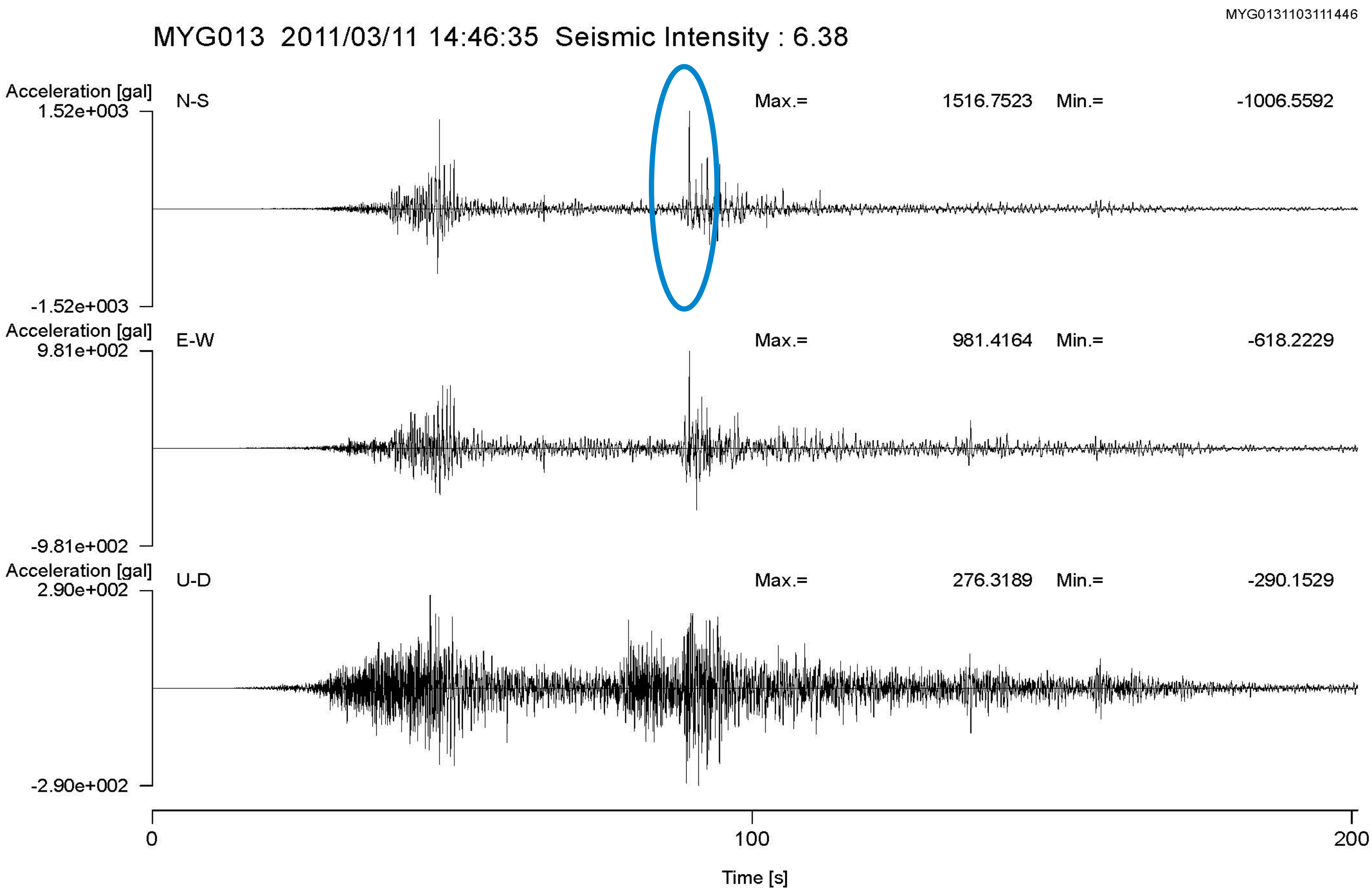
By NIED

K-NET Shiogama（MYG012) strong motion record

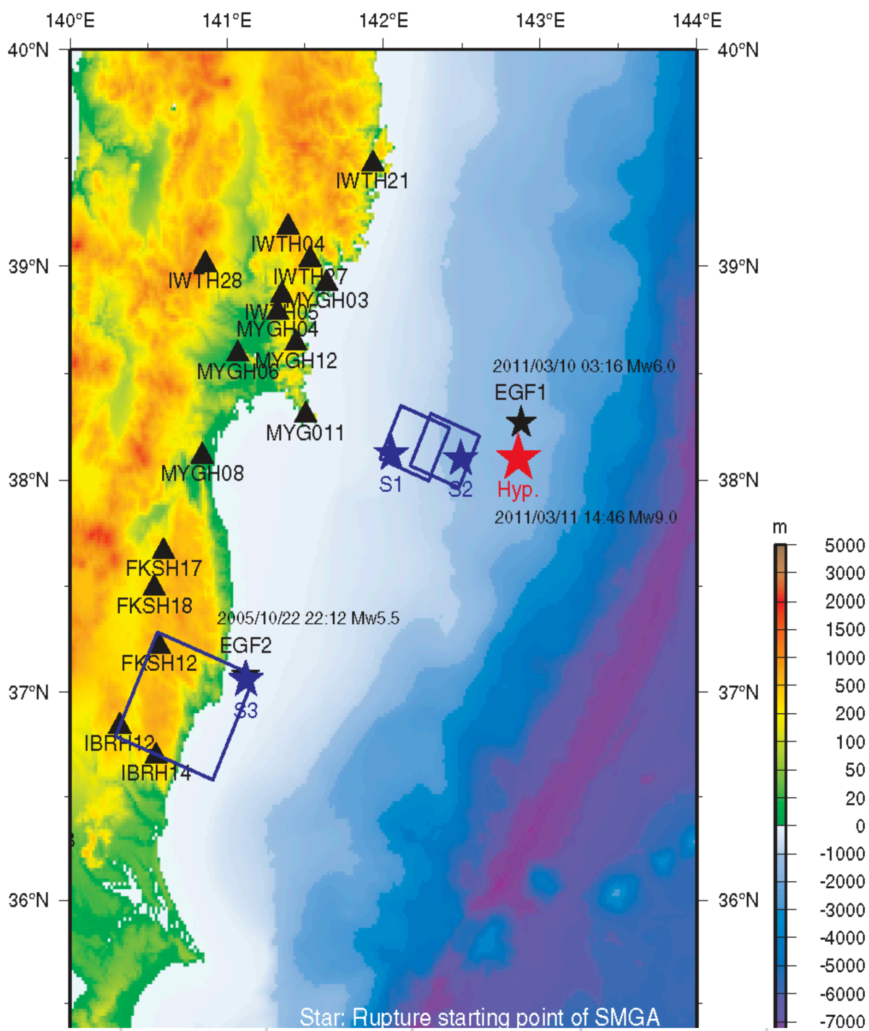


By NIED

K-NET Sendai（MYG013) strong motion record



By NIED

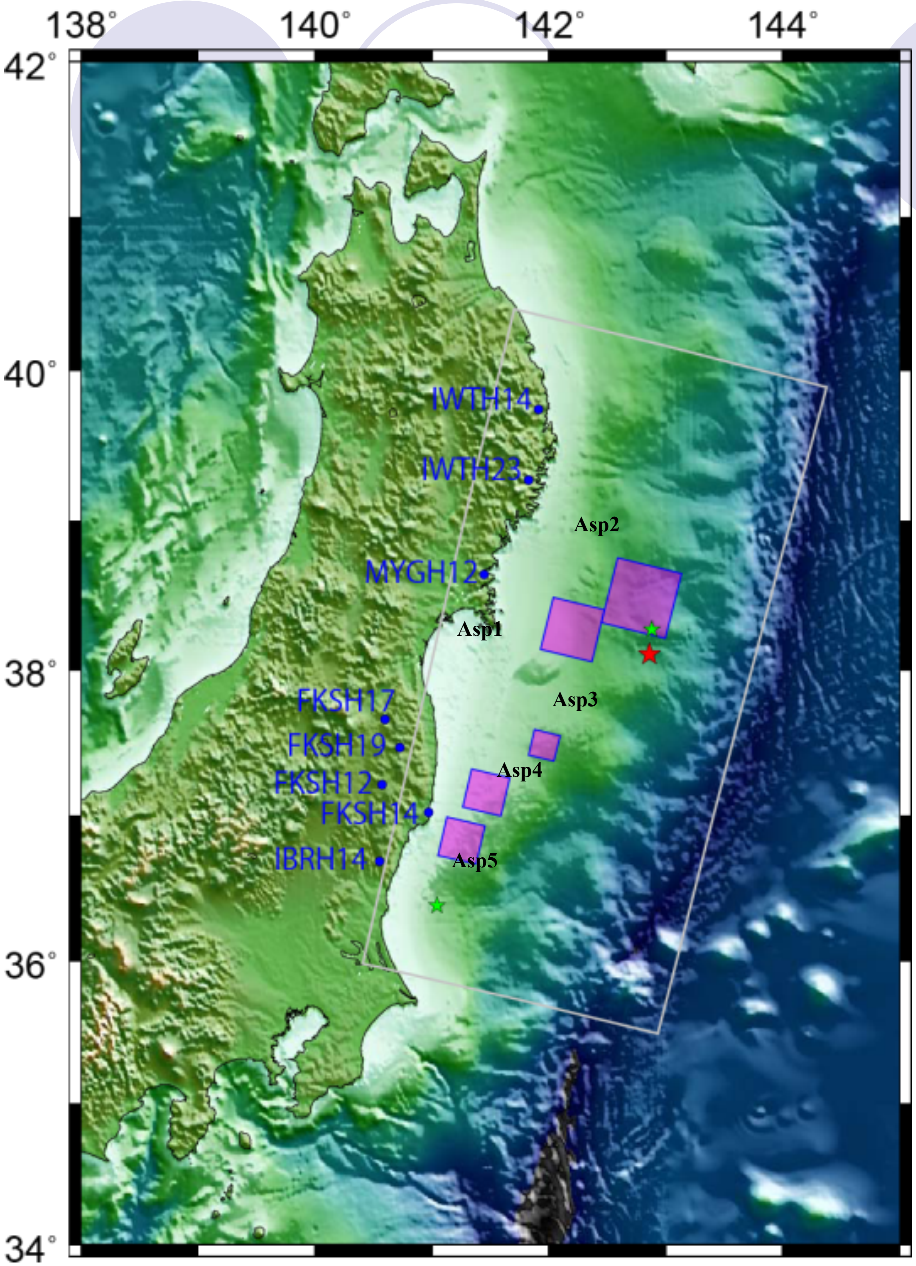


Asano & Iwata(SSA 2011http://sms.dpri.kyoto-u.ac.jp/) obtained 3 strong motion generation areas (SMGA) .

They found 2 SMGAs west of the hypocenter★（Mw7.6&7.7) and another SMGA（Mw7.7) in Fukushima.

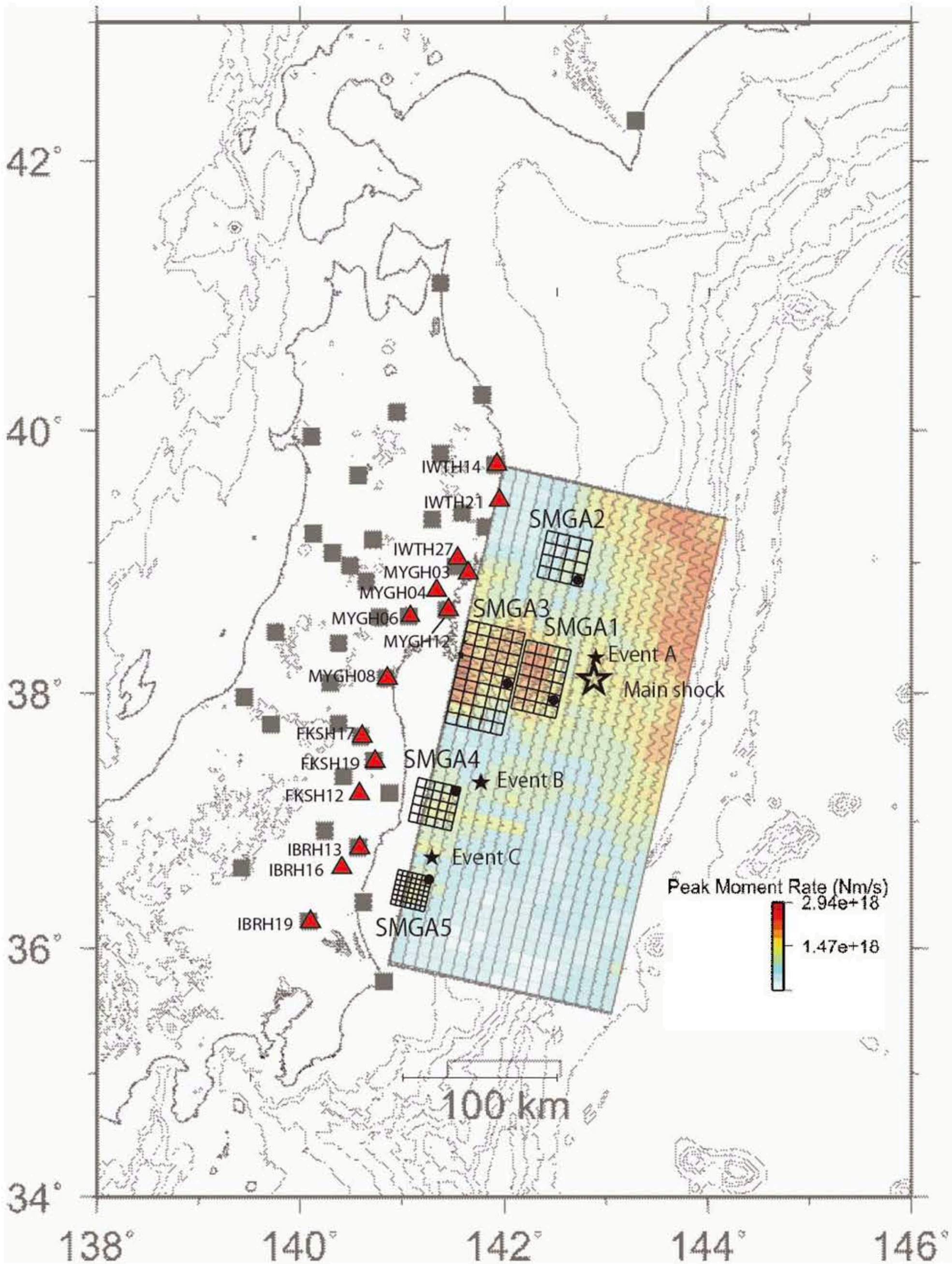
Total moment corresponds only Mw8.0.

