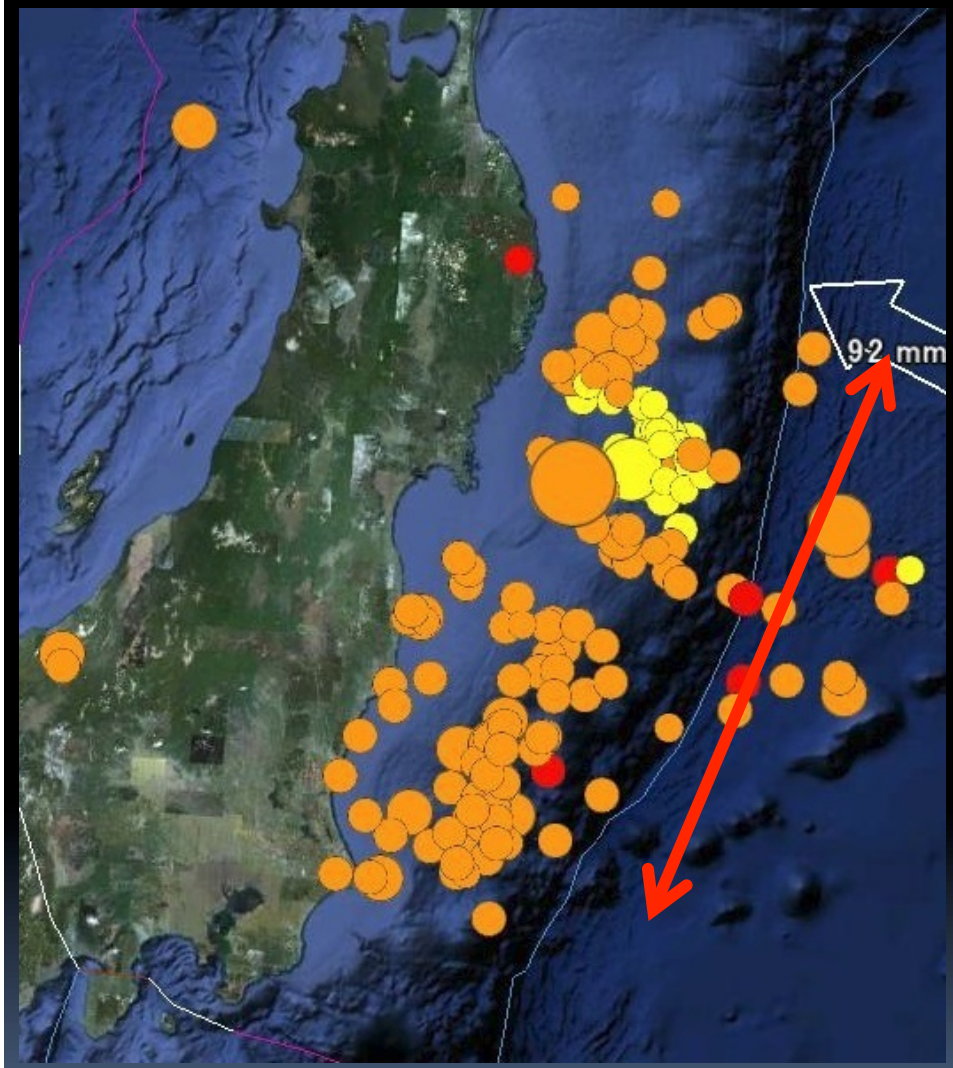
Strong Motions of the 2011 Tohoku-oki Earthquake: Impact on Nuclear Power Plants

Jim Mori
Disaster Prevention Research Institute
Kyoto University

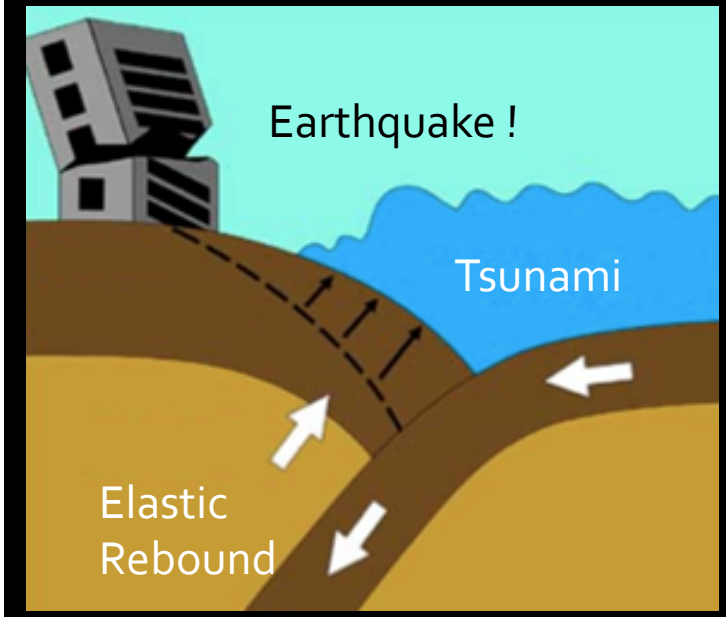
- Overview of strong-motions during 2011 Tohoku-oki earthquake
- Shaking and tsunami at nuclear power plants
- Present status on evaluating safety at nuclear plants in Japan
- Early Warning for strong-motions

11 March 2011 Tohoku-oki Earthquake Mw9.0



(Aftershock map from USGS)

- 400 x 200 km fault
- Over 18,000 people killed
- Damage and deaths mainly from tsunami, not shaking
- About $300 billion damage



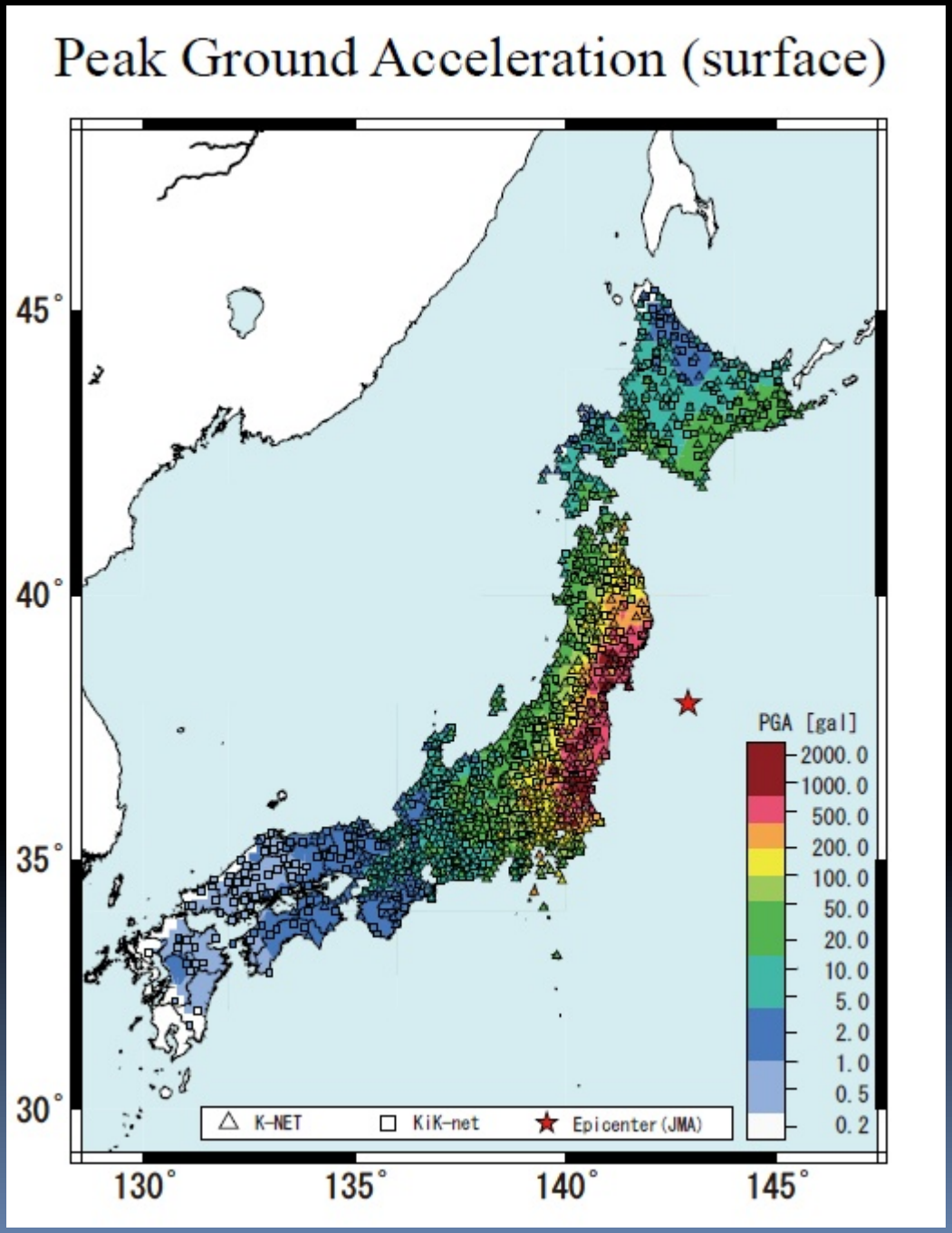
Largest slip ever recorded for an earthquake
maximum over 50 meters

Huge slip on shallow portion of megathrust
generated devastating tsunami

Collapsed buildings in Sendai

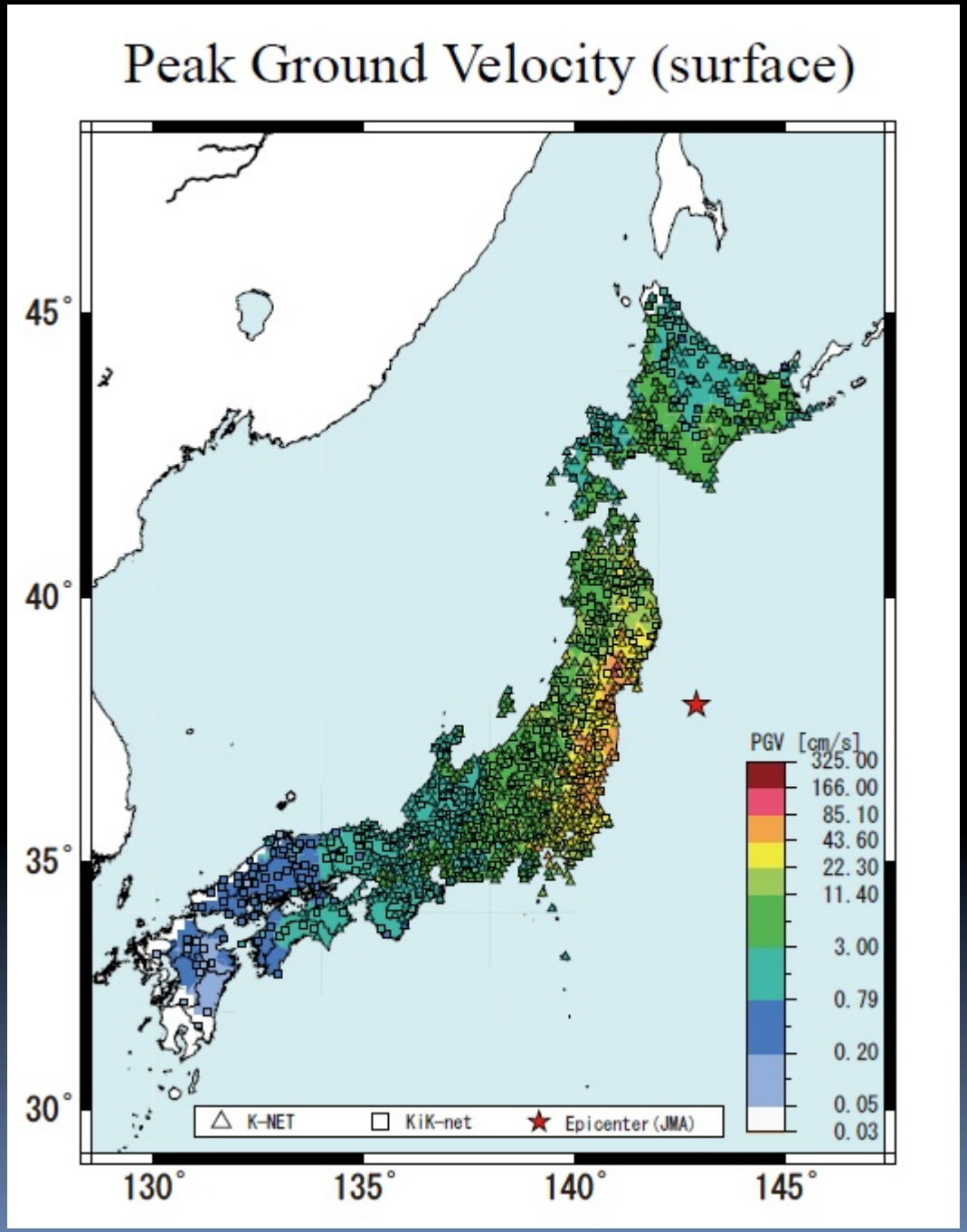
4.4% of the deaths from collapsed buildings and landslides

Peak Ground Acceleration (surface)