	Length (km)	Width (km)	Area (km^2)	Rise Time (s)	M_0 (Nm)	Δσ (MPa)	Rupture Starting Point of SMGA			Delay Time from Origin Time (s)
							Latitude (deg)	Longitude (deg)	Depth (km)	
S1	30	30	900	0.60	3.05×10^{20}	27.5	38.125	142.052	35.4	25.0
S2	30	30	900	0.60	4.57×10^{20}	41.2	38.102	142.494	29.0	67.2
S3	60	60	3600	1.36	4.20×10^{20}	4.7	37.059	141.123	40.5	114.3



Likewise, Kawabe et al (2011) obtained strong motion generation areas by using the empirical Green function method.

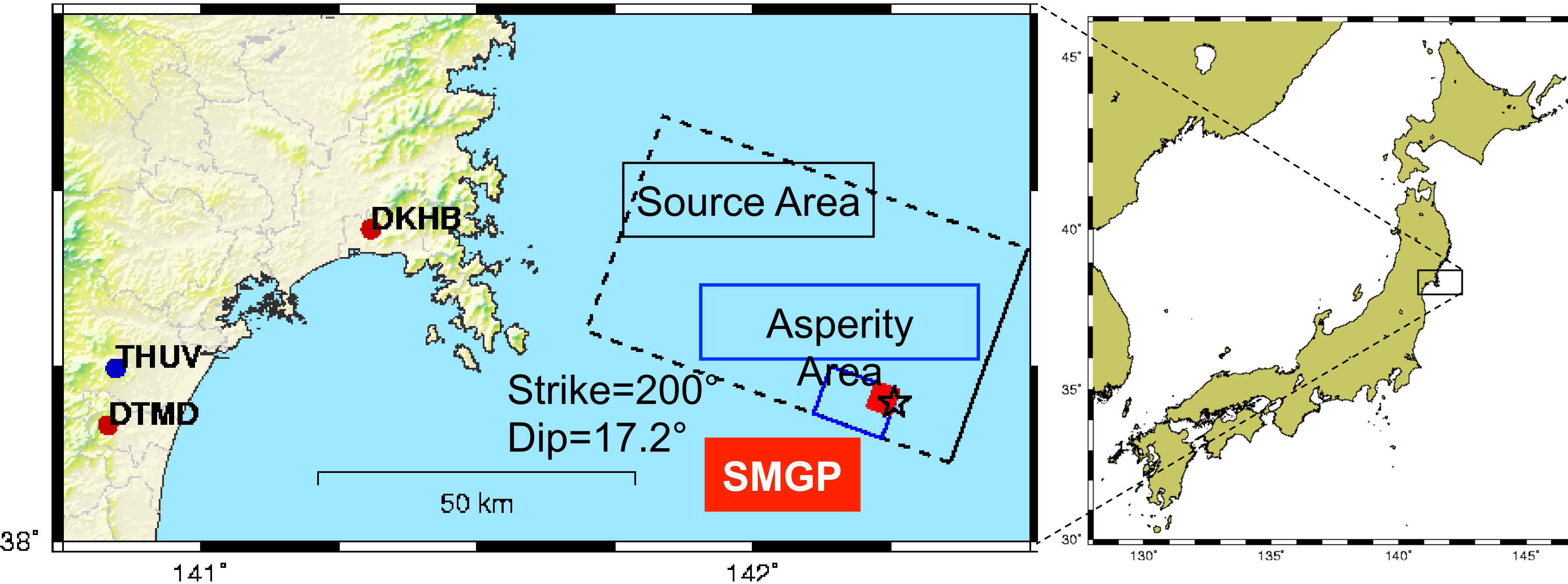
They found 2 SMGAs west of the hypocenter★ as Asano and Iwata and 3 SMGAs in Fukushima Oki
.
Total moment corresponds only Mw8.3.



SMGAs obtained by Kurahashi and Irikura (2011). Background contour is the distribution of peak moment-rate from long-period strong motion data (Yoshida et al., in preparation).

They found 2 SMGAs west of the hypocenter★ and 1 SMGAs in the north and 2 SMGAs in Fukushima.
Total moment corresponds to Mw8.5.

Source Model of the Miyagi-Oki Earthquake of 1978 by Matsushima et al.

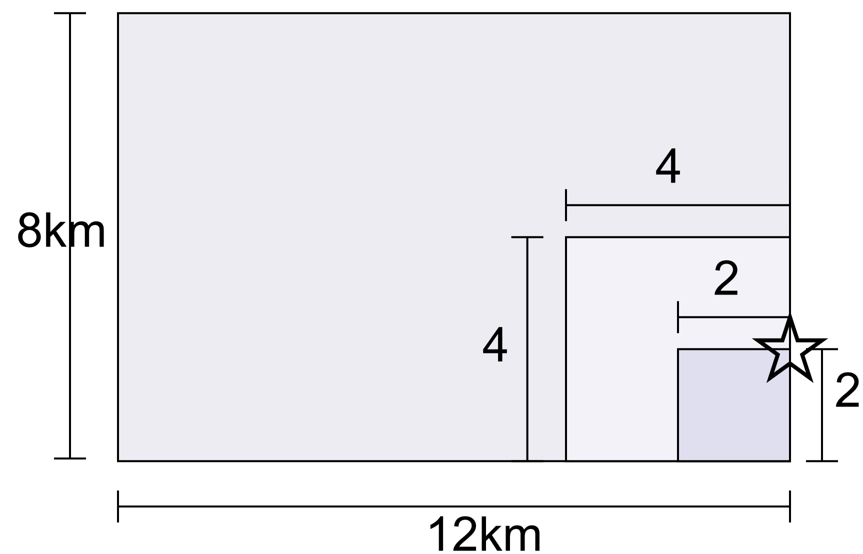


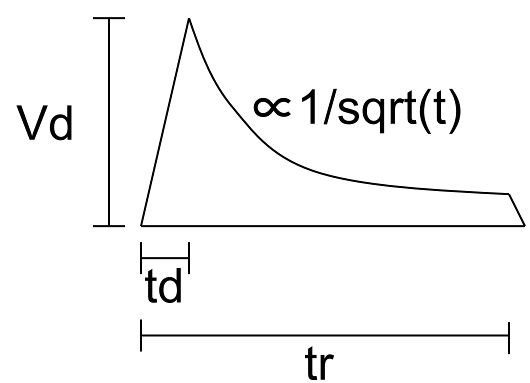
☆Start of Rupture
●Strong Motion Stations

・Consider only the asperity area close to the start of rupture
・Source location is based on report by Headquarters for Earthquake Research Promotion (2003)

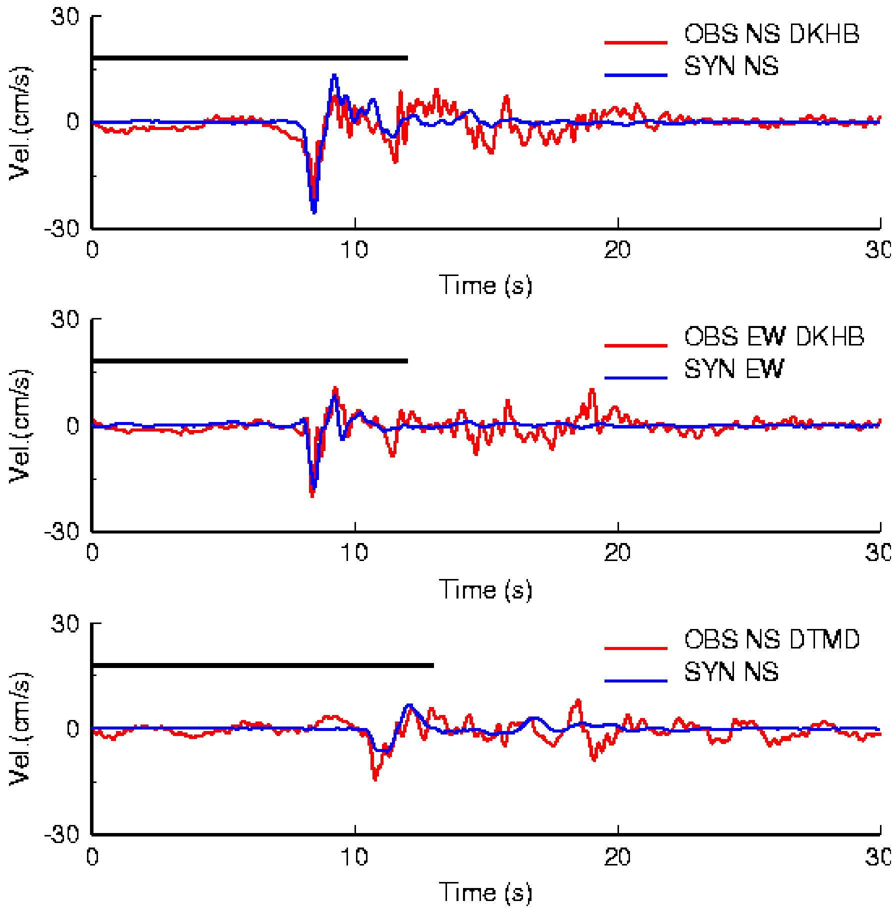
Grid Search Method

- Search for best size and slip velocity function of the SMGPs
- Use velocity pulse as target
- Assume a flat layered structure
- Wavenumber integration method (Hisada, 1996)
- 6 parameters to search
  - Size (4x4 or 2x2)
  - Maximum velocity (Vd)
  - Time of Max. vel. (td)
  - Duration (tr)
  - α (Coefficient to 1/sqrt(t))
  - Rake
- Location is fixed



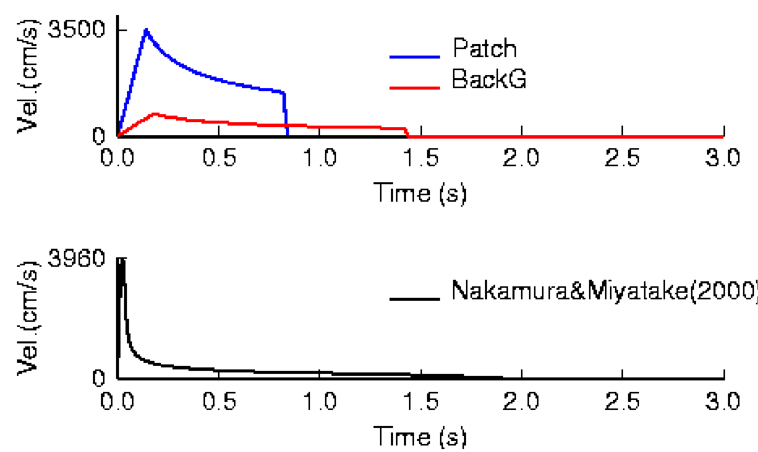


Best Fit Case (1)



Velocity waveform (f < 4.0Hz)

		Best Case		Nakamura&Miyatake (2000)	
		Patch	Back	total	HERP (2003)
size	km^2	16	80	96	96
time to max. vel.	sec	0.14	0.18	-	0.024
duration	sec	0.84	1.44	-	1.333
coefficient		1	1	-	-
max. vel.	cm/s	3500	750	-	3956
rake	deg	15	15	-	90
slip	m	16.5	5.59	7.408	5.9
M_0	10^{19}Nm			3.3	2.6

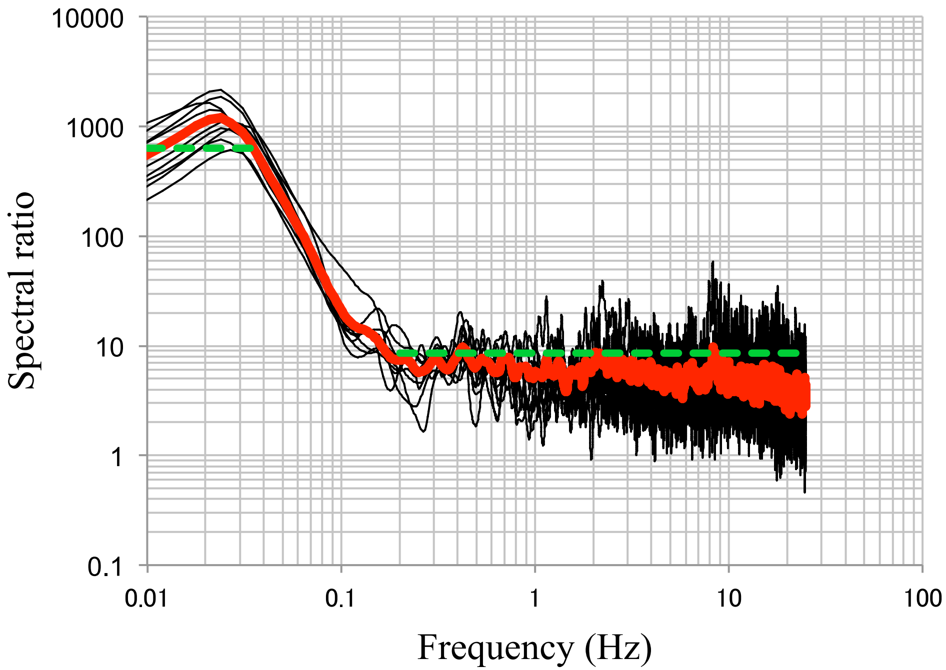


Slip velocity time function

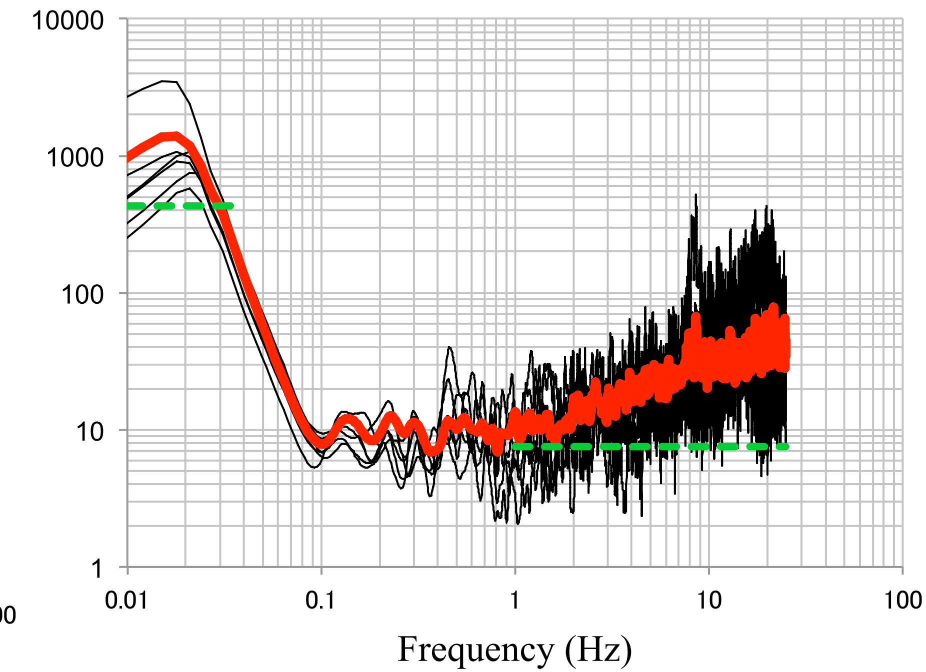
- The slip velocity time function of the smaller patch has a larger amplitude and shorter duration
- The slip velocity time function by Namakura&Miyatake is derived from parameters in the report by HERP

Spectral ratios between main shock and two foreshocks, 2005/8/16 M7.3 and 2011/3/9 M7.3

Tohoku2011/Miyagi2005
UD-comp Average for MYG only

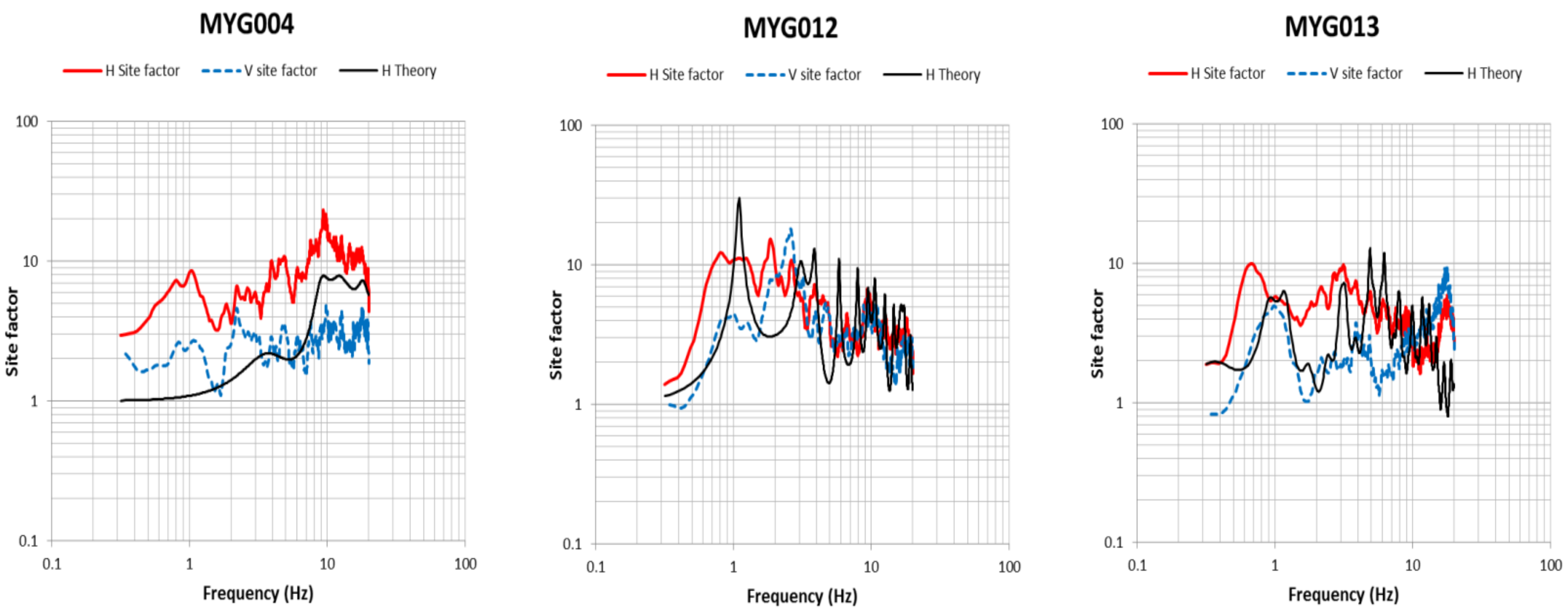


Tohoku2011/Sanriku2011.03.09
UD-comp Average MYG only



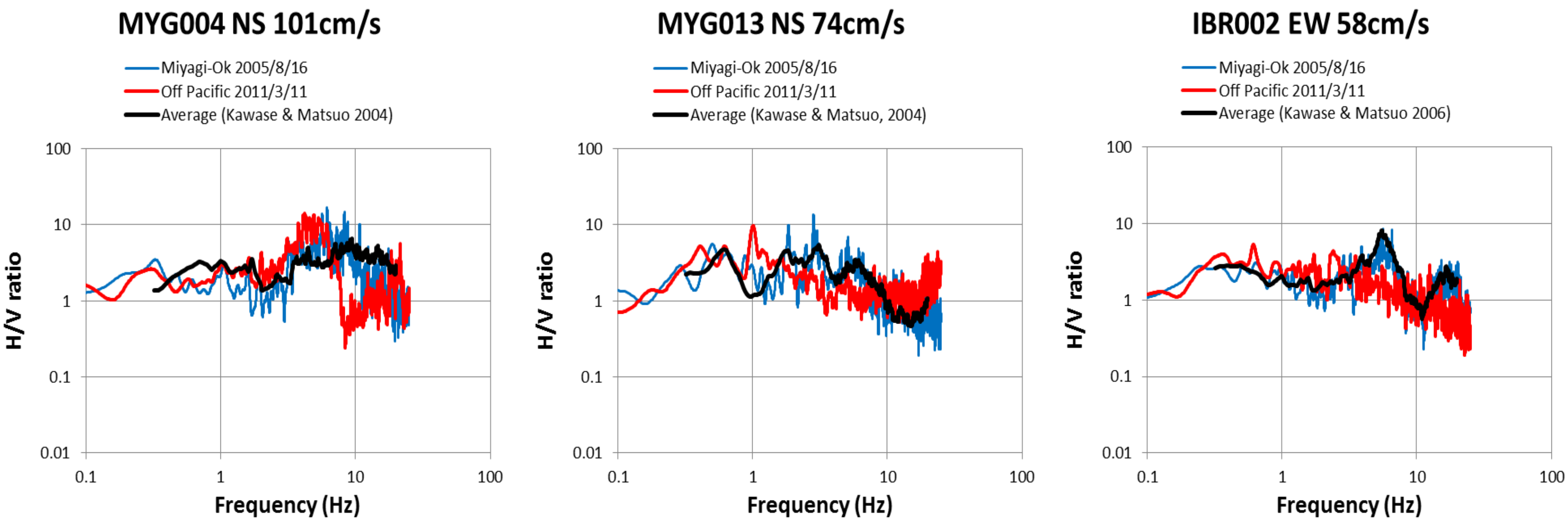
Seismic moment ratios are 632 for 2005, 430 for 2011. High freq. ratios are 8.6 and 7.6, respectively.

MYG004, MYG012, and MYG013 site amplifications



Site amplification factors determined by the generalized spectral inversion by Kawase and Matsuo (2004) and Kawase (2006) for three sites in Miyagi Prefecture for horizontal components (two components' RMS value) with red lines and vertical component with blue dotted lines. One-dimensional theoretical amplification characteristics for S-wave velocity structures taken from the PS logging for top 10 or 20 m and inverted by using genetic algorithm down to the bedrock are shown with black lines.

MYG004, MYG013, and IBR002 H/V nonlinearity



Horizontal-to-Vertical (H/V) spectral ratios for observed strong motions during the main shock (red lines) and the 2005 Miyagi-ken Oki earthquake (blue lines), together with the H/V ratios of the site factors determined by the generalized spectral inversion by Kawase and Matsuo (2004) for tens of weak to moderate ground motions .

Structural damage by seismic motion

- In terms of strong ground motions we have observed high PGA records, more than 1g at 18 K-NET and KiK-net sites.
- The largest PGA was observed at the site MYG004 with HPGA of 2,700 cm/s^2
- Although full-scale investigation has not been performed yet, preliminary survey shows quite limited numbers of damaged structures.

➔Why? Were the buildings constructed better than expected?

Structural damage by seismic motion

Virtually no severe damage around MYG004, 2.7g site.

Several wooden houses collapsed around MYG006, JMA intensity 6+ site.

Photo by Prof. Goto of Kyoto Univ.(on the left) and by Prof. Morikawa of Tokyo

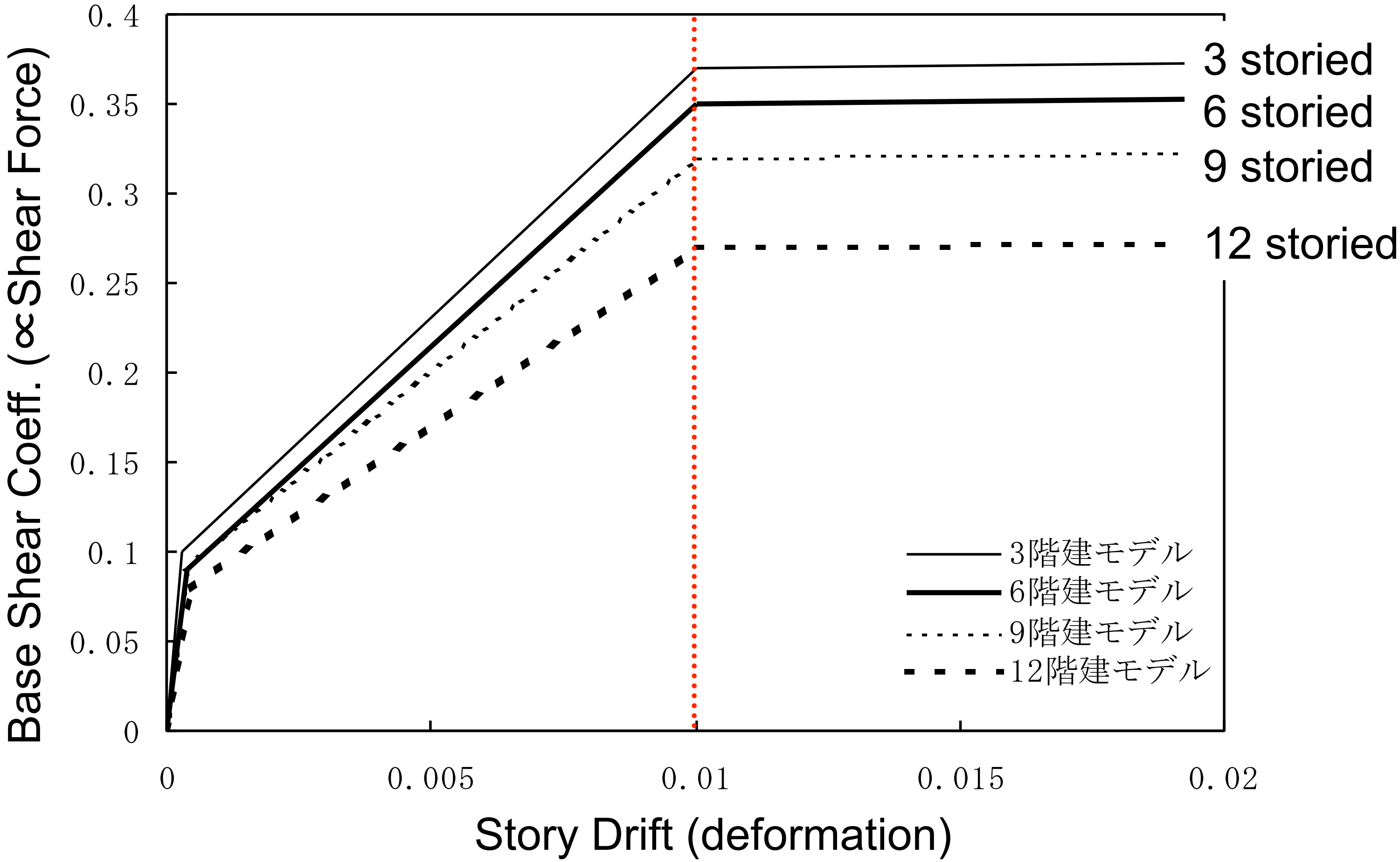
Structural damage by seismic motion

Virtually no severe damage around IBR003, 1.6g site.