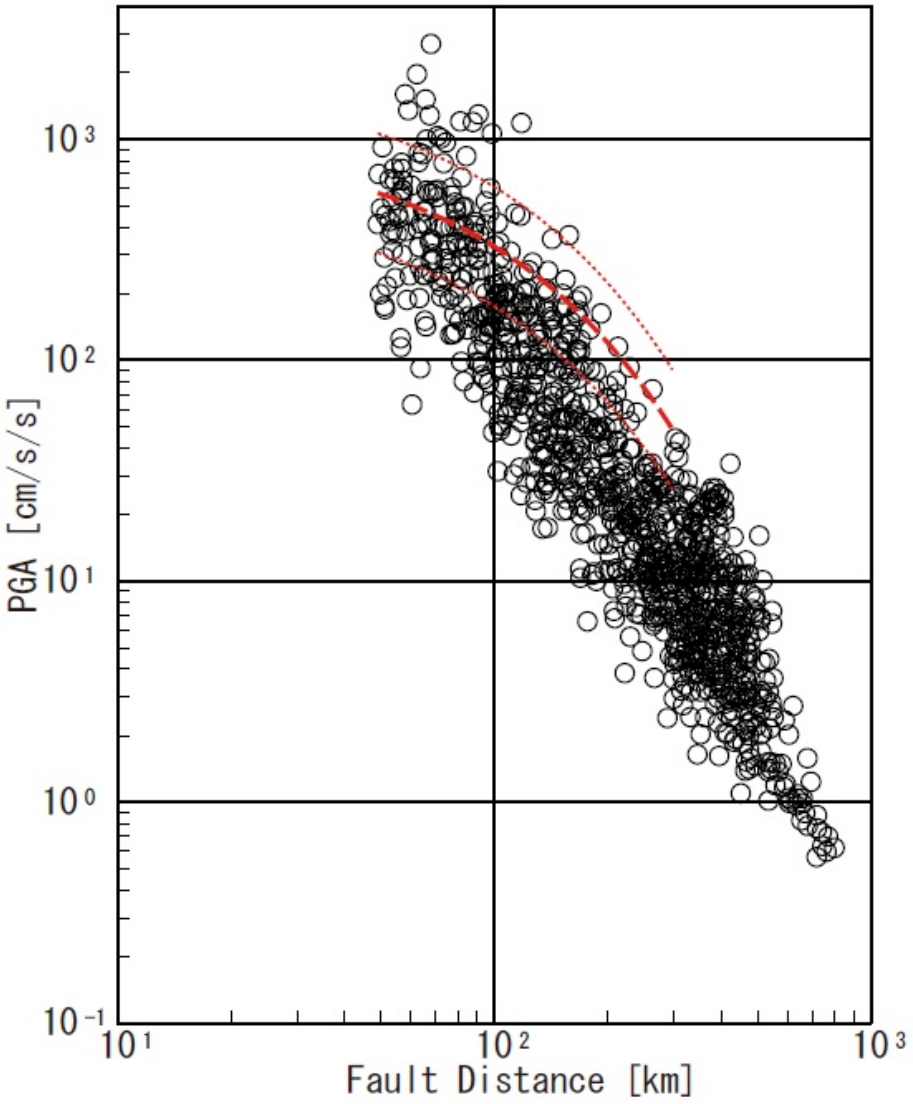


NIED

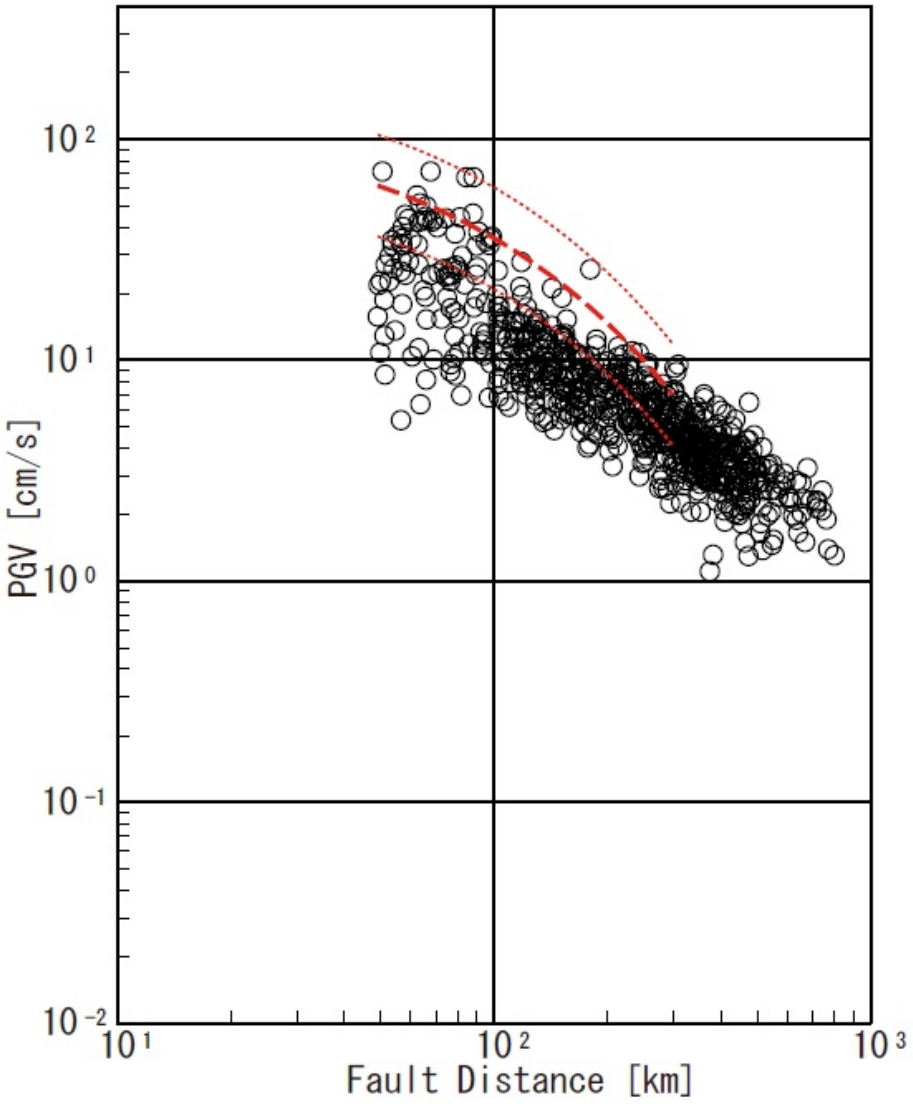
Peak Ground Velocity (surface)



NIED

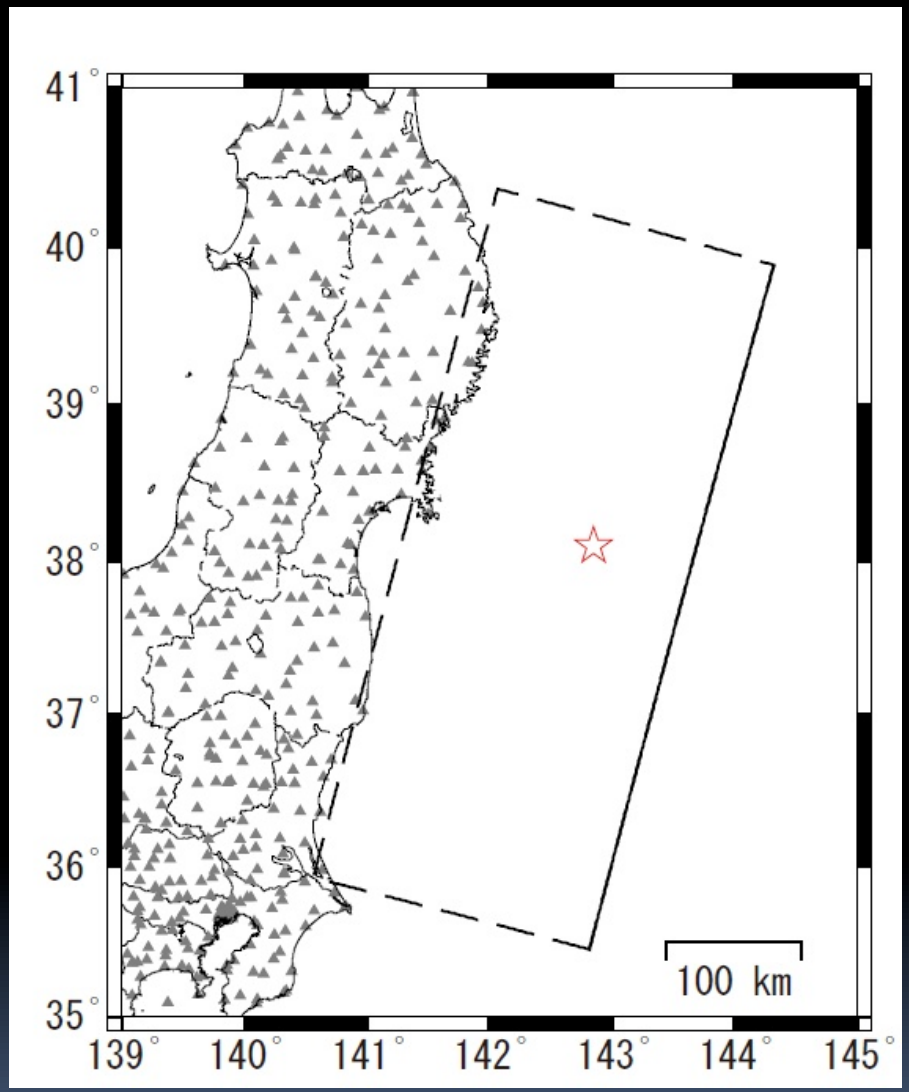


Peak Ground Acceleration （PGA）

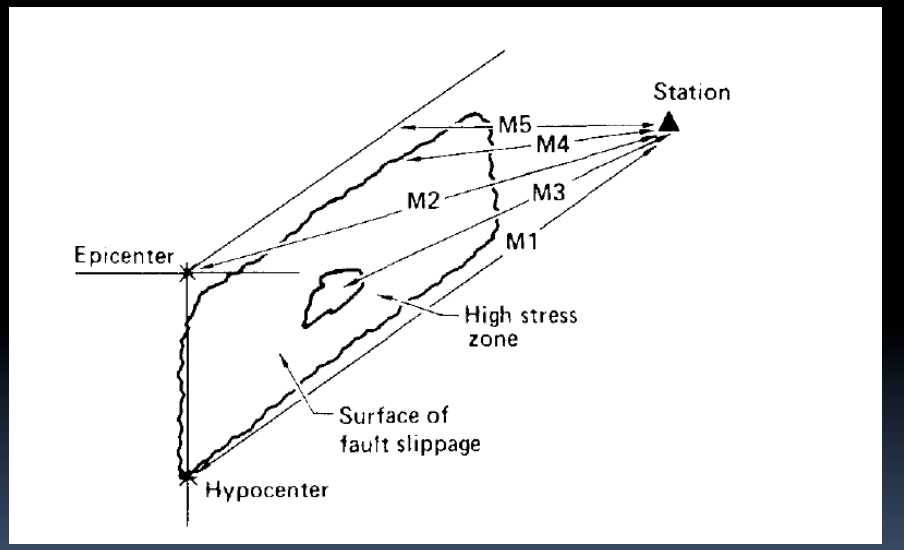


Peak Ground Velocity （PGV）

NIED

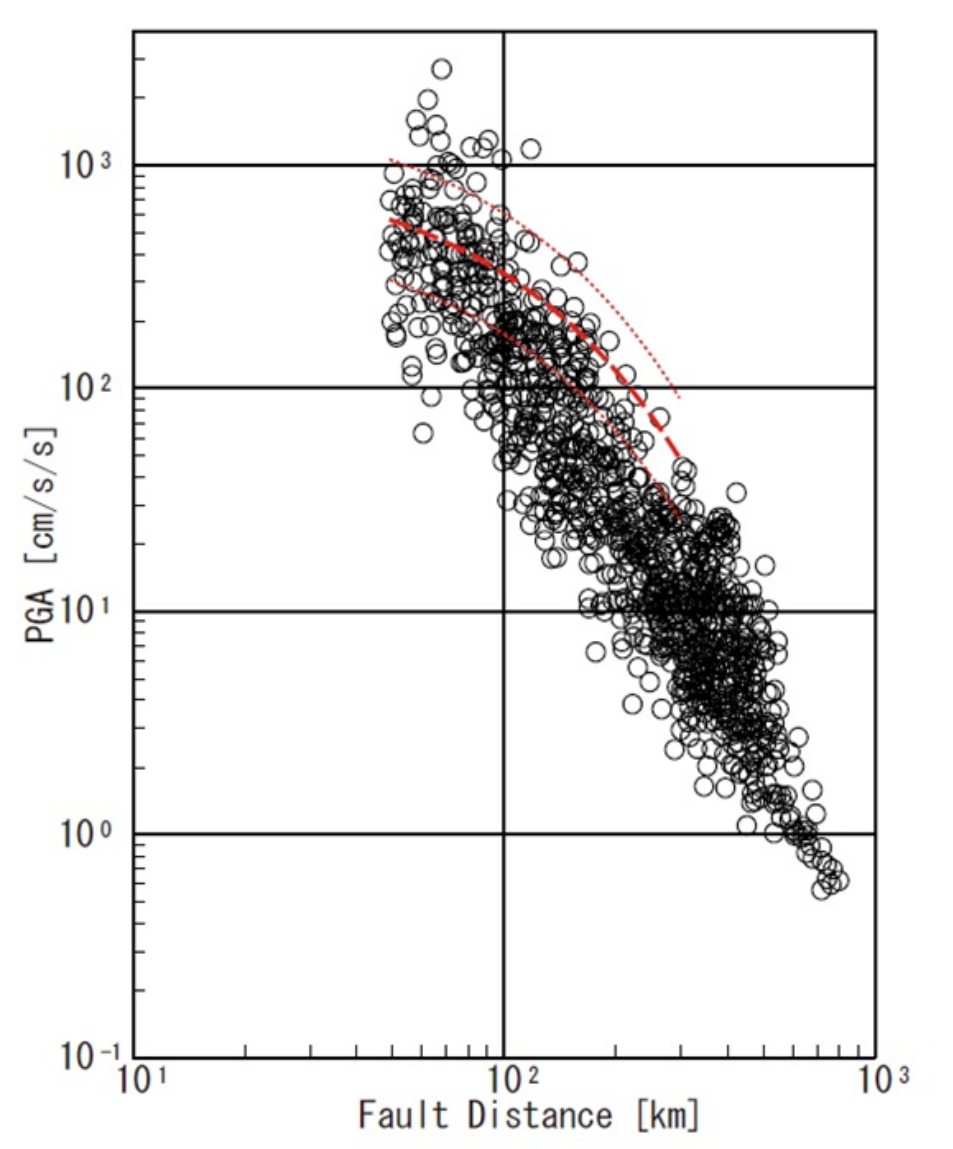


'Distance' is closest distance to the fault (M4)