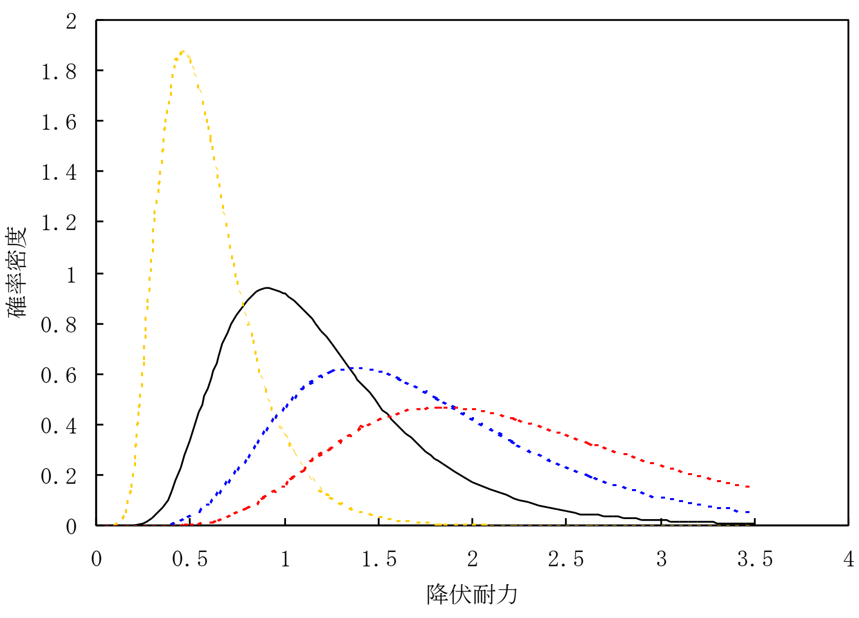
Several houses have damage in the roof around TCGH16, 1.2g site.

Photo by Prof. Sakai of Tsukuba University (See

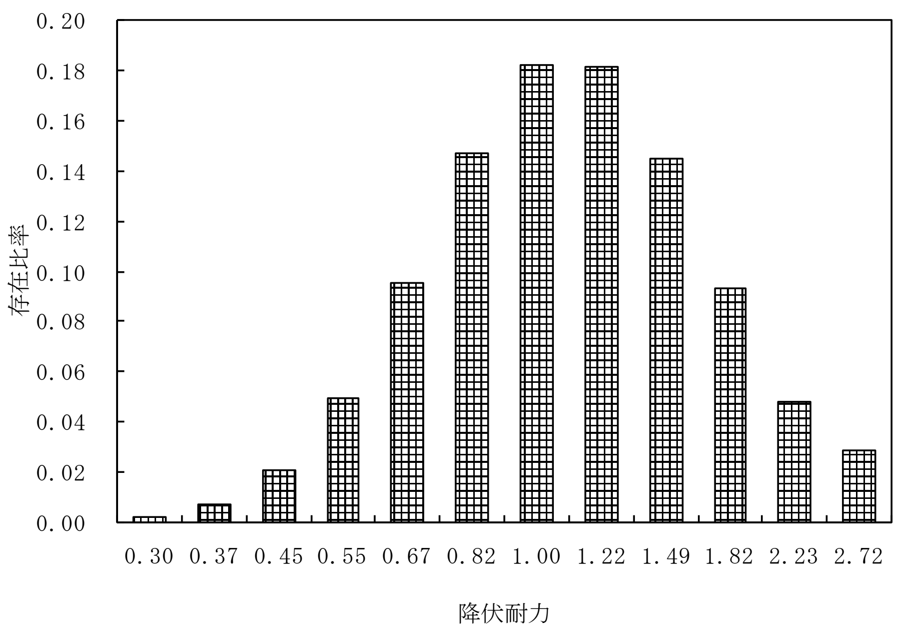
Nonlinear characteristics of RC buildings



Statistical Strength Distribution

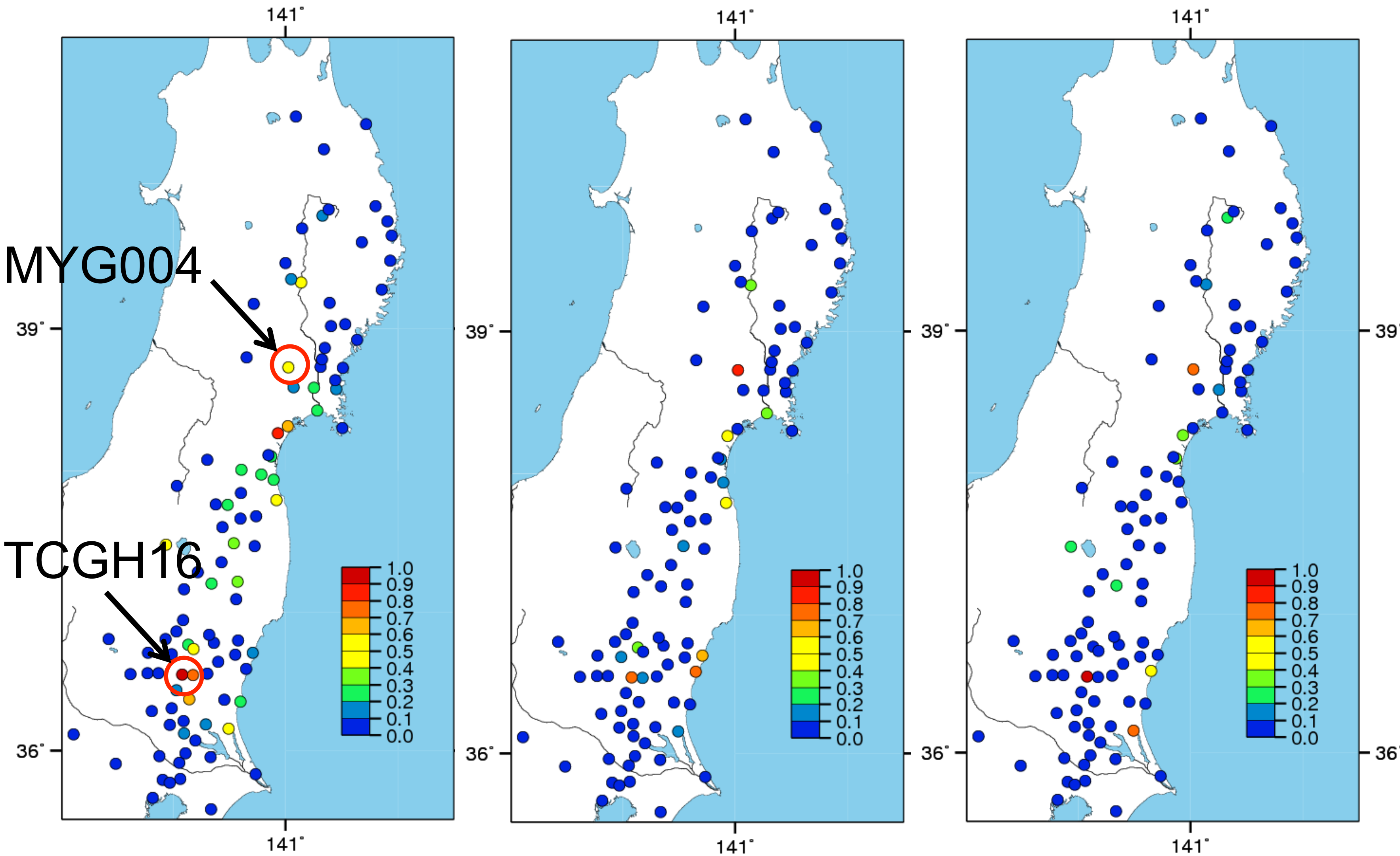


Probability distribution of Shibata(1980) based on the field data



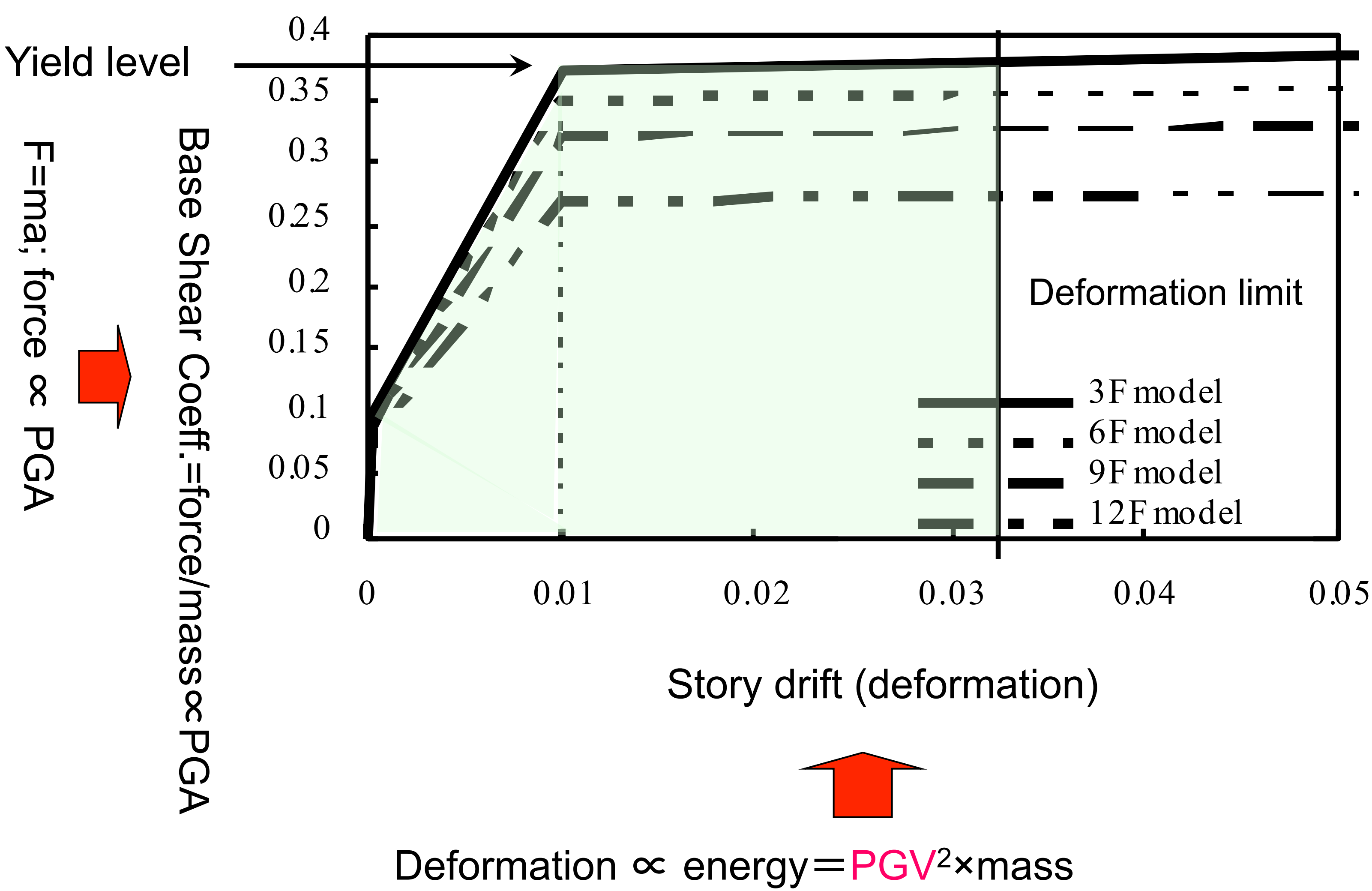
Discretized bins of buildings’ yield capacity

Building damage potential by simulation

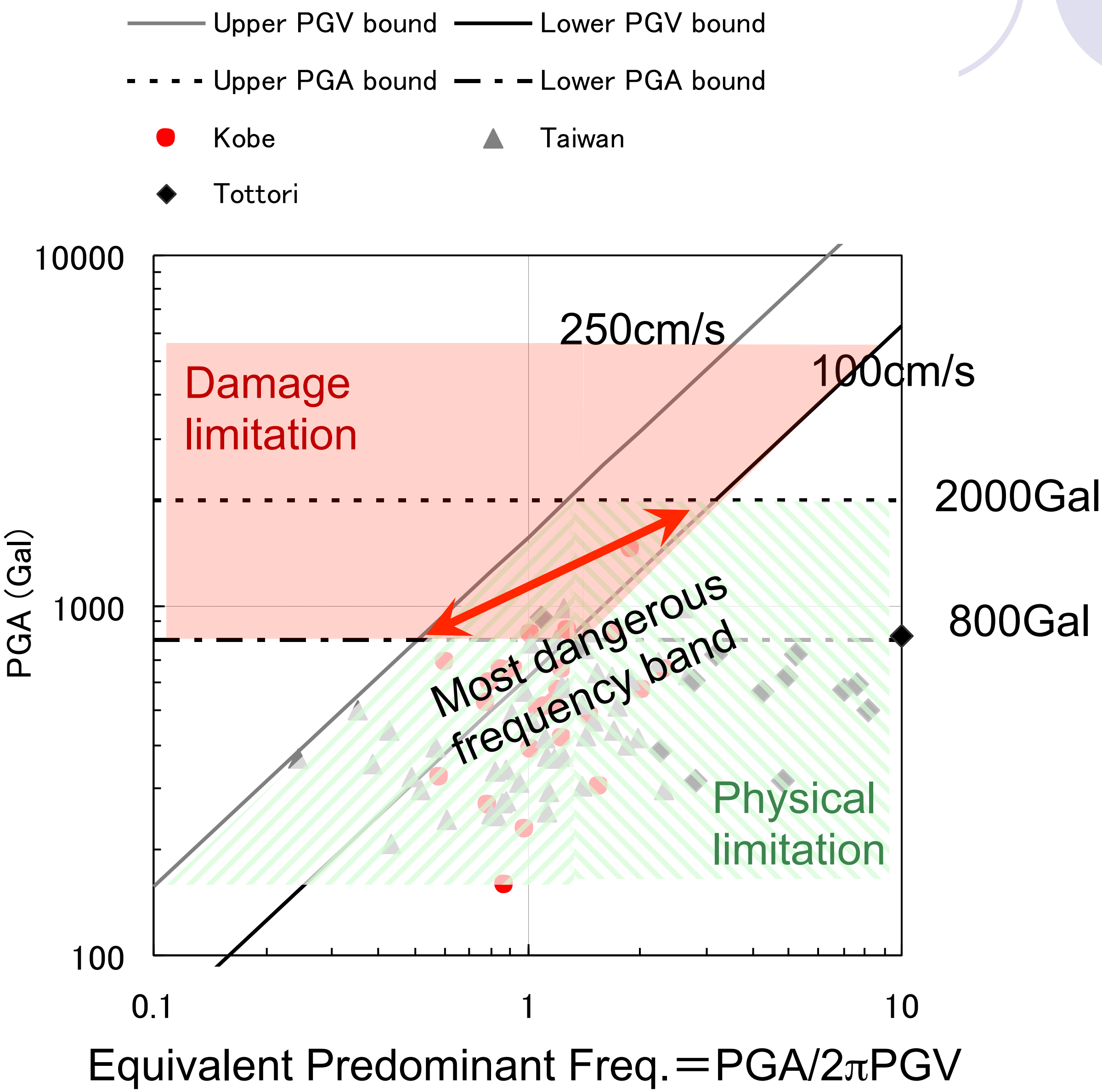


Wooden, 2st | **RC, 9 st.（Old）** | **Steel, 5 st.（Old）**

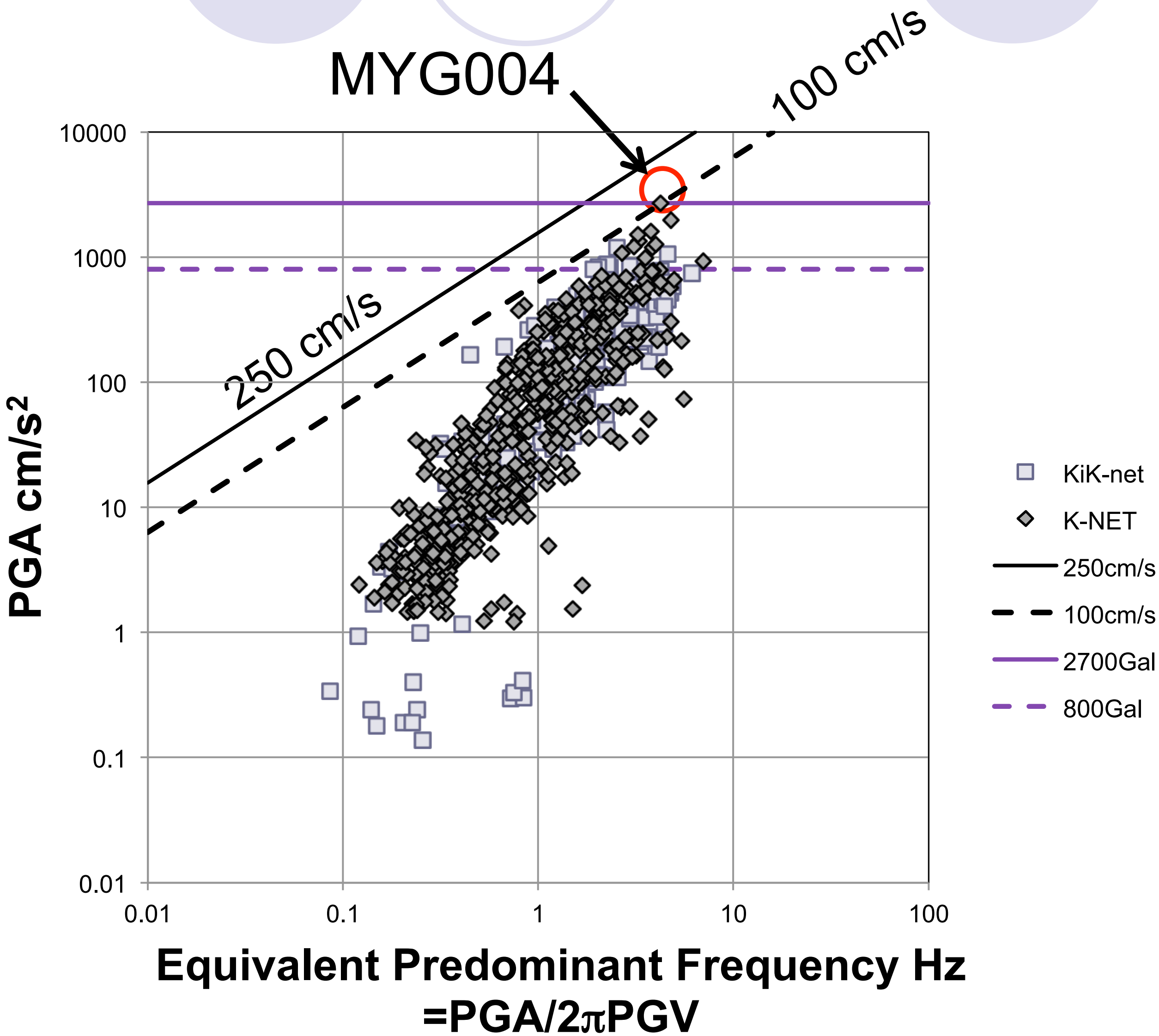
Simple interpretation



PGA and equivalent predominant frequency

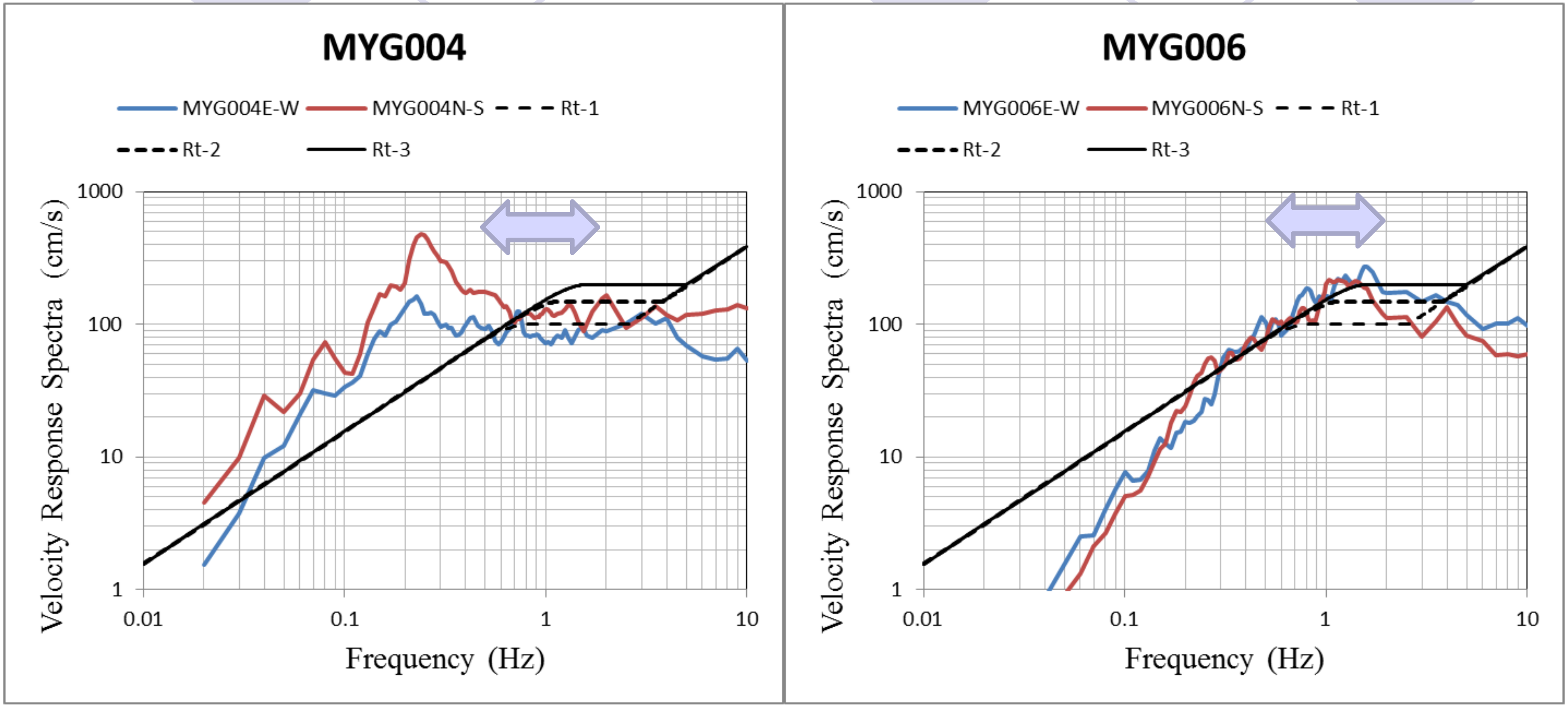


PGA and Equivalent Predominant Frequency



At many sites PGAs exceed 1,000 Gal (1g) but PGVs did not exceed 100cm/s
➔explain why structural damage was not so intense.

Velocity Response Spectra in Comparison to Design Level



Based on the velocity response spectra for those high PGA sites, we can see very high responses in high frequency range (higher than 2 Hz).

In comparison to the design code level for the limit state (=1g in response), they are also exceeding the design level only in high frequency range.

Summary-1

- From crustal deformation, tsunami waveforms, teleseismic waves, and long-period strong motions delineate quite similar slip distributions, namely very high value of slip in relatively compact (100km×200km) area close to the Japan trench.
- As the Headquarters for Earthquake Research Promotion assumed to occur in near future, this earthquake had similar characteristics to the Sanriku-Oki Tsunami earthquake.
- When we take spectral ratios between main shock and foreshocks they seems obey the normal scaling law.
- This suggests that this earthquake is also a high stress event as in usual subduction earthquakes in this region, not like a usual tsunami earthquakes.

Summary-2

- Along the Pacific coast of Tohoku and in the northern part of Kanto, we have observed really strong ground motions, namely, at 18 sites PGAs are more than 1 g.
- Though, structural damage due to ground motions were not so severe, primarily because velocity pulses with a dominant frequency in the “moderately short-period” range (~ 1 second) were not generated.
- Based on the comparison of velocity spectra with design code levels in Japan, observations significantly exceeded only in high frequency components.
- The records show that significant nonlinearity was generated mainly at points where a high acceleration and/or velocity was recorded.

Thank you!

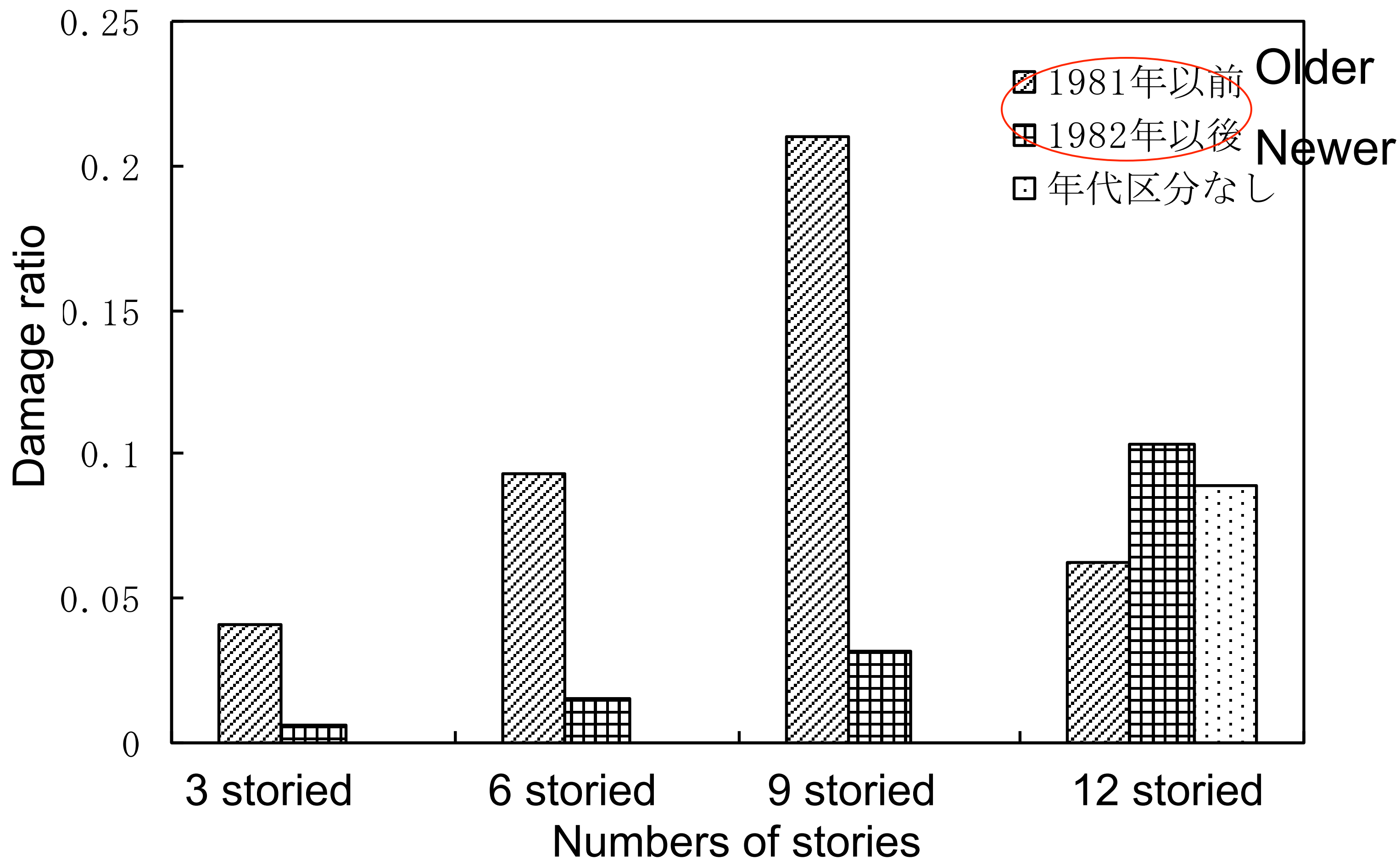
Acknowledgement

Microtremor observations at MYG004 were performed by the joint investigation team of DPRI (H.K, S. Matsushima, Baoyintu, F. Nagashima, K. Nakano) and Shimizu Corp. (T. Satoh, T. Hayakawa, M. Ohshima). Data from K-NET and KiK-net distributed promptly by NIED are highly appreciated. Thanks are also given to Profs. K. Irikura, H. Kawabe, K. Asano, Y. Sakai and H. Morikawa for their kind and prompt supply of their unpublished materials and to all the institutions who

provided us their nice scientific findings on the web.