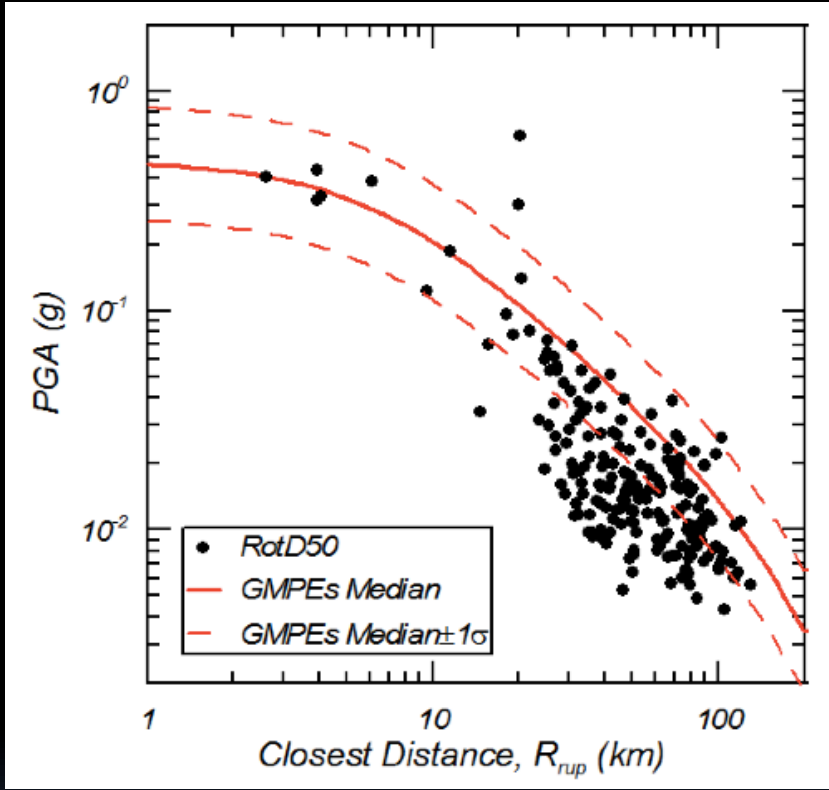


Boore and Joyner, 1982

2011 Tohoku

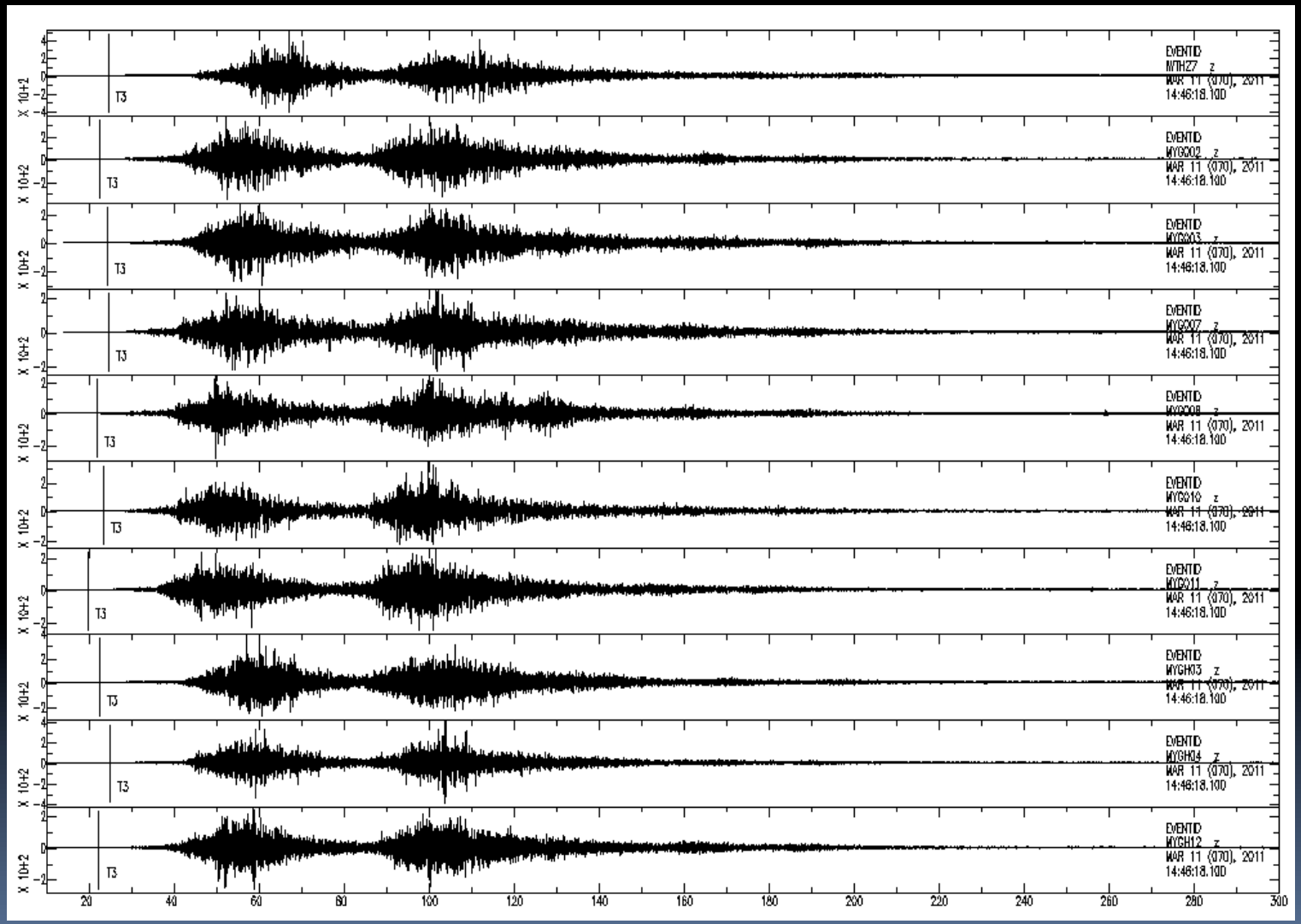


2014 Napa Valley



Center for Engineering Strong Motion Data

10 stations with highest PGA



2933 gals

2019

1845

1808

1762

1335

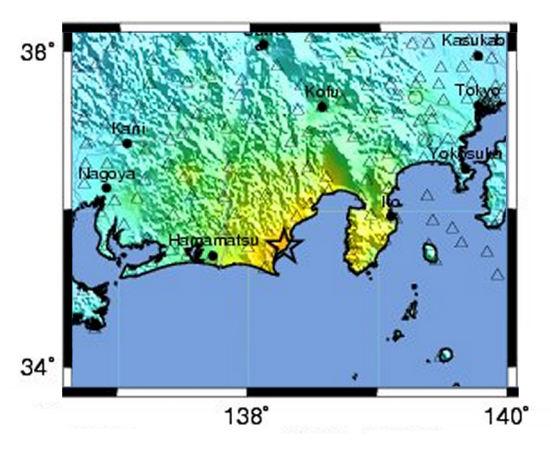
1305

1291

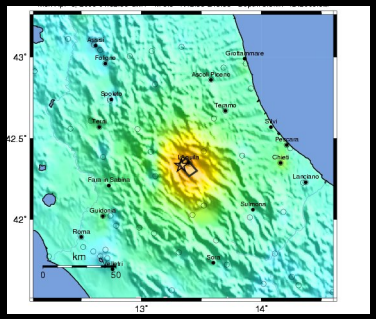
1224

1137

2009
Suruga Bay, Japan
Mw 6.4

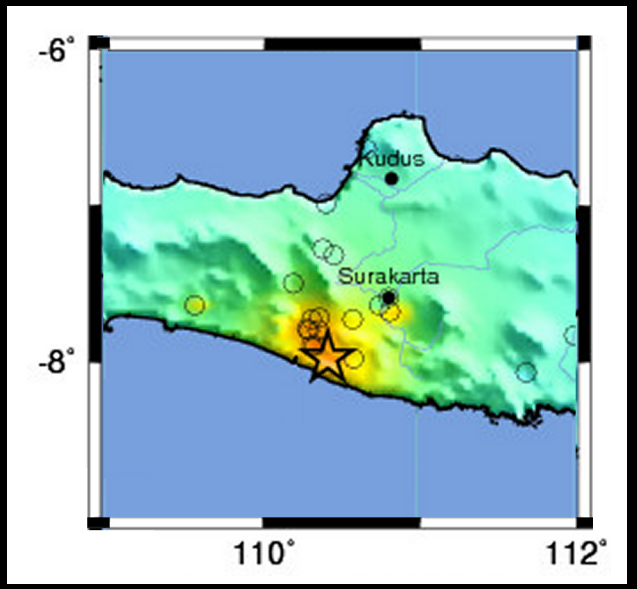


2009
L'Aquila, Italy
Mw 6.3



0 50 km

2006
Jogyakarta, Indonesia
Mw 6.3

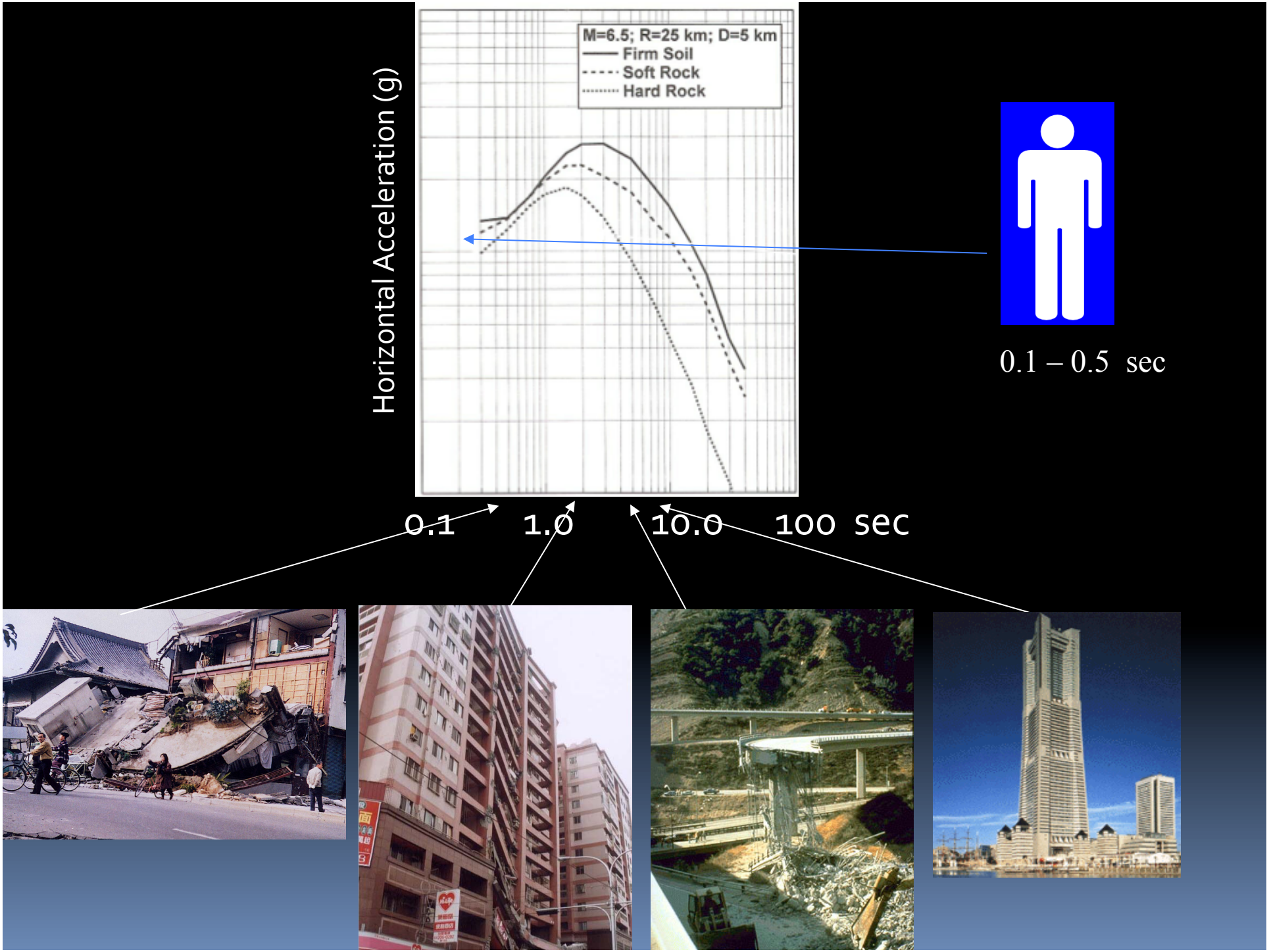


deaths 1

295

5749

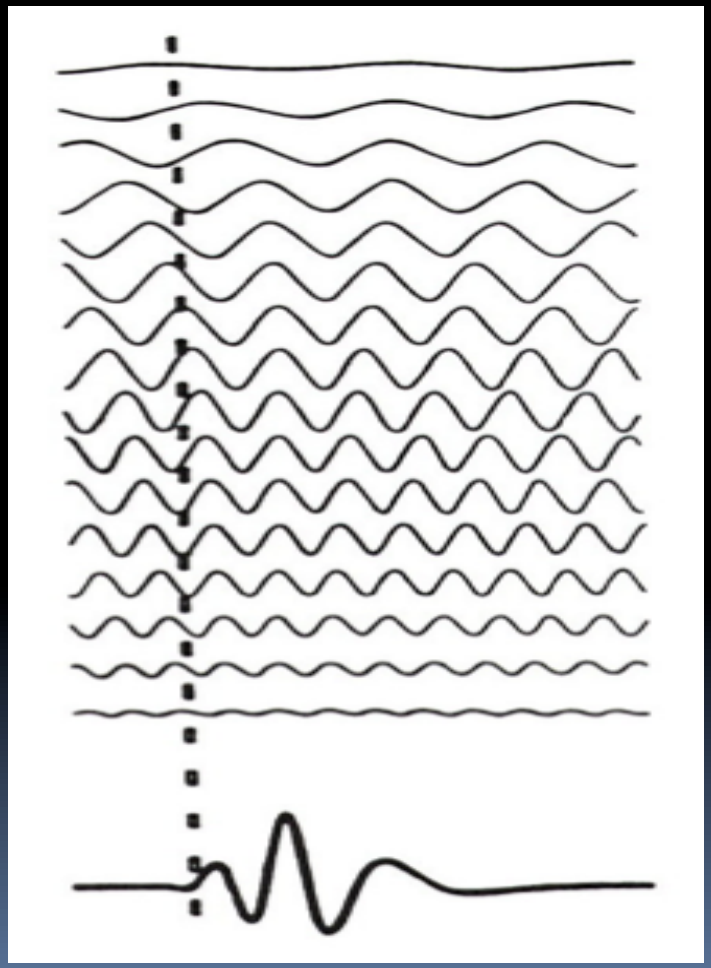
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
震度		1	2	3	3-4	4－5 弱	5 弱- 5強	5強－6弱	6強-7


Horizontal Acceleration (g)
M=6.5; R=25 km; D=5 km
Firm Soil
Soft Rock
Hard Rock
0.1 – 0.5 sec
0.1
1.0
10.0
100 sec

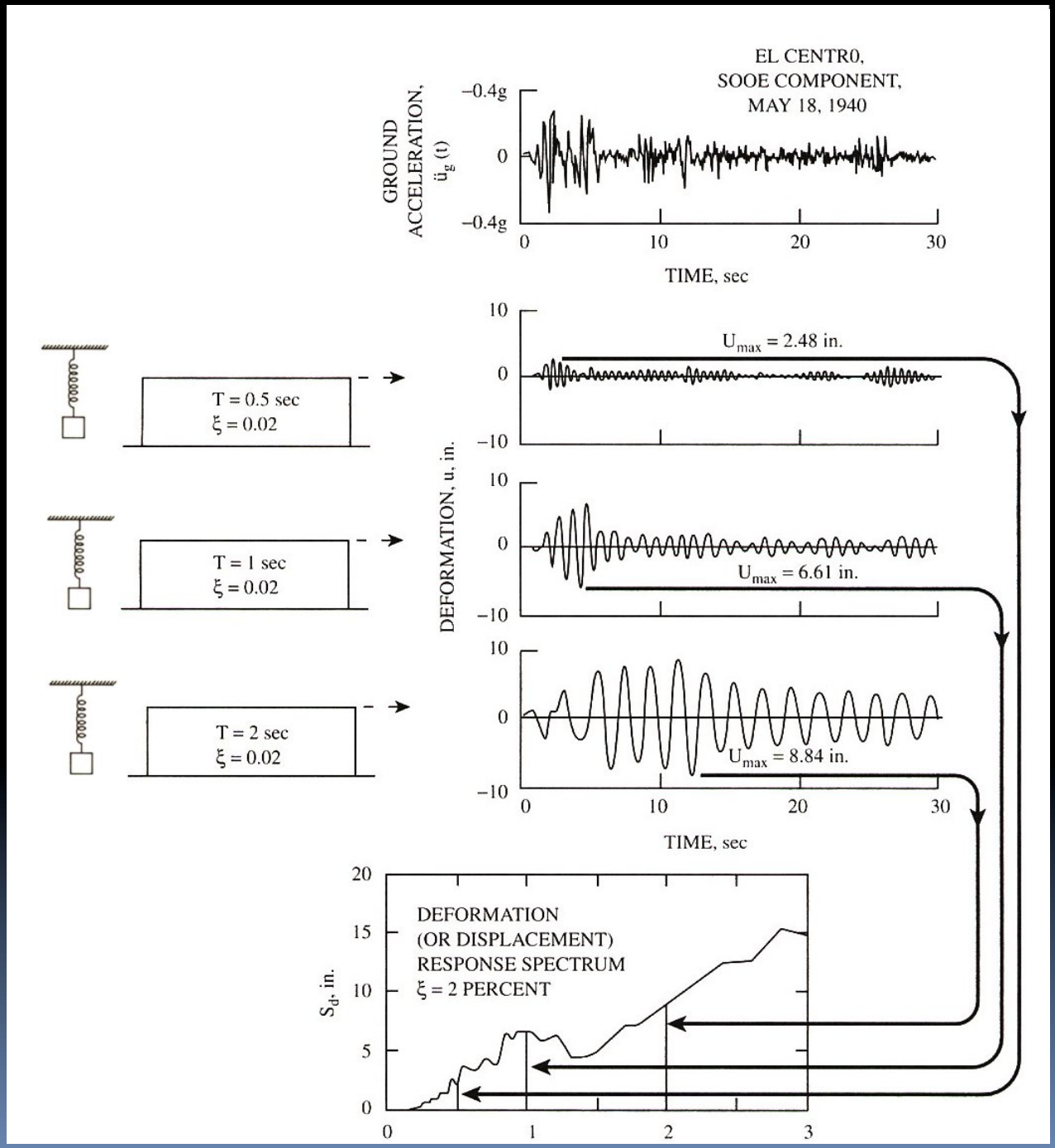
Fourier Spectra

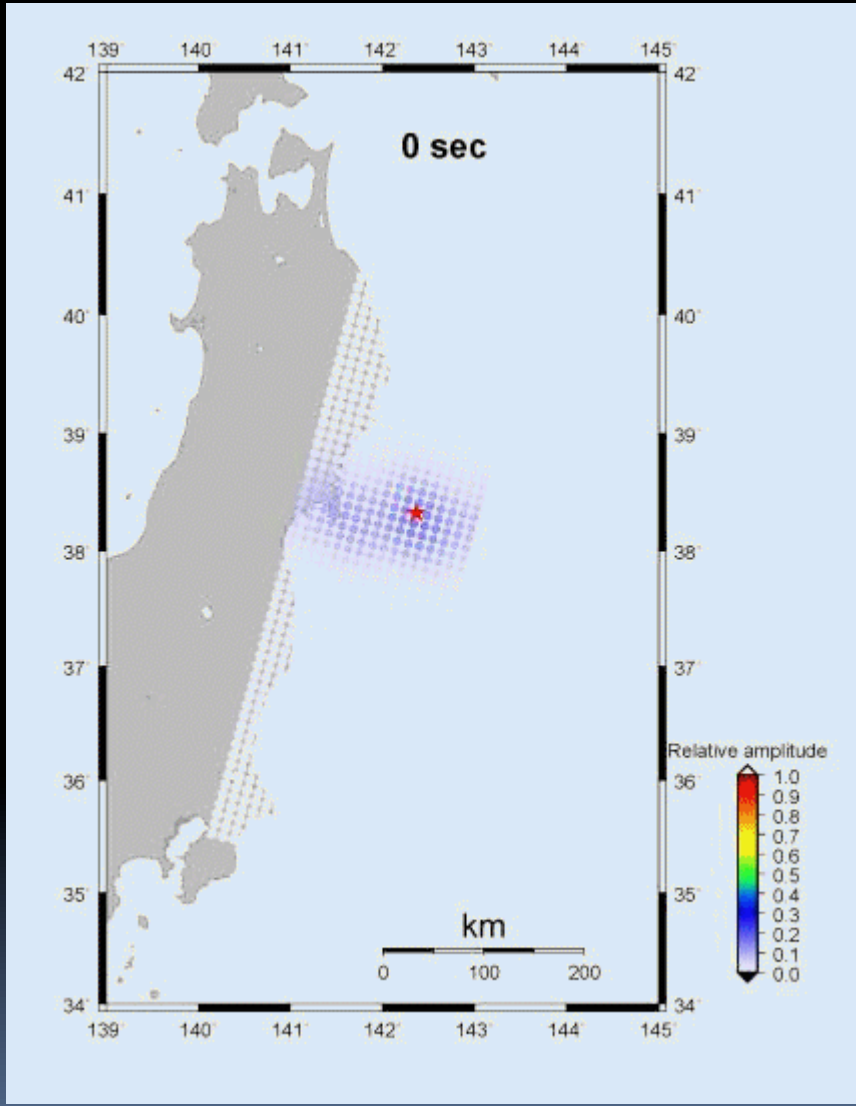
$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} F(\omega)e^{i\omega t}\,d\omega$$

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} F(\omega)[\cos(\omega t) + i\sin(\omega t)]\,d\omega$$

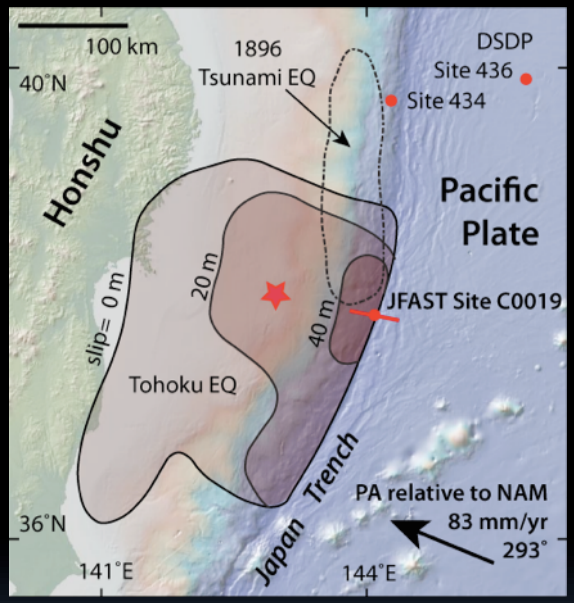


Response Spectra

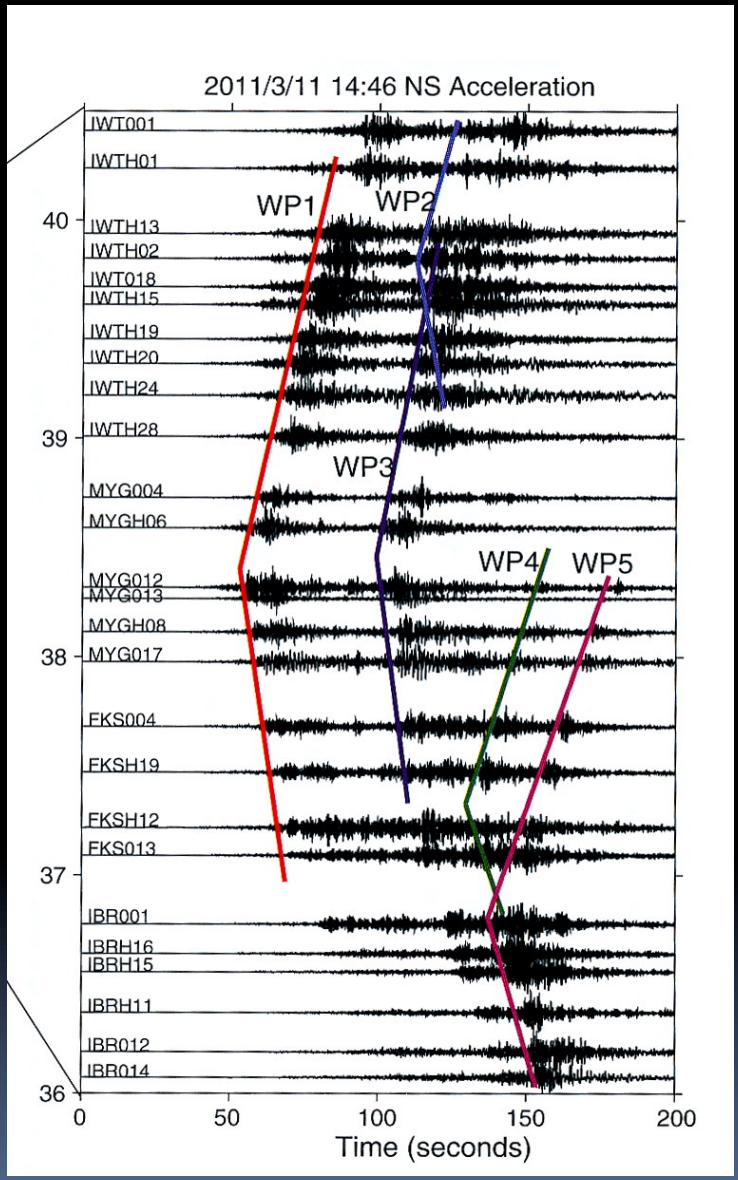


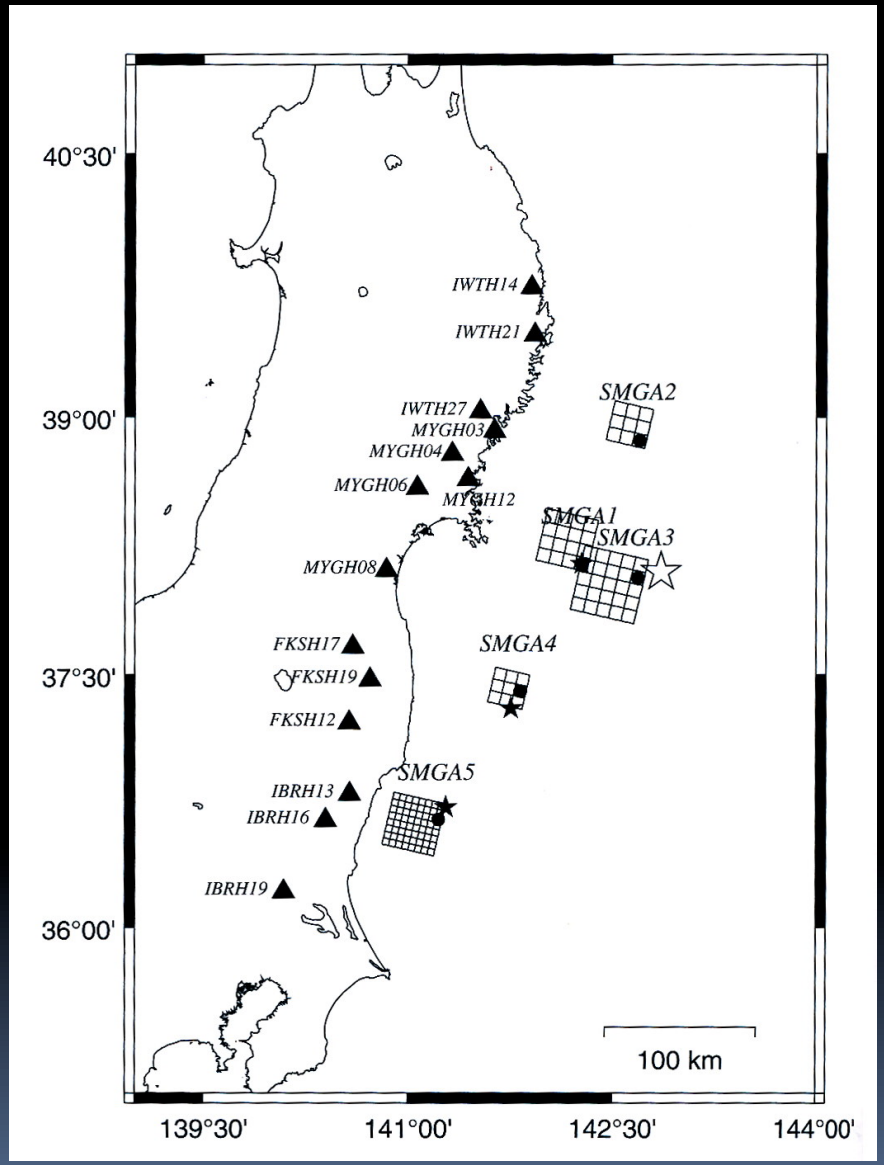


Wang and Mori, 2011



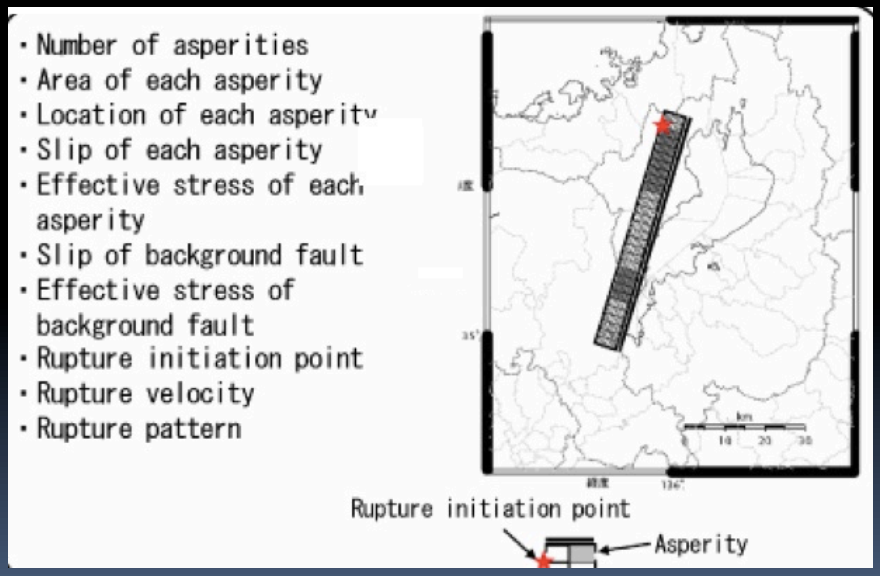
Chester et al., 2013

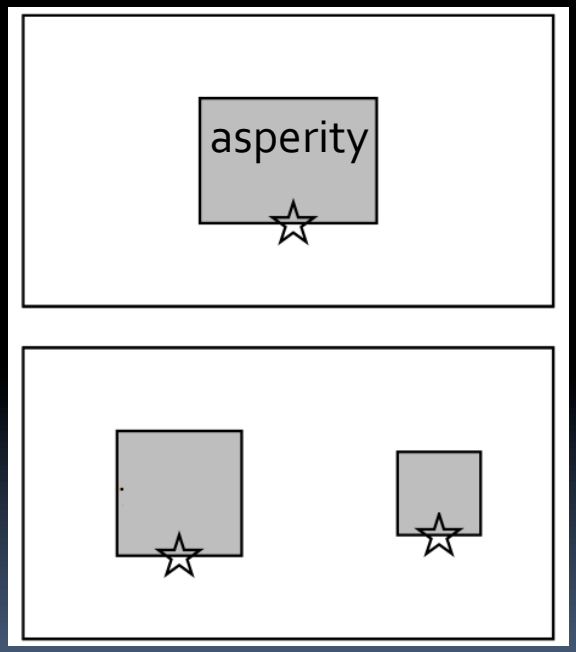




Kurahashi and Irikura, 2013

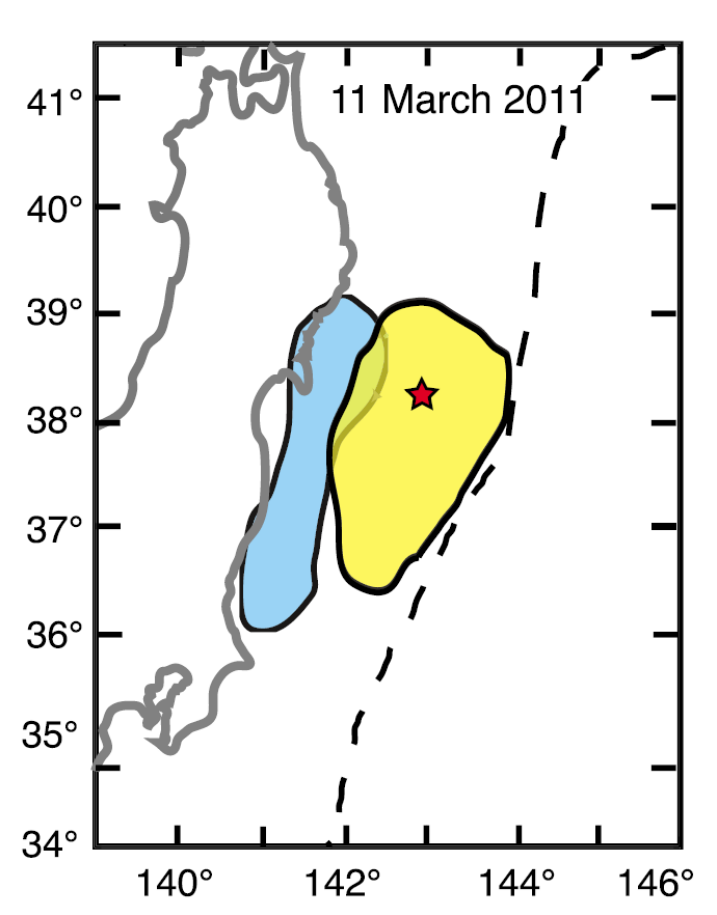
For crustal earthquakes,
sources of high-frequency strong motions
correspond to areas of large slip