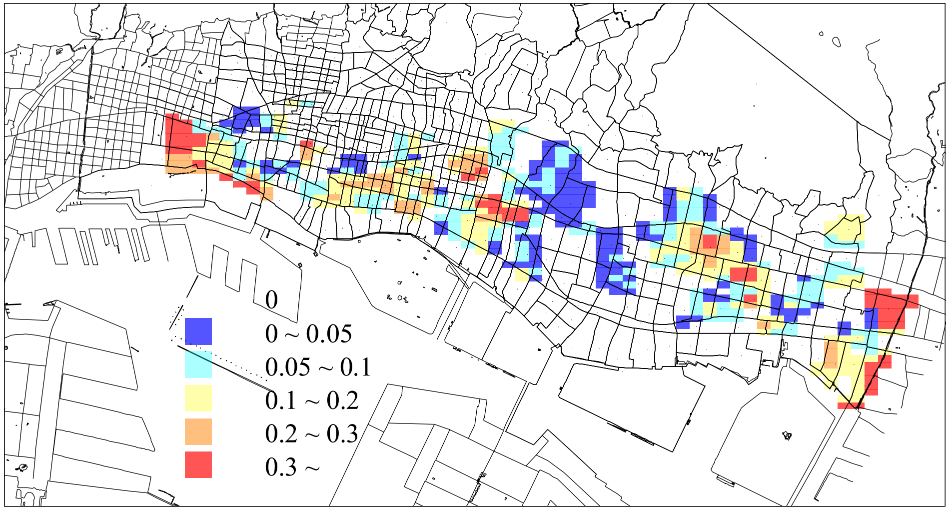
During the 1995 Hyogo-ken Nanbu, Kobe earthquake, heavy damage occurred to wooden houses as well as RC and Steel st.

Observed damage ratios of reinforced concrete (RC) buildings in Kobe during the 1995 Kobe earthquake

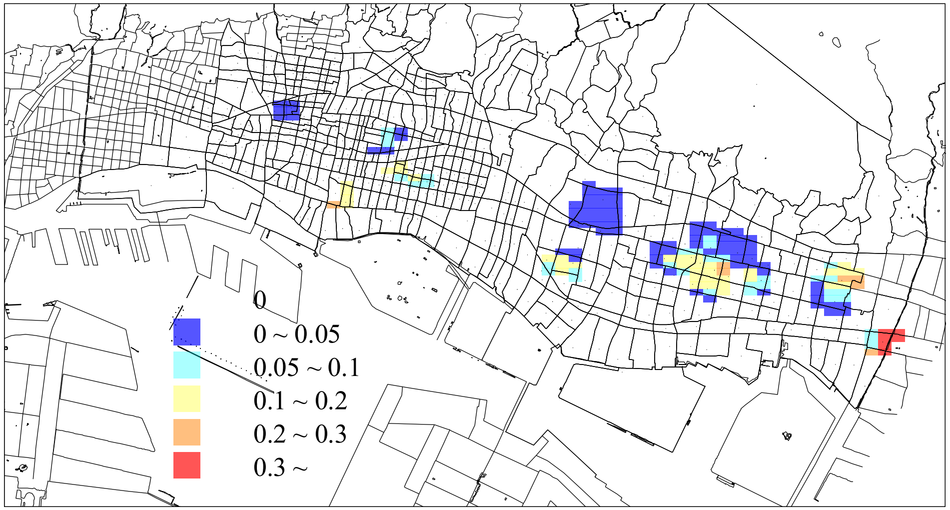


Based on the survey by Kinki branch of AIJ

Observed damage ratios

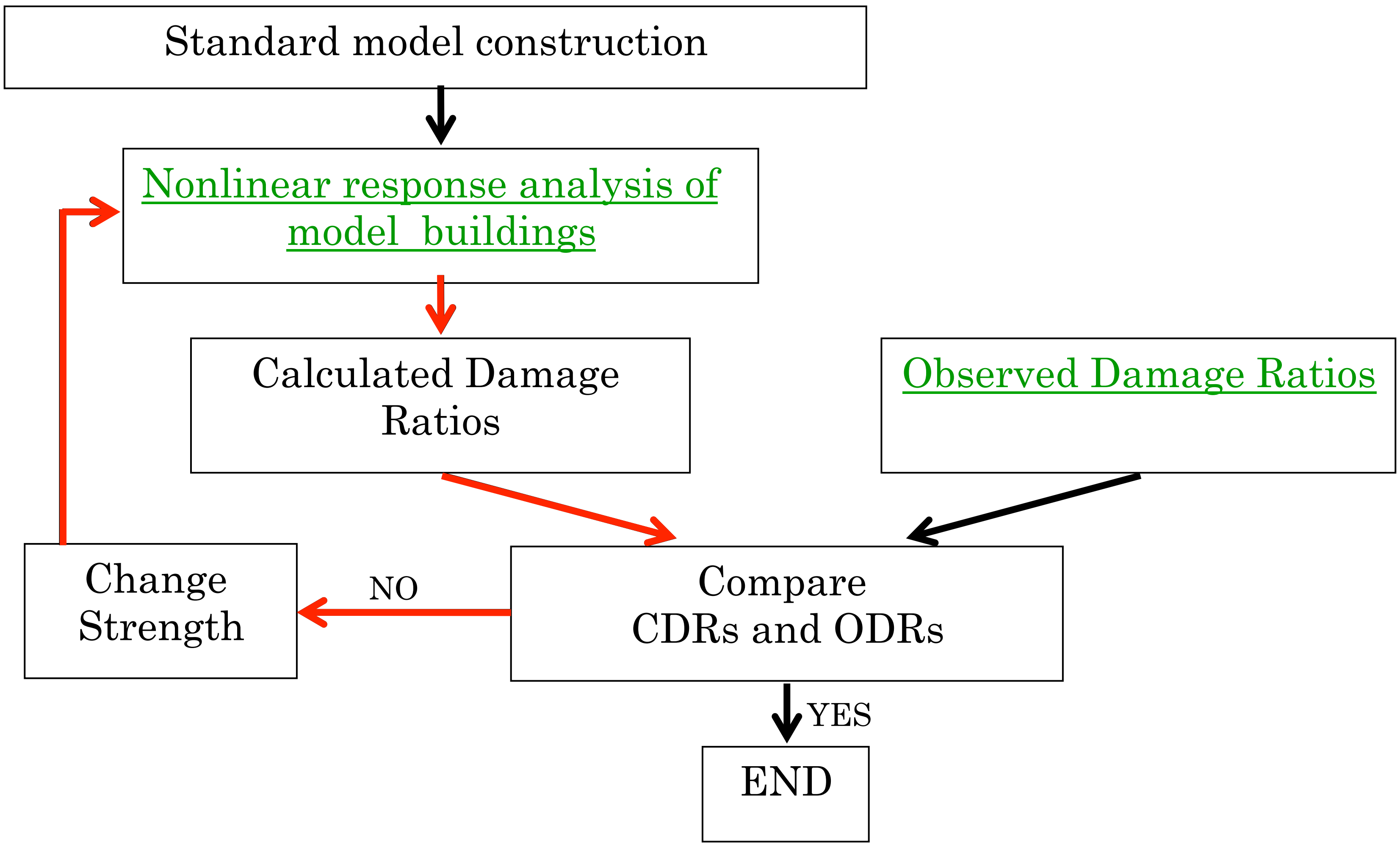


Pre 1981



Post 1982

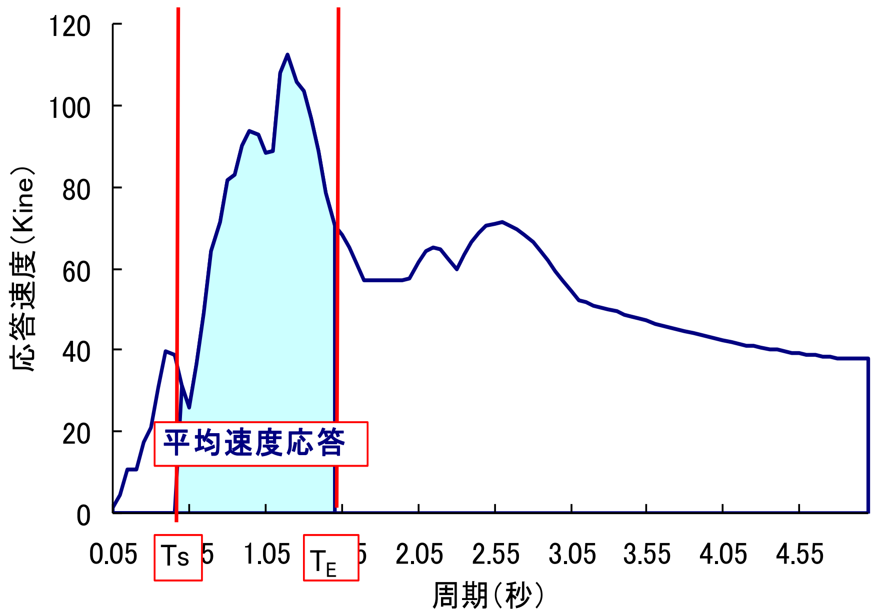
Inversion process for statistical strength



Best strength index for wooden houses in Japan

応答スペクトルの平均する周期範囲を様々に変化させ、
被害率と相関が良い周期範囲を検討した➔周期1秒付近が重要

応答スペクトルは 減衰定数 5%
水平2成分のベクトル和
Ts : 下限周期
T_E : 上限周期

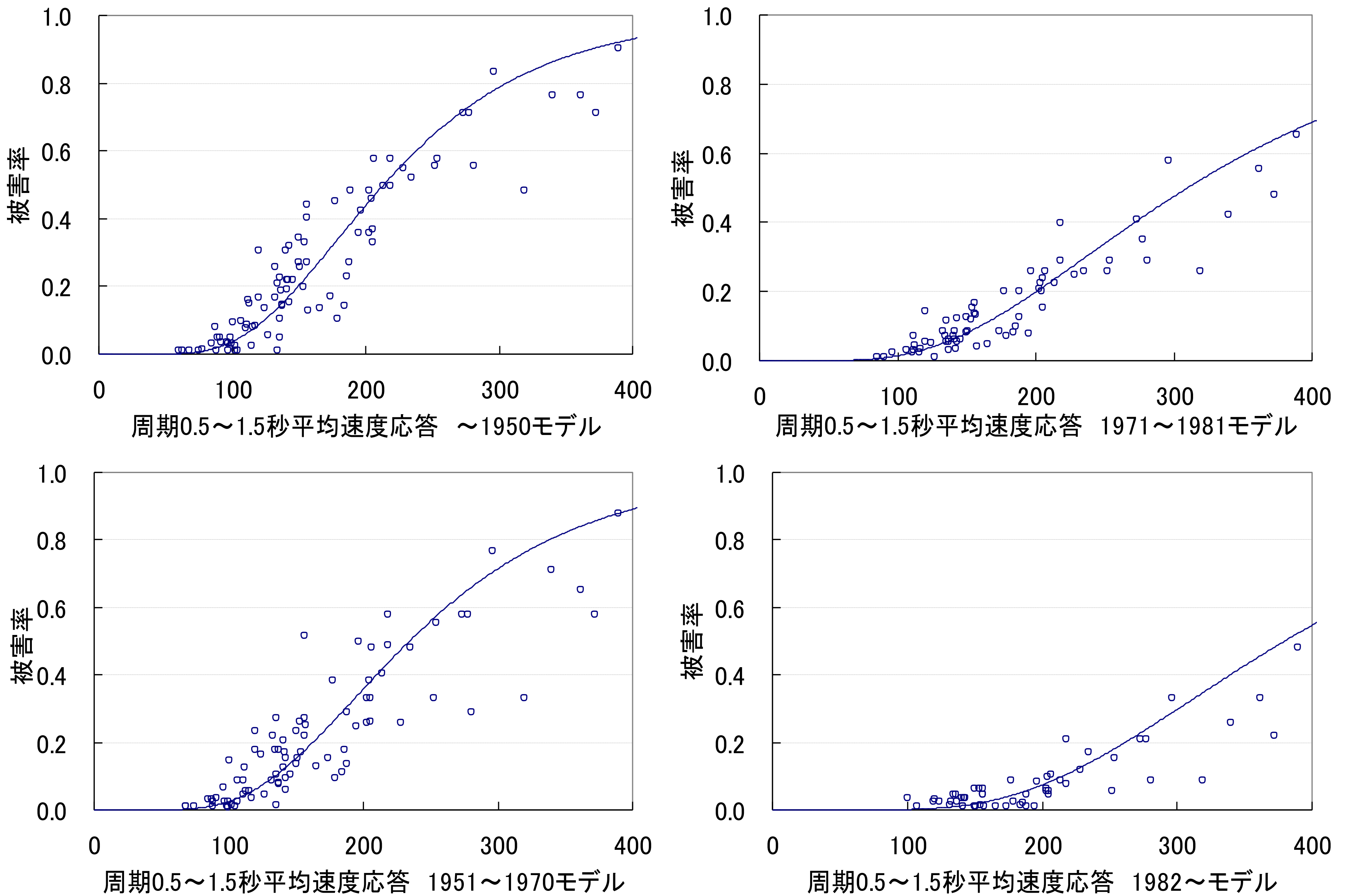


各年代モデルの最適周期範囲と相関係数

	～1950	1951～1970	1971～1981	1982～	年代区分無し
下限周期(T_S)	0.68	0.67	0.64	0.53	0.65
上限周期(T_E)	1.35	1.31	1.11	1.09	1.32
相関係数	0.924	0.919	0.917	0.882	0.910

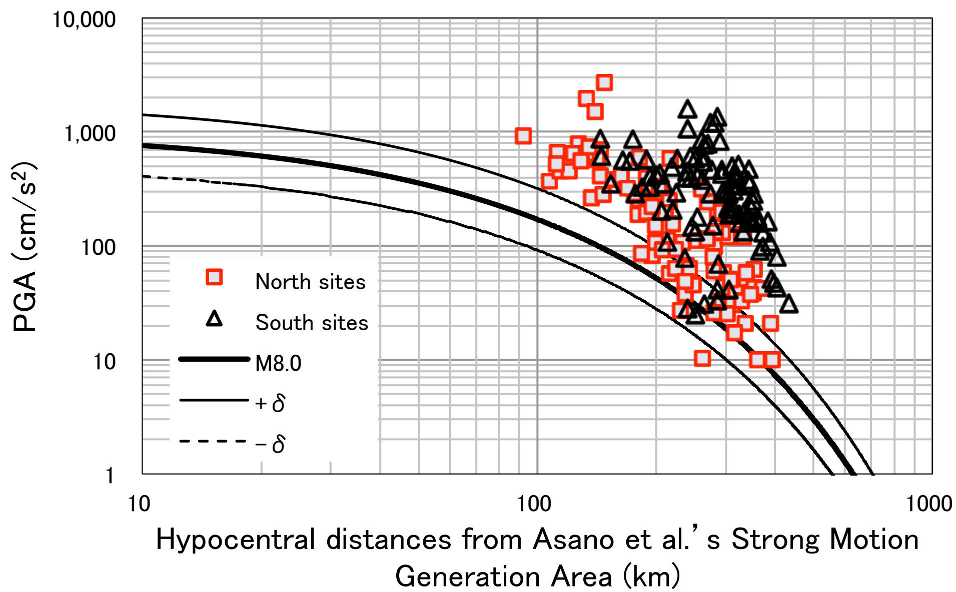
Vulnerability function for average pSv~1sec

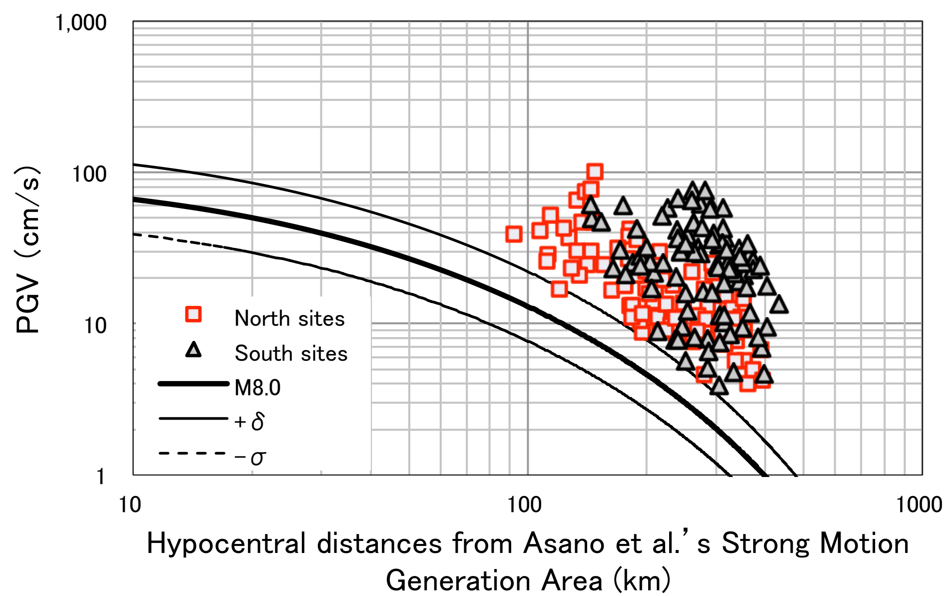
吉田・久田・川瀬（2003）建築学会大会



Vulnerability function and calculated damage ratios

PGAs and PGVs

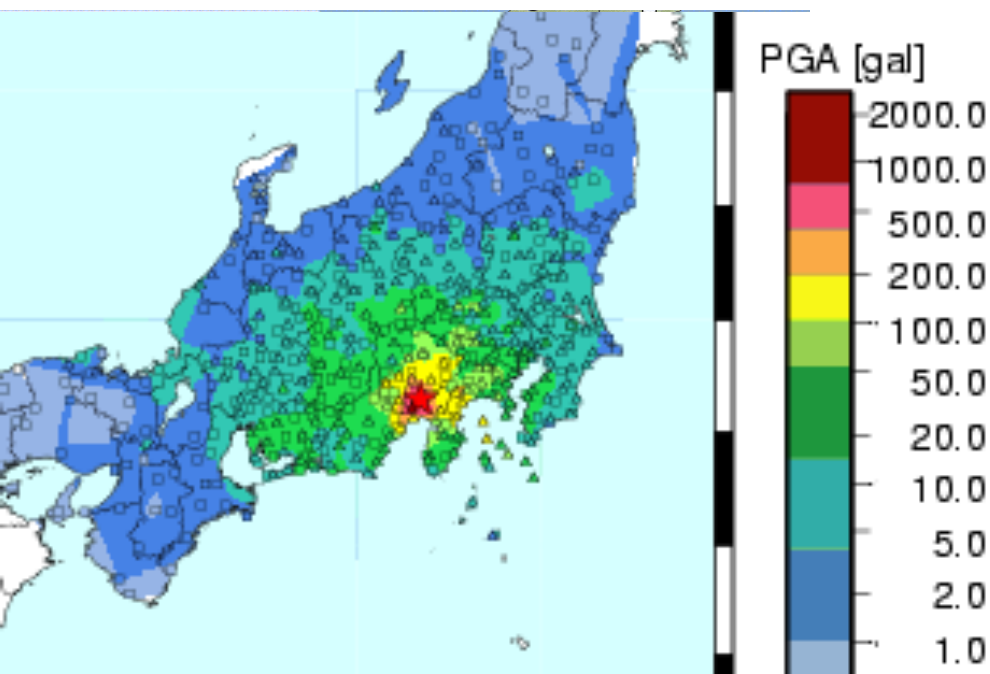




We see strong underestimation if we use the whole fault. But if we use the hypocentral distance from the 2nd "Strong Motion Generation Area (SMGA)" in Miyagi-Oki, we do not see underestimation.
➔SMGA area may not be extended so much to the south as shown by the aftershock distribution.

Shizuoka-ken Tobu, March,15 Earthquake

- On March 15, 2011, at 22:31 local time, M6.0 inland earthquake occurred (14km deep). JMA intensity was 6+ at two sites.



- K-NET SZO011 observed strong motions with PGA 1,076Gal

ByJMA & NIED

Left lateral strike-slip event below Mt. Fuji

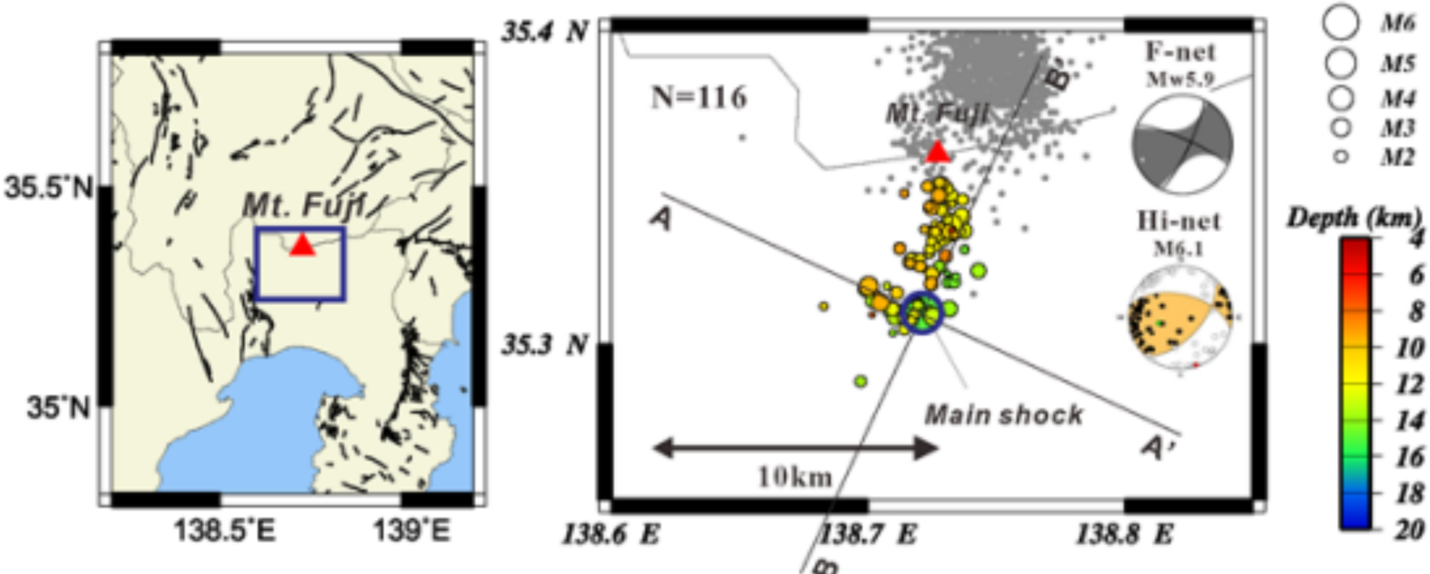
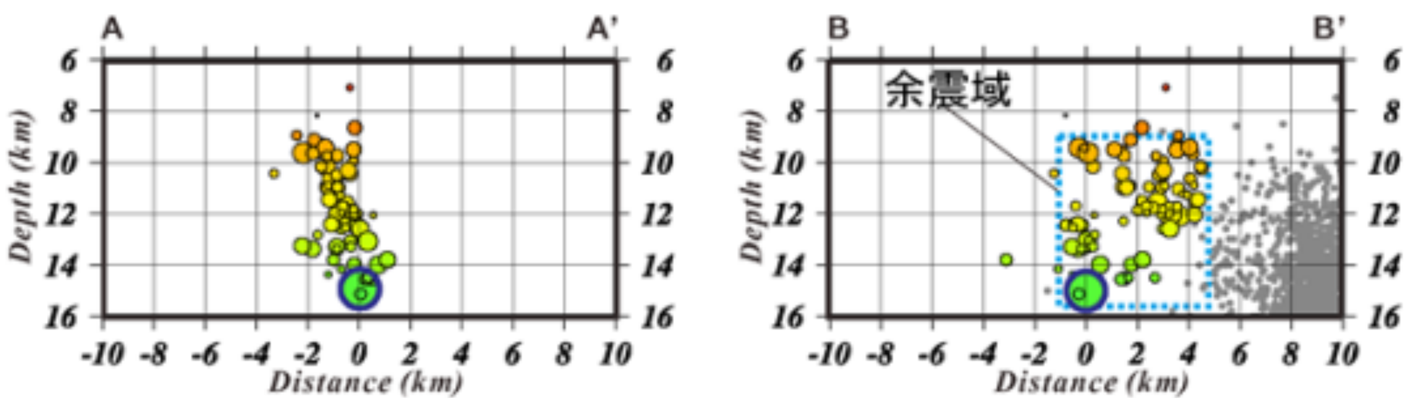