'Irikura Recipe'

For large subduction zone earthquakes, there can be large difference in radiation as a function of depth (Lay et al., 2012, Frankel, 2013)

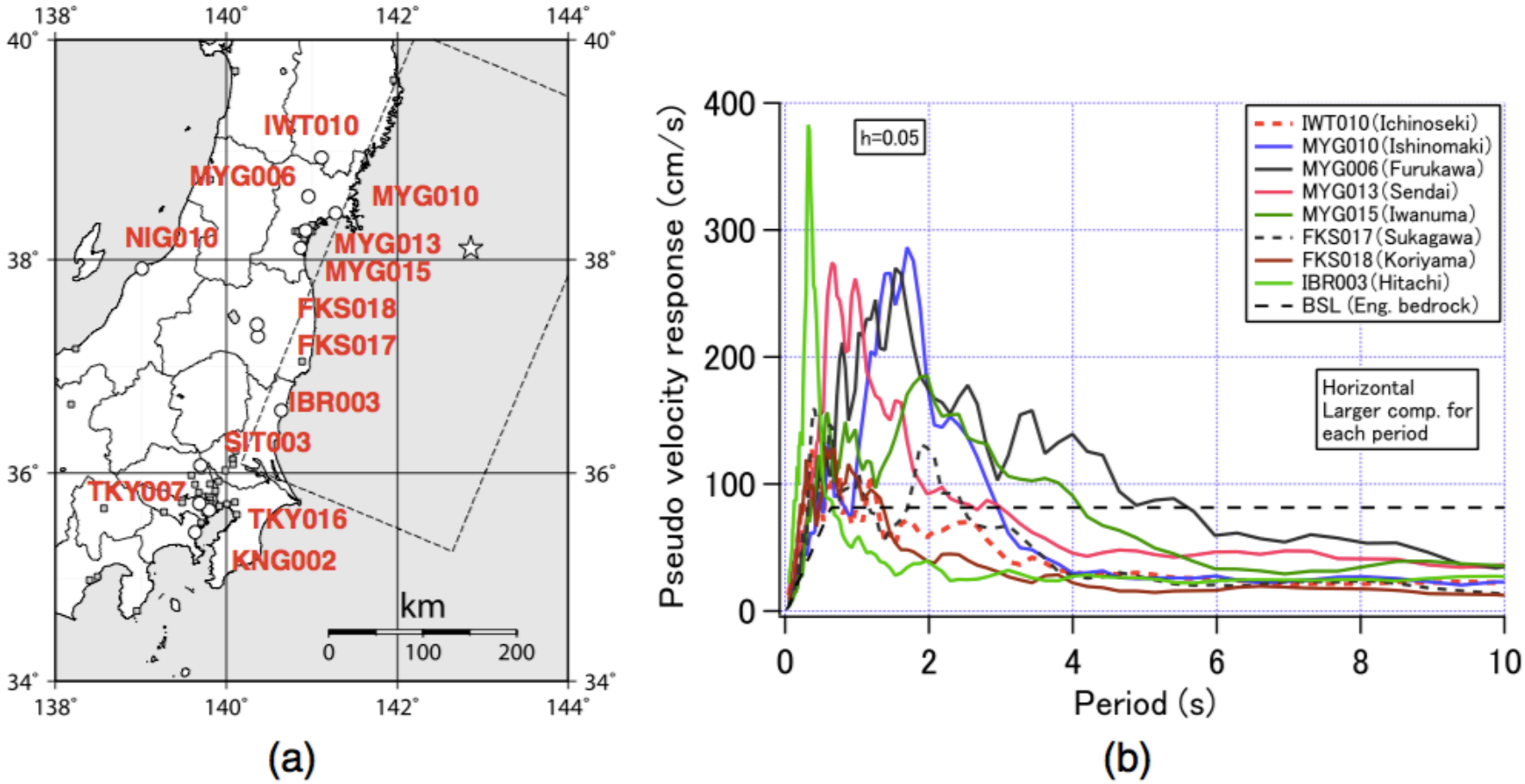


Modest slip, strong short-period radiation

Large slip, weak short-period radiation,
Strong tsunami generation

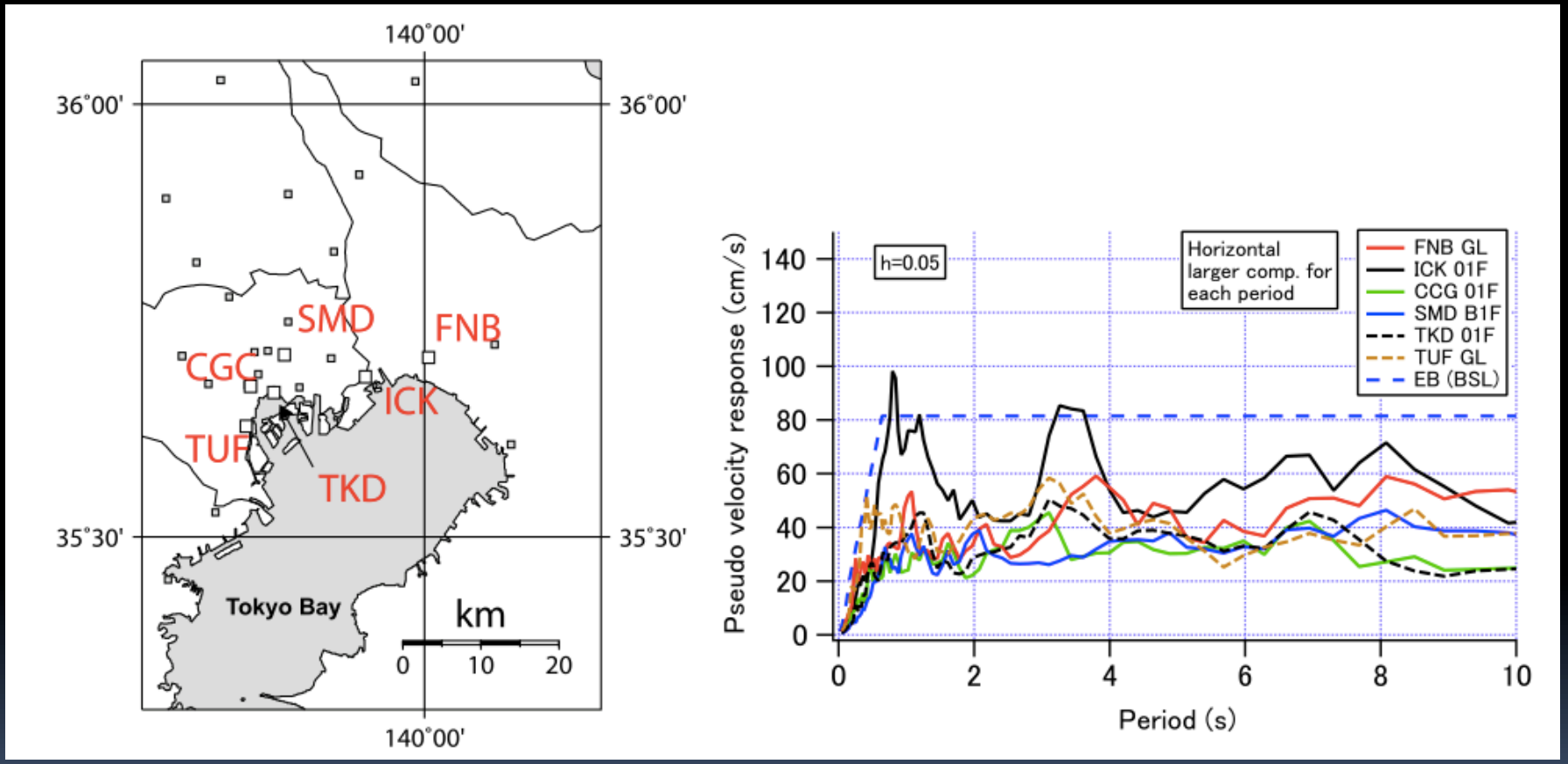
(Lay et al., 2012)

Long-period Motions in Tohoku



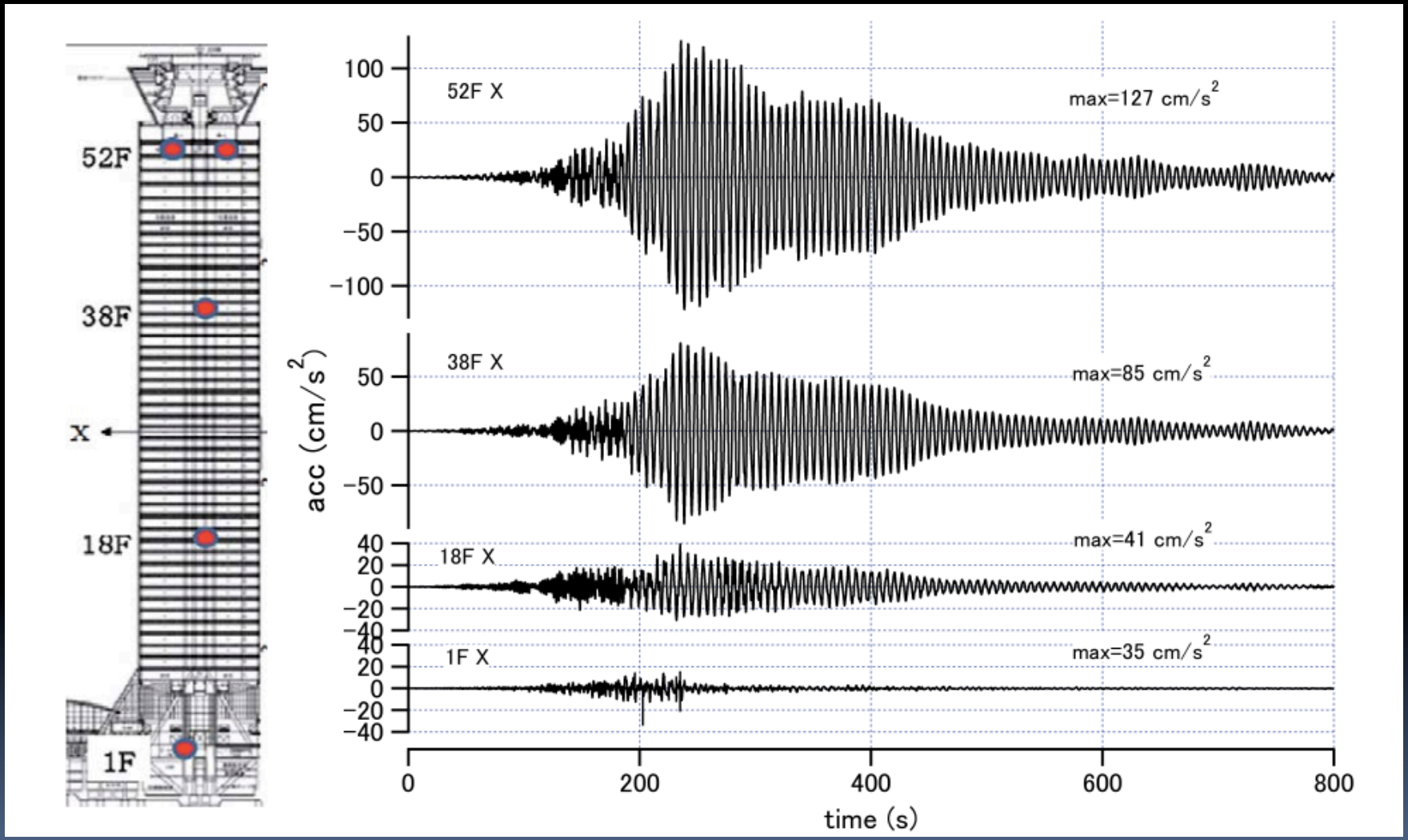
Okawa et al., 2013

Building Response in Tokyo Area



Okawa et al., 2013

55 story SKS building in Osaka, 770 km from epicenter



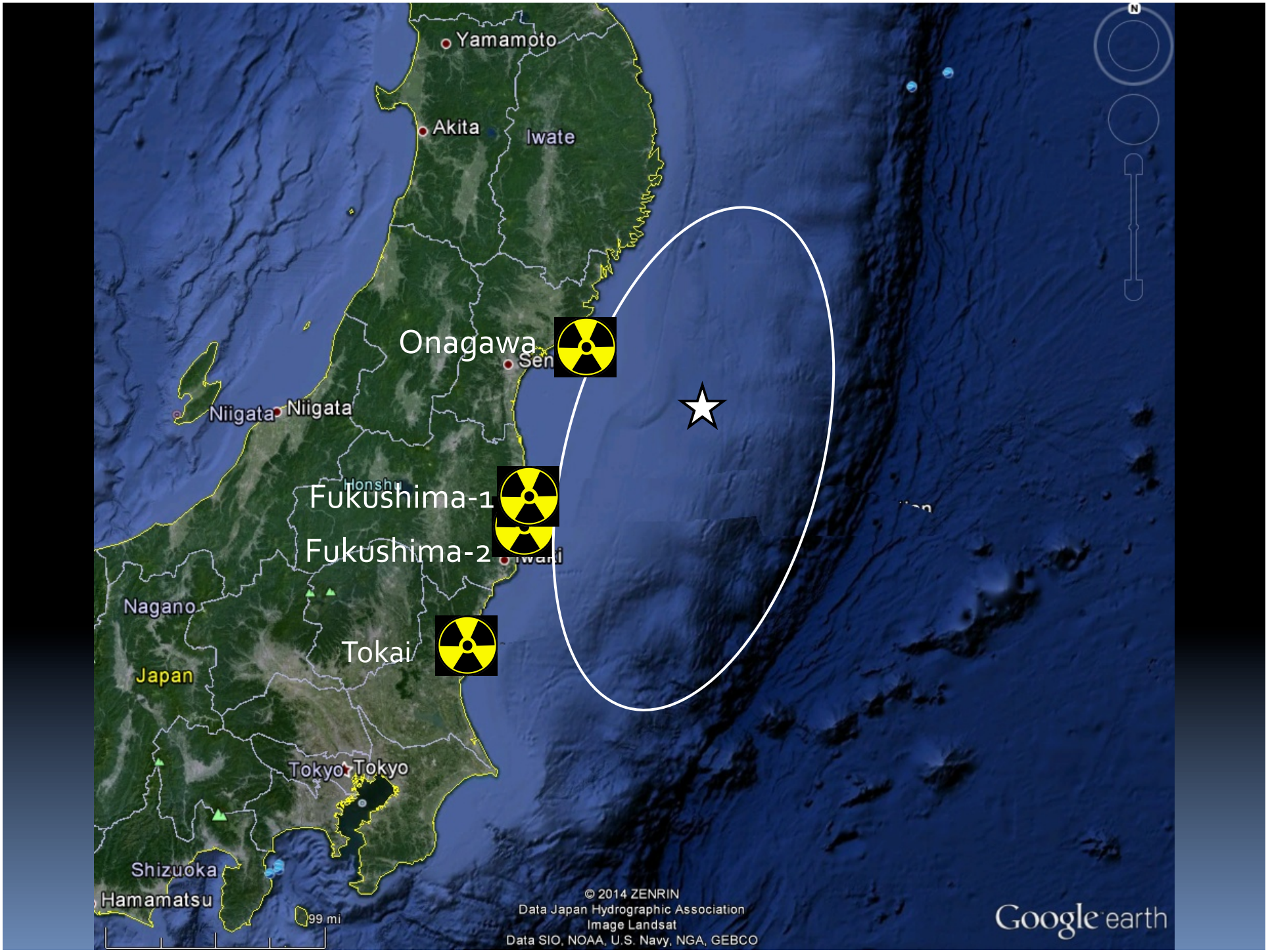
Okawa et al., 2013

Strong ground motions

- Very intense strong ground motions
  - Wide area shaken strongly
  - Large high-frequency acceleration, 1-3 g
  - Long duration shaking, 1-2 minutes

- Separation of low- and high-frequency sources
  - high-frequency on deeper portion closer to land
  - low-frequency on shallow portion near trench

- Only moderate damage to buildings in area of strong shaking


Yamamoto
Akita
Iwate
Onagawa
Niigata
Niigata
Honshu
Fukushima-1
Fukushima-2
Nagano
Tokai
Japan
Tokyo
Tokyo
Shizuoka
Hamamatsu
99 mi
© 2014 ZENRIN
Data Japan Hydrographic Association
Image Landsat
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
Google earth

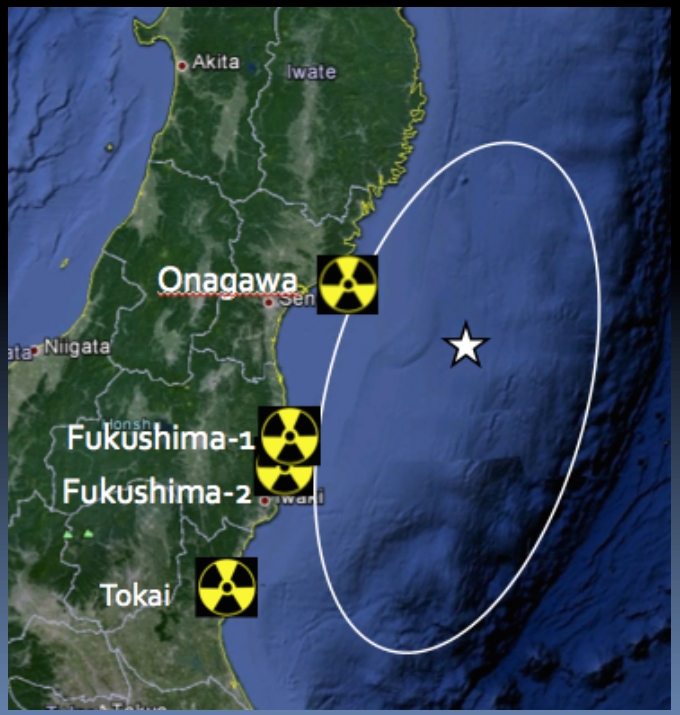
Explosions at Fukushima-1 nuclear power plant on March 12 and 14

- Explosions caused by overheating because cooling systems did not have power.
- Tsunamis destroyed the back-up power supplies.
- Power could not be restored

(Photo from http://174.143.24.167/home/green-living/206356-reconsidering-the-nuclear-option)

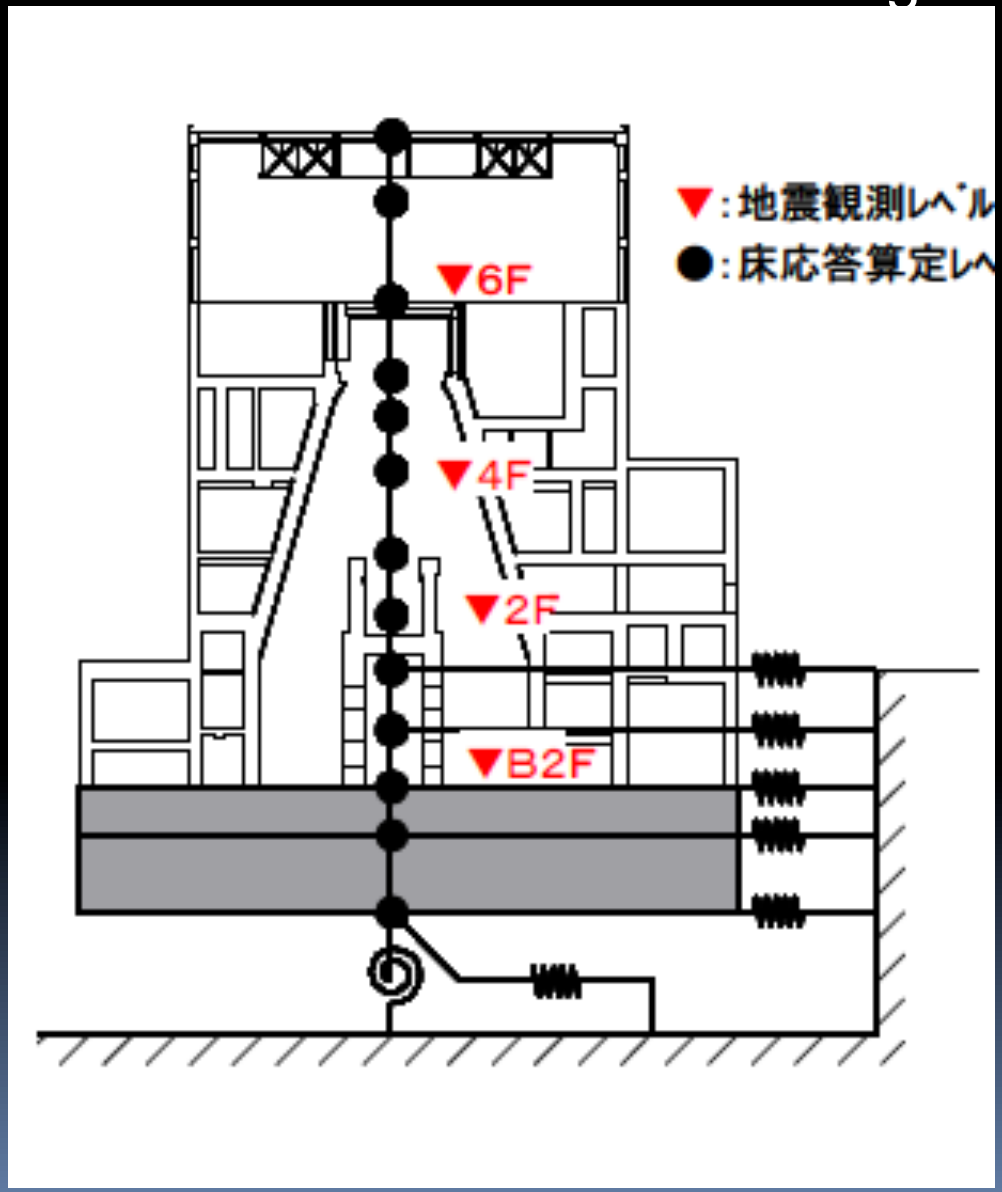
Onagawa and Fukushima-2 Nuclear Power Plants

- Tsunami destroyed back-up power supplies
- Power was restored with cables and portable generators
- No radiation leaks reported
- Shaking was stronger and tsunami larger at Onagawa than Fukushima 1



Tokai Nuclear Power Plant
1 of 3 back-up generators was operational and provided power to cooling system

Reactor Model for Seismic Design



Observed and Design PGA at Fukushima 1 and 2

Observed

Design

観測点（原子炉建屋最地下階）		観測記録（暫定値※1）最大加速度値（ガル）			基準地震動 Ss に対する最大応答加速度値（ガル）		
		南北方向	東西方向	上下方向	南北方向	東西方向	上下方向
Fukushima 1 福島第一	1 号機	460※2	447※2	258※2	487	489	412
	2 号機	348※2	550※2	302※2	441	438	420
	3 号機	322※2	507※2	231※2	449	441	429
	4 号機	281※2	319※2	200※2	447	445	422
	5 号機	311※2	548※2	256※2	452	452	427
	6 号機	298※2	444※2	244	445	448	415
Fukushima 2 福島第二	1 号機	254	230※2	305	434	434	512
	2 号機	243	196※2	232※2	428	429	504
	3 号機	277※2	216※2	208※2	428	430	504
	4 号機	210※2	205※2	288※2	415	415	504

N/S E/W Z N/S E/W Z

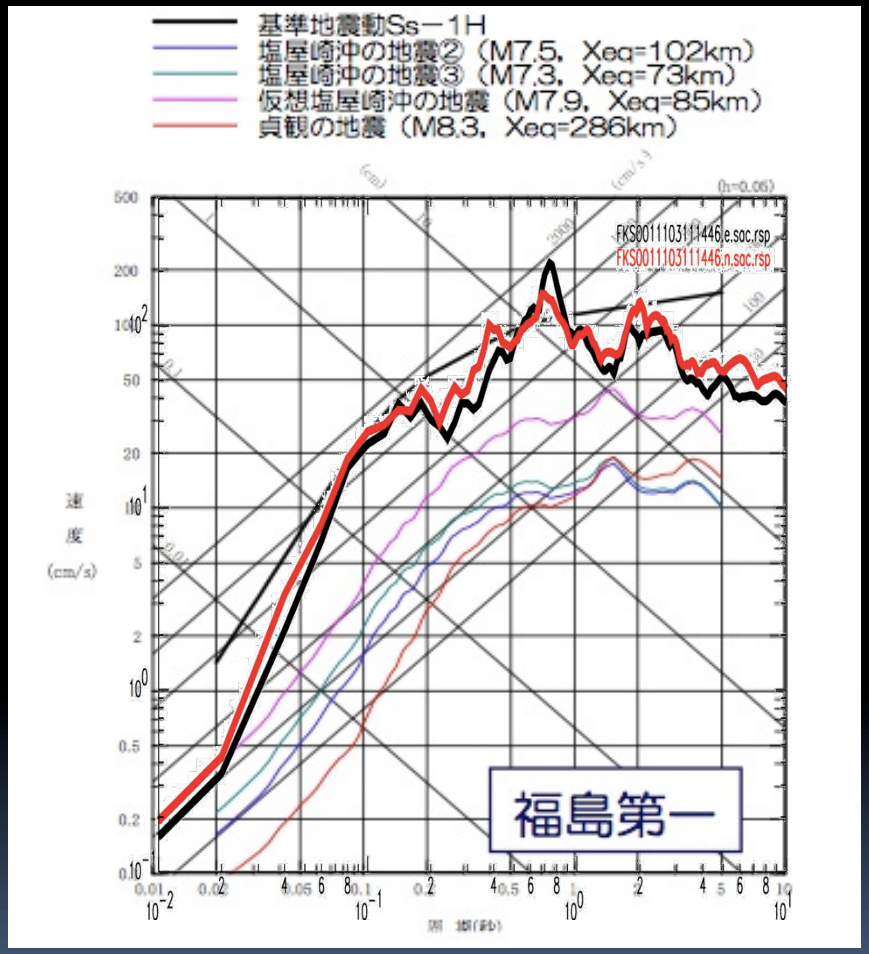
600 gals (PGA at free rock)

Observed and Design PGA at the Onagawa

観測位置		Observed Ground Motion Peak Acceleration (gal)			Design Values Peak Acceleration (gal)		
		N/S	E/W	Z	N/S	E/W	Z
1号機	屋上	2000※7	1636	1389	2202	2200	1388
	燃料取替床（5階）	1303	998	1183	1281	1443	1061
	1階	573	574	510	660	717	527
	基礎版上	540	587	439	532	529	451
2号機	屋上	1755	1617	1093	3023	2634	1091
	燃料取替床(3階)	1270	830	743	1220	1110	968
	1階	605	569	330	724	658	768
	基礎版上	607	461	389	594	572	490
3号機	屋上	1868	1578	1004	2258	2342	1064
	燃料取替床(3階)	956	917	888	1201	1200	938
	1階	657	692	547	792	872	777
	基礎版上	573	458	321	512	497	476

Design Basis Ground Motions at the Onagawa NPP: 580 gals (PGA at free rock)

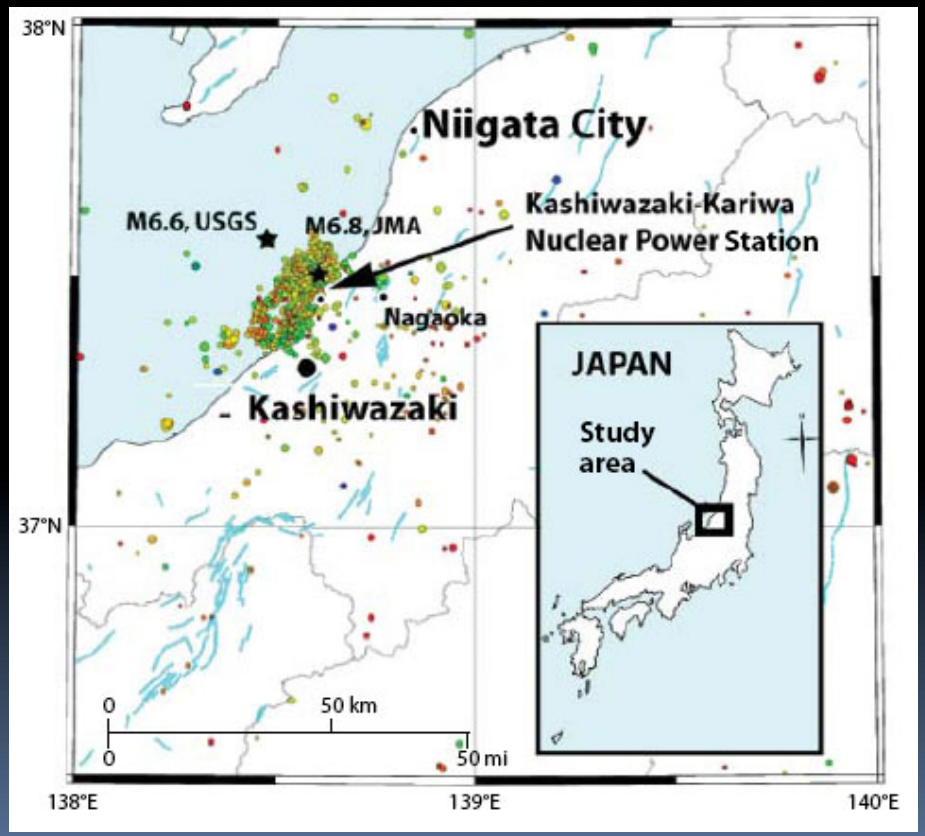
Fukushima 1 Earthquake Scenarios

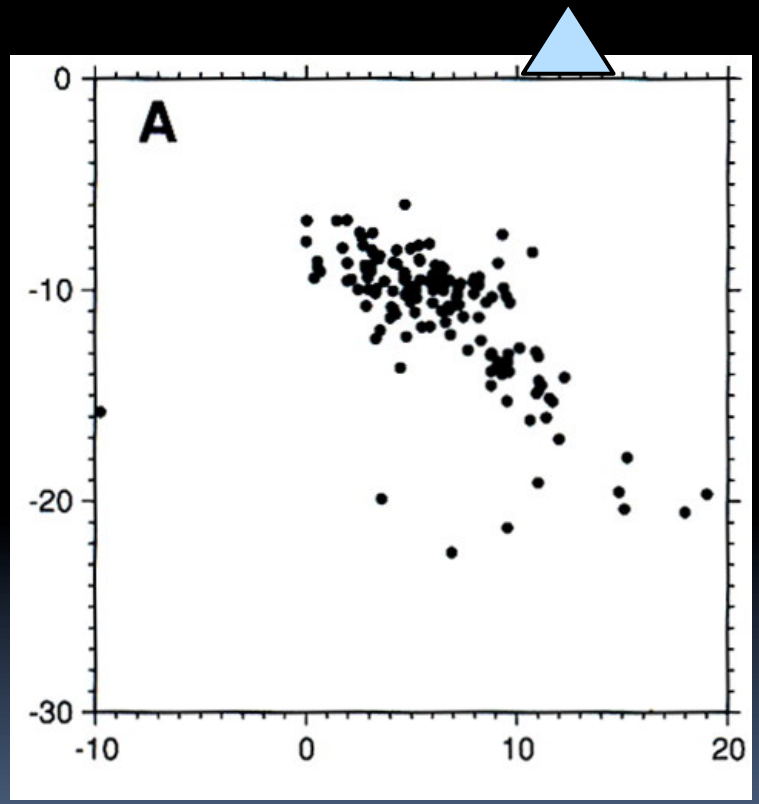


- Recorded ground motions close to design levels
- No apparent structural damage to nuclear power plants