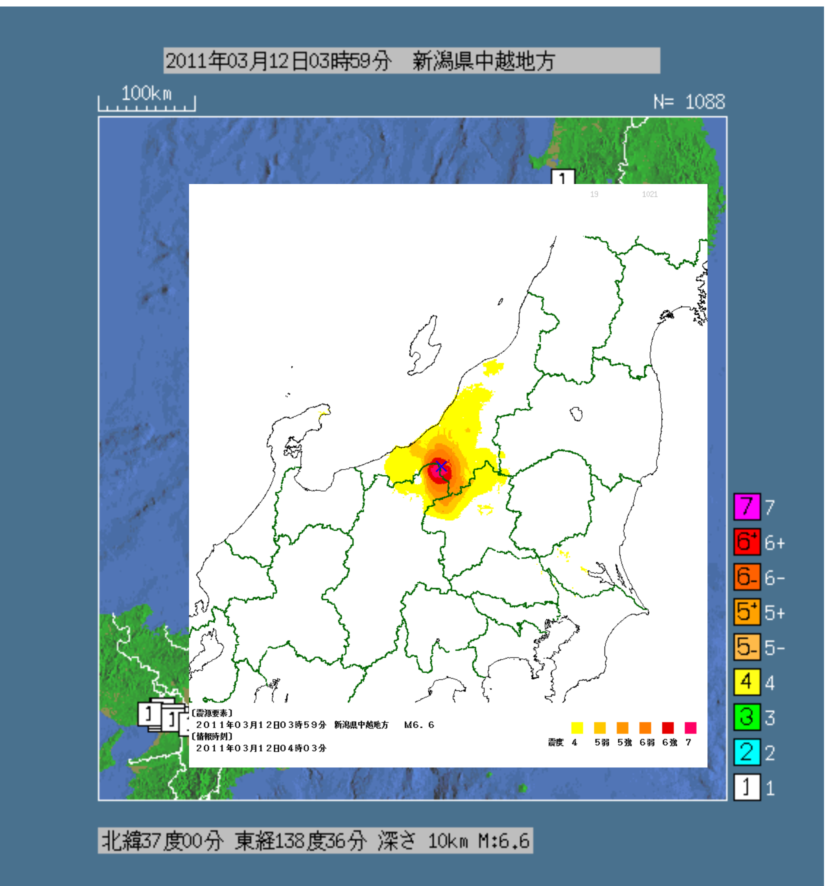
図1　波形相関データを用いたDD法による精密震源分布。赤三角は富士山を示す。灰色は低周波地震（気象庁，1999年以降）。また、F-netとHi-netによるCMT解およびHi-netによるP波初動発震機構解を合わせて示す。



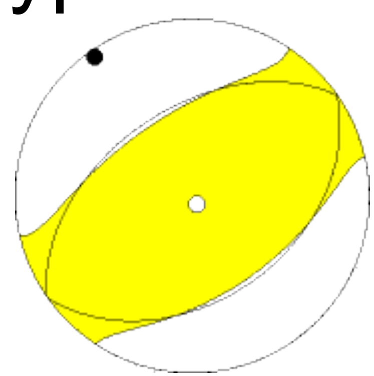
By NIED

Nagano-ken Hokubu M6.7 earthquake

- On March 12, at 03:59 (local time), M6.7 inland earthquake occurred.



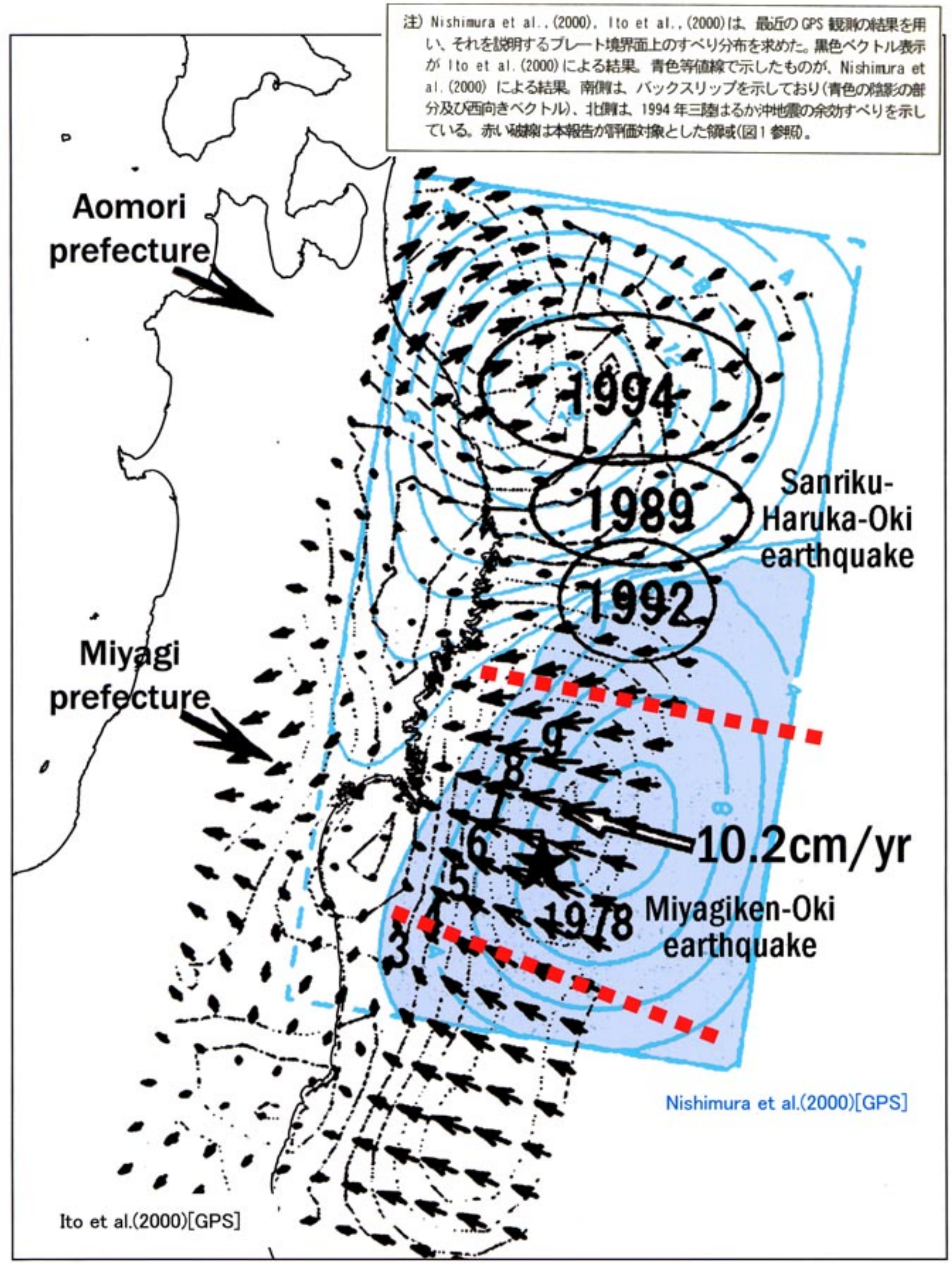
- JMA reported seismic intensity of 6+
- USGS determined as CMT of a deep thrust type shown below.



By JMA and USGS

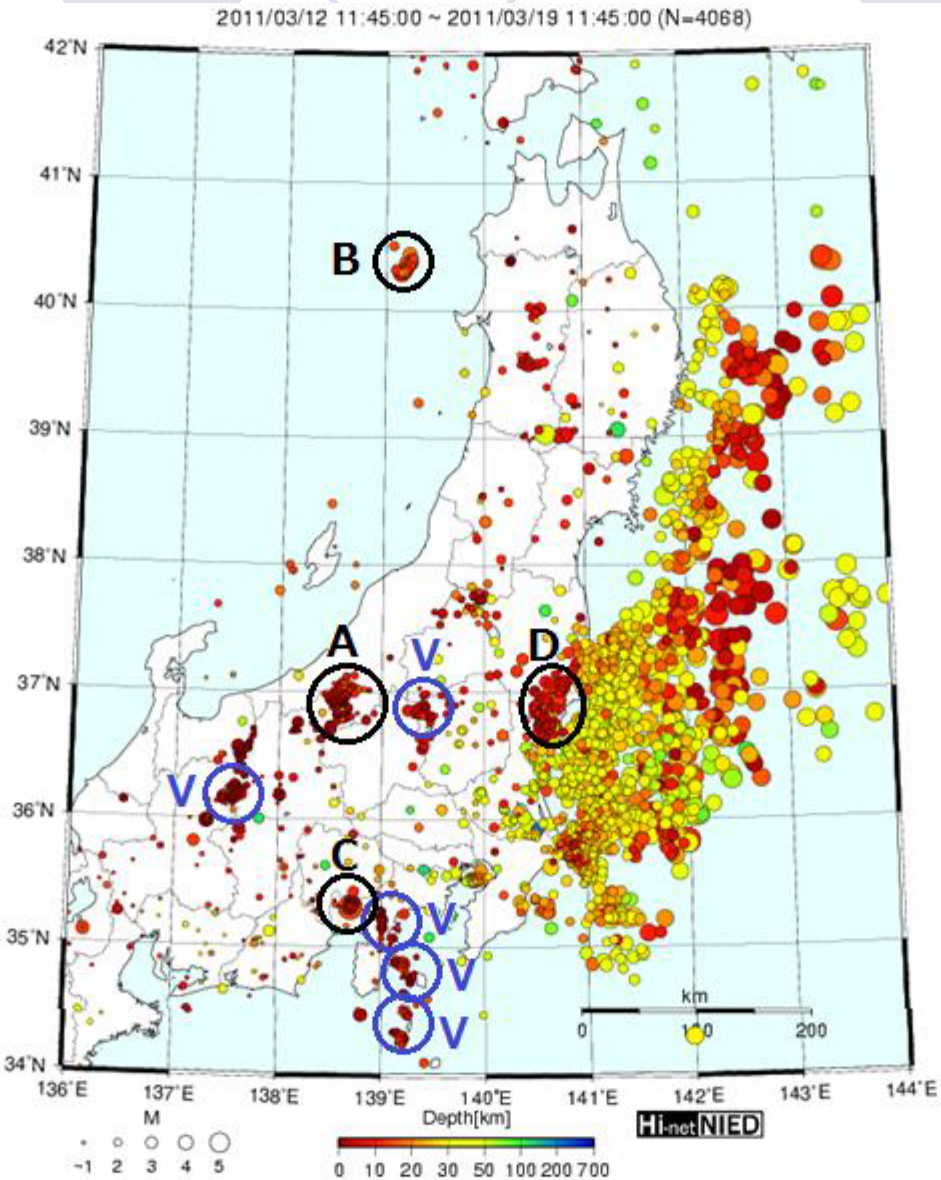
Back-slip distribution along the rocked region of the Pacific plate in Tohoku.

By Ito et al., (2000) subduciting plate motion in the ruptured zone of the mainshock looks rocked from Sanriku to Ibaraki-Oki.



Ito et al.(2000) & Nishimura et al.(2000) from MEXT site

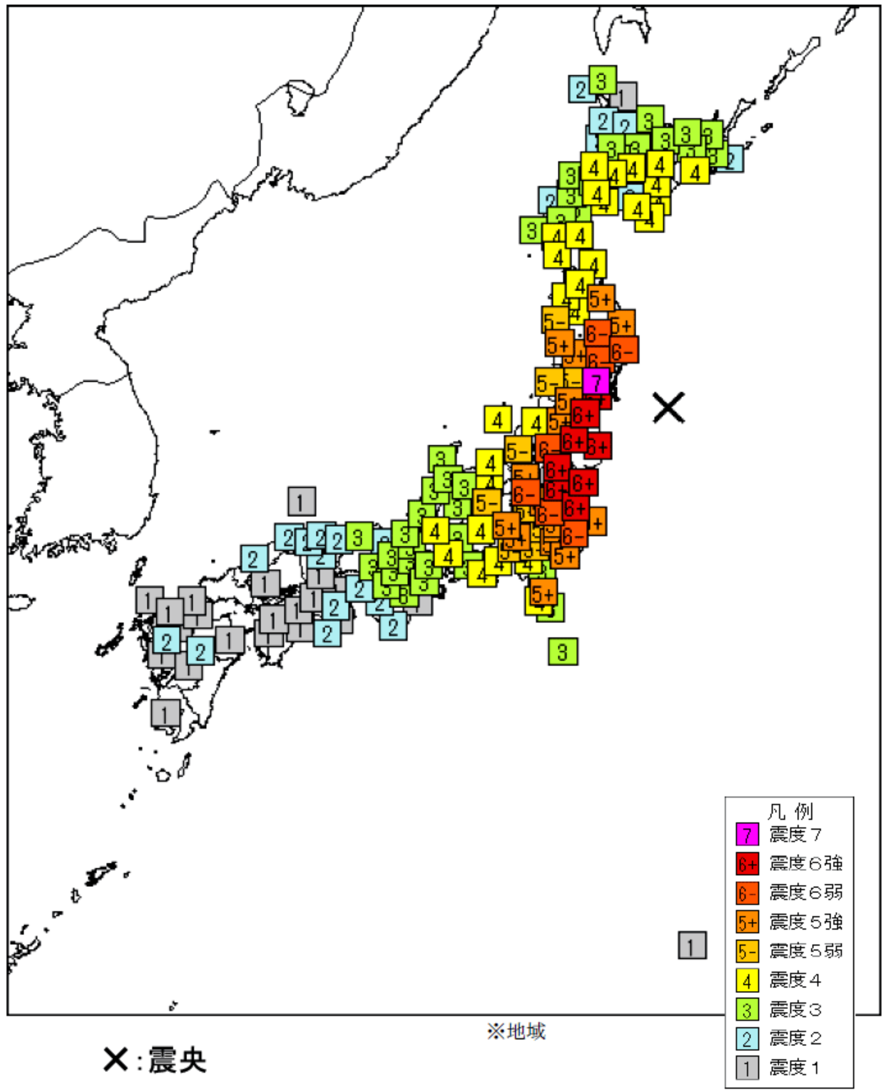
Nagano-ken Hokubu &Shizuoka-ken Tobu



- Two inland earthquakes occurred immediately after the Tohoku earthquake, at A and C.

By Okada at NIED

Seismic Intensity broadcasted by JMA



By JMA