Niigata Chuetsu-oki Earthquake
July 16, 2007 Mw6.6

Kashiwazaki largest nuclear power plant in the world by amount of power generation





http://soundwaves.usgs.gov/2008/01/

Mori, 2008

- PGA 680 cm/s^2 at Unit 1 exceeded design level of 450 cm/s^2 for safe shutdown
- No structural damage
- Successful shutdown at all units
- Fire in electrical transformer
- Small amount of radiation leak from storage area of waste material

- Seismic design of structural was successful
- Conservative safety factor in construction ?
- Problem in auxiliary components (transformer, waste storage)

Mihama Nuclear Power Plant

- March 2011
  19 Active Plants
  3 Planned

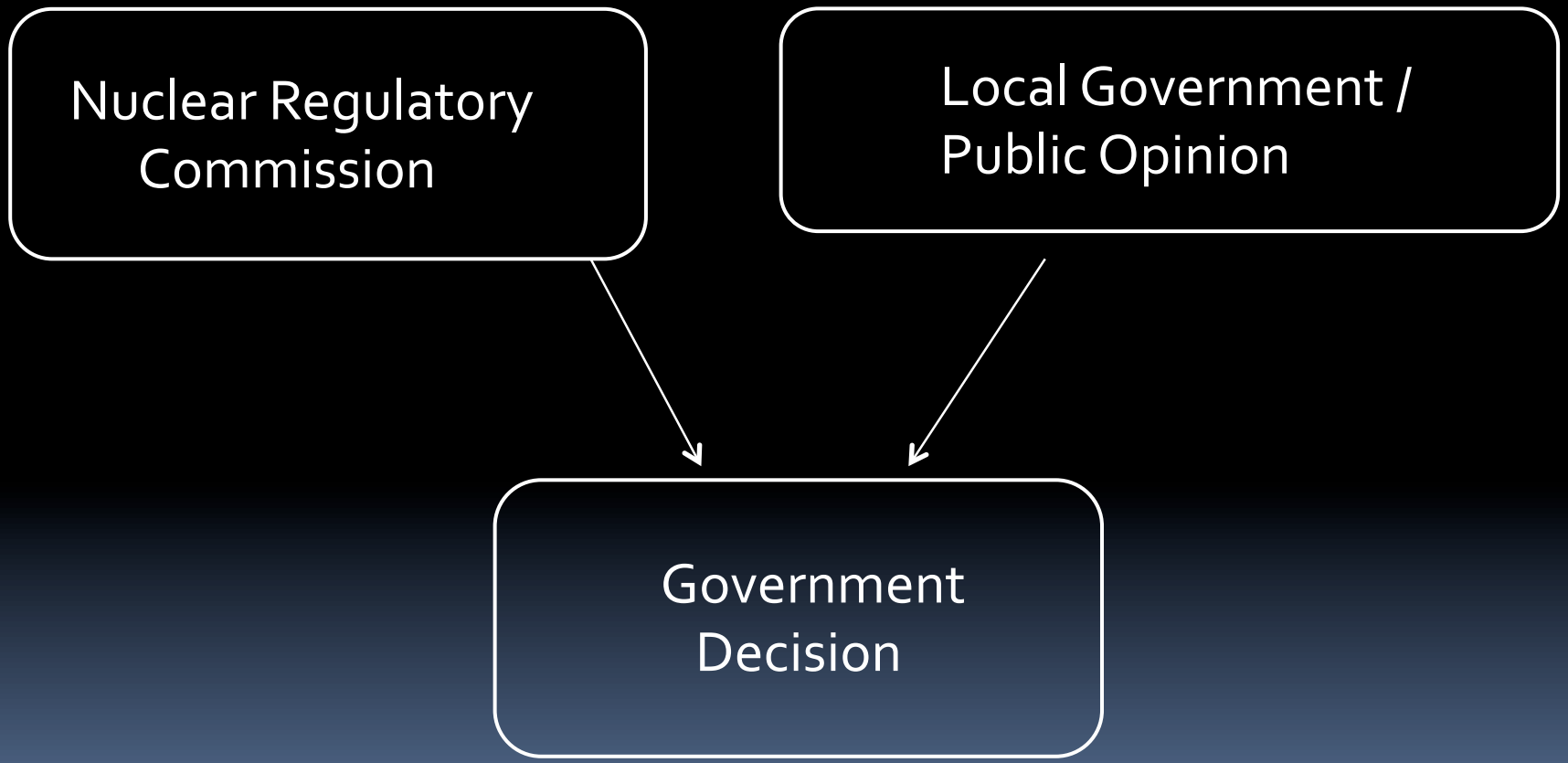
- 20% - 30% of Japan's power

- 2014
  0 Active Plants

- Procedures to restart plants

- Permanently shut down all by 2030 ?

Process for Restarting of Nuclear Power Plants in Japan



* Decision does not include Agency for Natural Resources and Energy

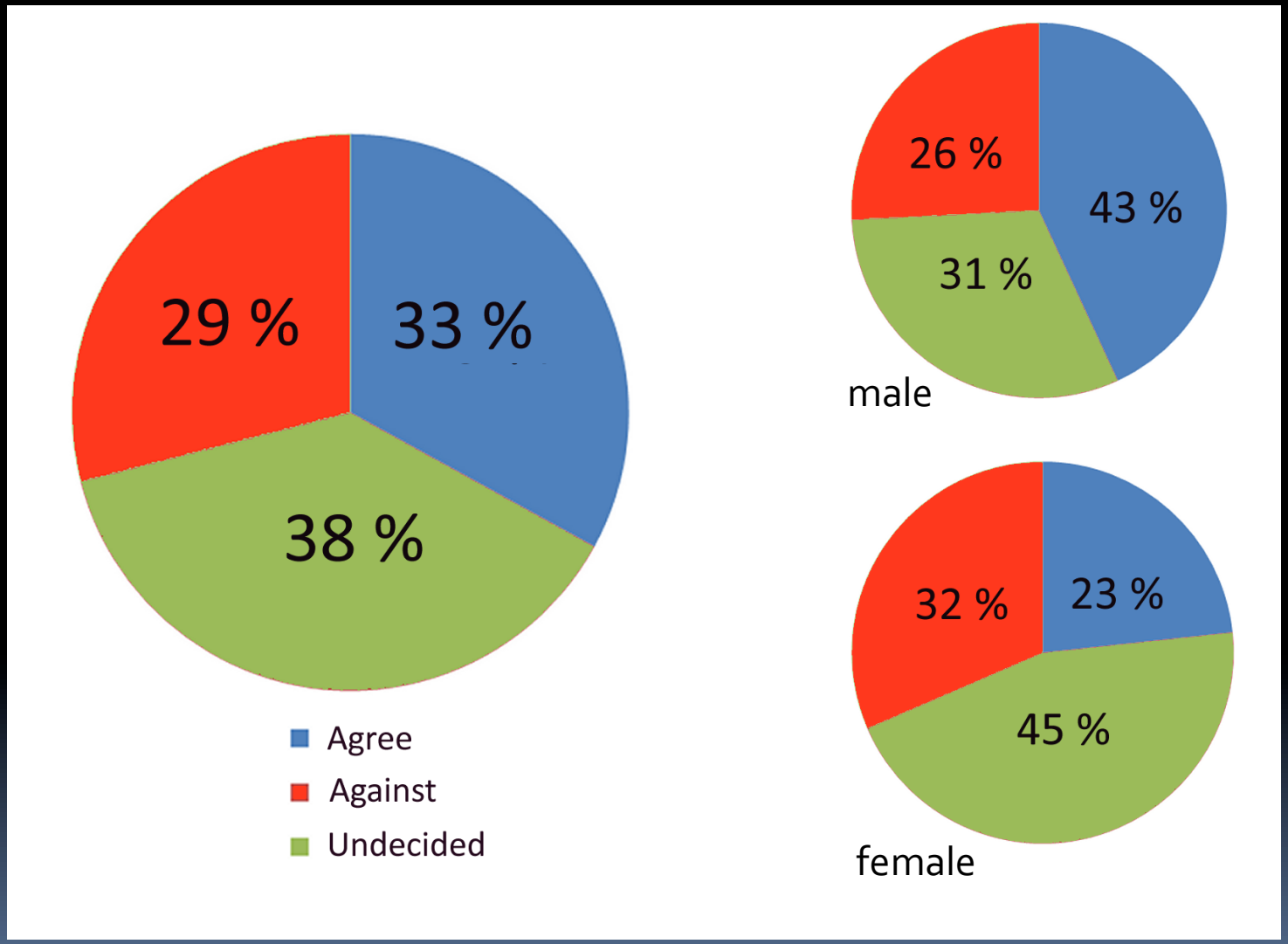
Nuclear Regulatory Commission

Seismic safety issues
- Active faults
  (100,000 years -> 300,000 year)
- Tsunami
  (only young deposits available)

First case is the Sendai Nuclear Plant in Kyushu

Prof. Kunihiko Shimazaki

Should the Sendai Nuclear Power plant in Kyushu be restarted ?



Internet Poll on July 20,2014 to August 8, 2014

USA TODAY | World

Subscribe | Mobile | Google USA TODAY stories, photos and more GO

Sign in | Be

Home | News | Travel | Money | Sports | Life | Tech

News: Communities | Education | Nation | Military | Politics | Religion | Offbeat | Washington | World | Opinion | Your Life

Germany to abandon nuclear power by 2022

Updated 5/30/2011 4:51 AM | Share

BERLIN (AP) — Germany's coalition government agreed early Monday to shut down all the country's nuclear power plants by 2022, the environment minister said, making it the first major industrialized power to go nuclear-free since the Japanese disaster.

By Gero Breloer, AP

Crowd holds a banner reading "stop nuclear power" in front of the Reichstag Building, housing the German parliament.

The country's seven oldest reactors already taken off the grid pending safety inspections following the catastrophe at the Fukushima nuclear power plant in March will remain offline permanently, Norbert Roettgen added. The country has 17 reactors total.

Roettgen praised the coalition agreement after negotiations through the night between the governing parties.

"This is coherent. It is clear," he told reporters in Berlin. "That's why it is a good result."

Chancellor Angela Merkel pushed through measures in

Videos you may be interested in

Breastfeeding photos are here to stay on Facebook

Syria, Iran slam US plan in fighting militants

USA TODAY MOST POPULAR

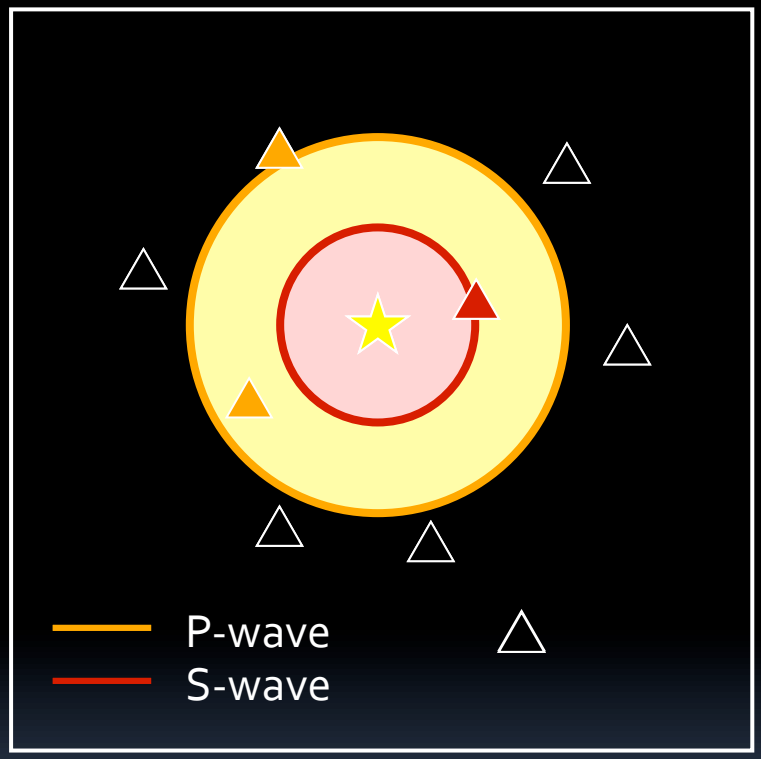
Germany has permanently shut down eight of its 17 reactors and pledged to close the rest by the end of 2022. Italy voted overwhelmingly to keep their country non-nuclear. Switzerland and Spain have banned the construction of new reactors.

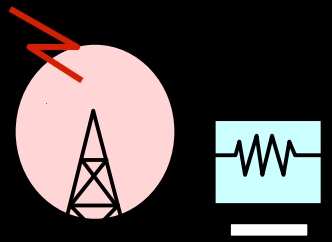
Impacts at Nuclear Power Plants

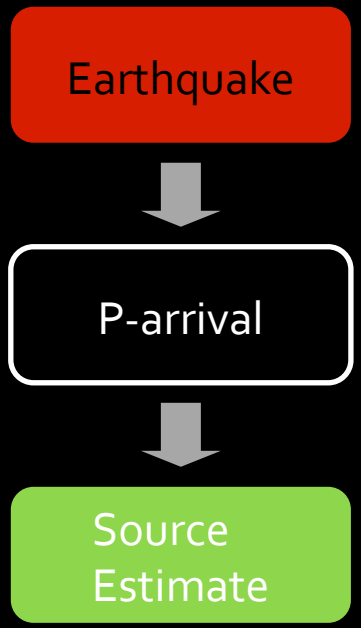
- Ground motions were close design limits
- No significant damage from shaking of M9 earthquake at 4 nuclear power plants
- Problems at Fukushima 1 caused by tsunami damage to back-up power supply

Future of nuclear power in Japan is a difficult and controversial issue

Earthquake Early Warning System



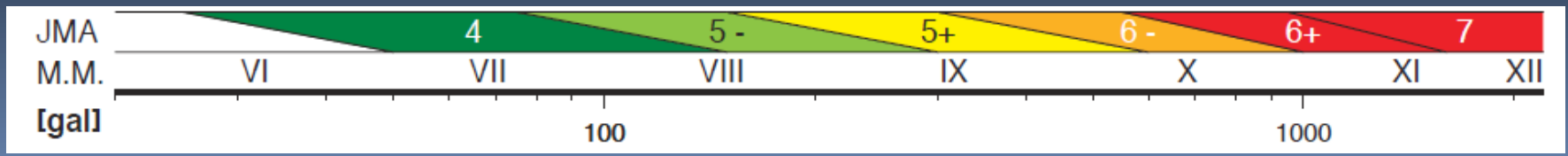




21 warnings have been issued 2008 - 2011
8 warnings for M6 to M7 earthquakes

	M	Predicted Intensity	Observed Intensity	Elapsed time* for public warning
May 8, 2008	7.2	6 +	6 -	4.5 sec
July 8, 2008	6.1	5 -	5 -	13.9
July 24, 2008	6.8	5 -	6 -	20.8
Sep. 11, 2008	7.1	5 +	5 -	9.7
Aug. 11, 200	6.5	5 +	6 -	3.8
Oct. 30, 2009	6.8	5 -	4	26.8
Feb. 27, 2010	7.2	6 -	5 -	4.1
Mar. 14, 2010	6.7	5 -	5 -	3.6

* Time measured from detection of first P wave



Distribution of Information

TV (98%)
124 stations

Radio (75%)
41 AM stations
35 FM stations

Early Warning for Mainshock
on March 11, 2011

Earthquake Early Warning System

Cellular phones

Phone companies (Docomo, AU, Softbank) broadcast Earthquake Early Warnings provided by JMA

52,300,000 cellular phones can receive the Earthquake Early Warnings (47% of total)

Earthquake Early Warning
An earthquake occurred off the southeast coast of Mie. Prepare for strong shaking (JMA)

http://www.nttdocomo.co.jp/english/

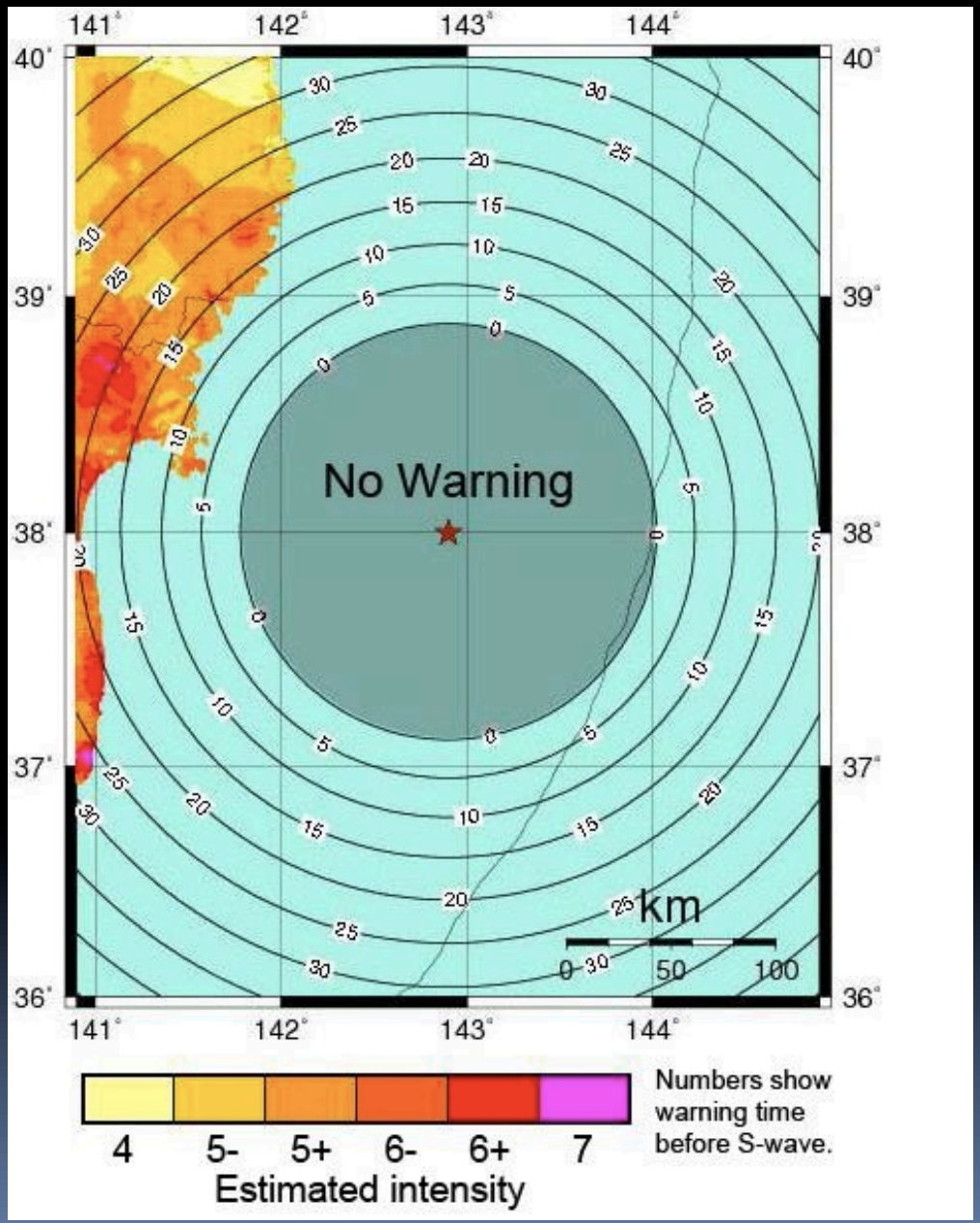
March 11, 2011 Tohoku Earthquake

[01] 11/03/11-14:46:19 01 M4.3 38.2E 142.7E 010km (11/03/11-14:46.46)
[02] 11/03/11-14:46:19 03 M5.9 38.2E 142.7E 010km (11/03/11-14:46.47)
[03] 11/03/11-14:46:19 04 M6.8 38.2E 142.7E 010km (11/03/11-14:46.48)
[04] 11/03/11-14:46:19 5- M7.2 38.2E 142.7E 010km (11/03/11-14:46.49)
[05] 11/03/11-14:46:19 04 M6.3 38.2E 142.7E 010km (11/03/11-14:46.50)
[06] 11/03/11-14:46:19 04 M6.6 38.2E 142.7E 010km (11/03/11-14:46.51)
[07] 11/03/11-14:46:19 04 M6.6 38.2E 142.7E 010km (11/03/11-14:46.52)
[08] 11/03/11-14:46:17 04 M7.2 38.1E 142.9E 010km (11/03/11-14:46.56)

°
°
°

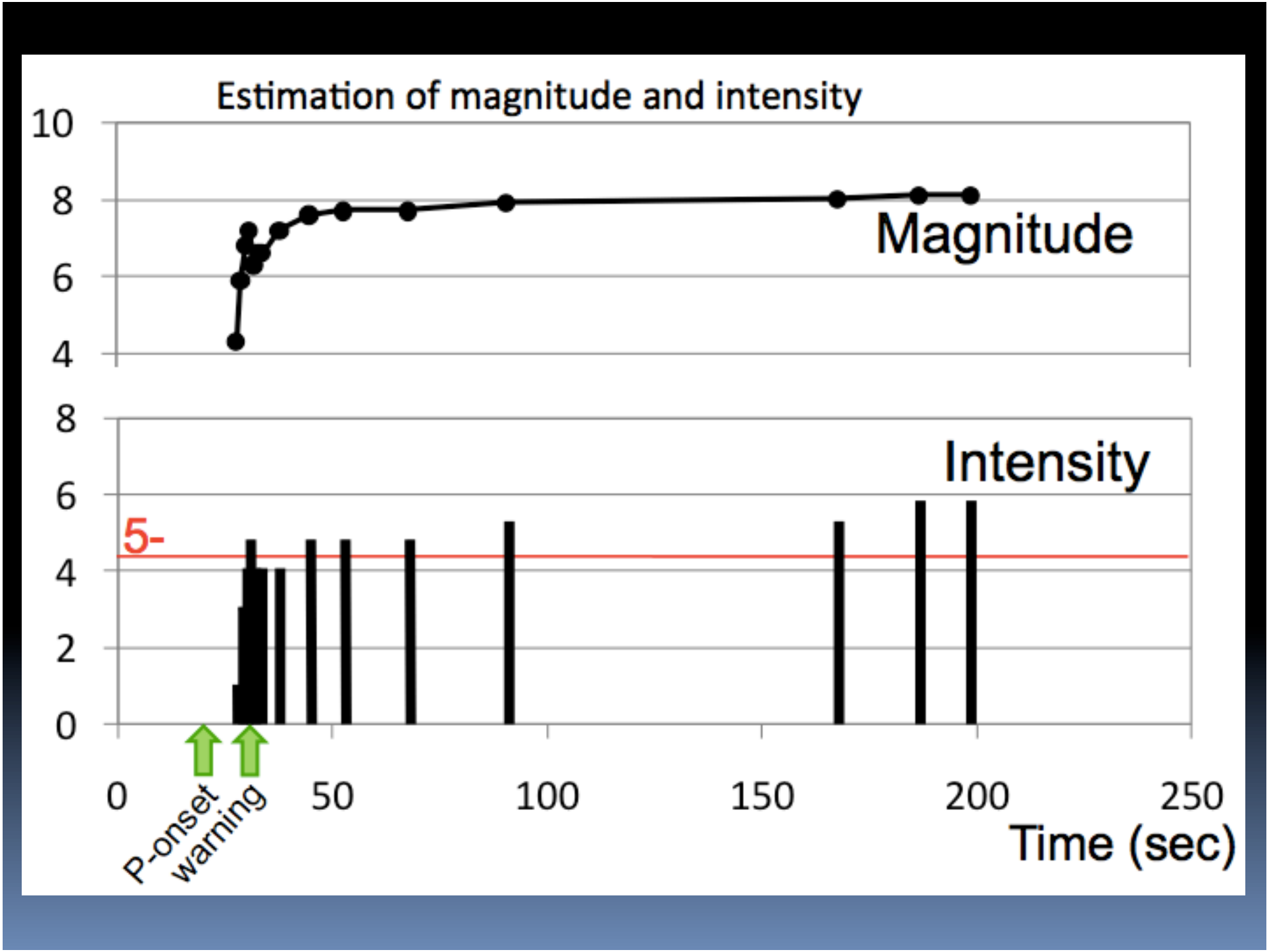
[14] 11/03/11-14:46:17 6- M8.1 38.1E 142.9E 010km (11/03/11-14:48:25)
[15] 11/03/11-14:46:17 6- M8.1 38.1E 142.9E 010km (11/03/11-14:48:37)

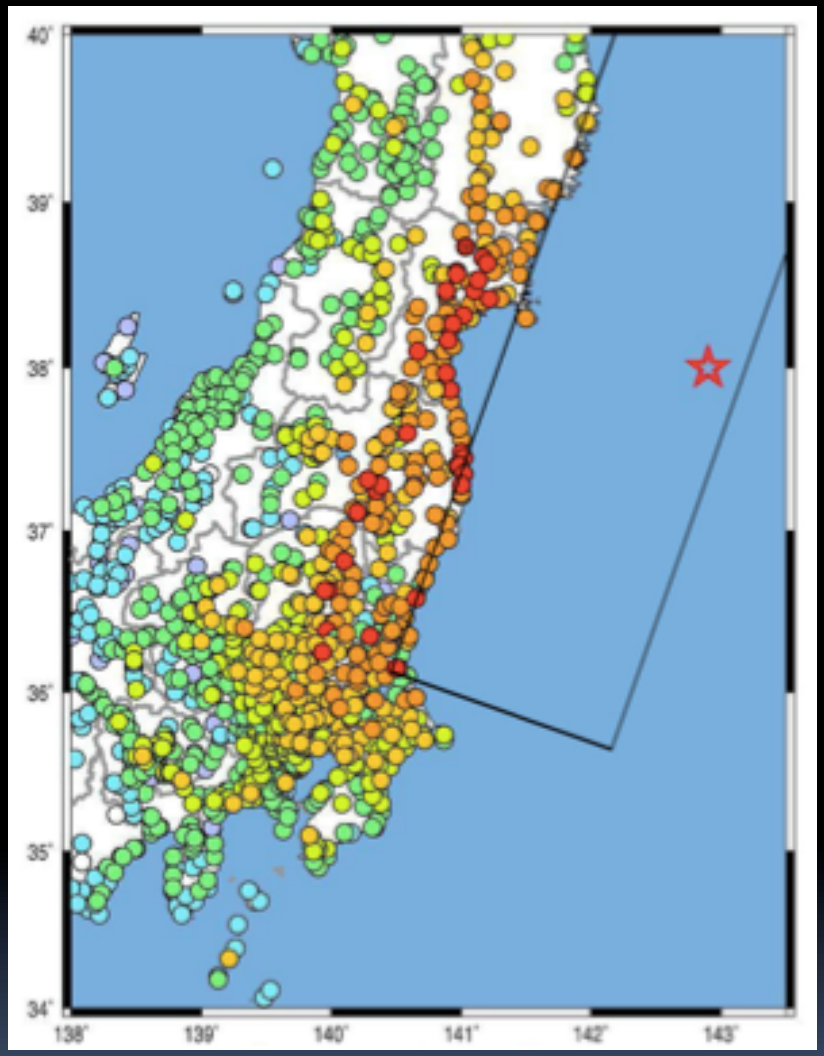
Warning was issued 8 sec after 1st P wave,
31 sec after origin time



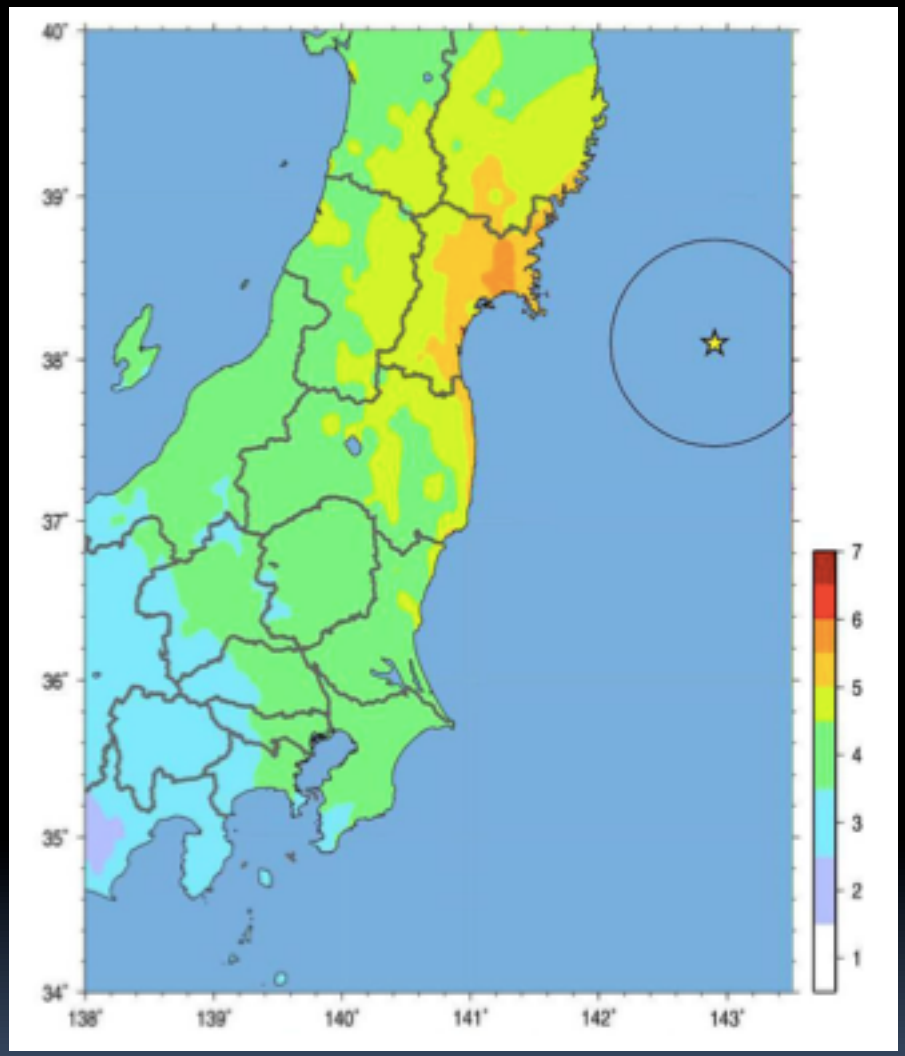
Warning issued 8 sec after P-wave detection. 31 sec after origin time.

Warnings gave at least 5 to 30 sec warning in Tohoku region


Estimation of magnitude and intensity
10
8
6
4
Magnitude
8
6
4
2
0
Intensity
5-
0
50
100
150
200
250
Time (sec)
P-onset
warning

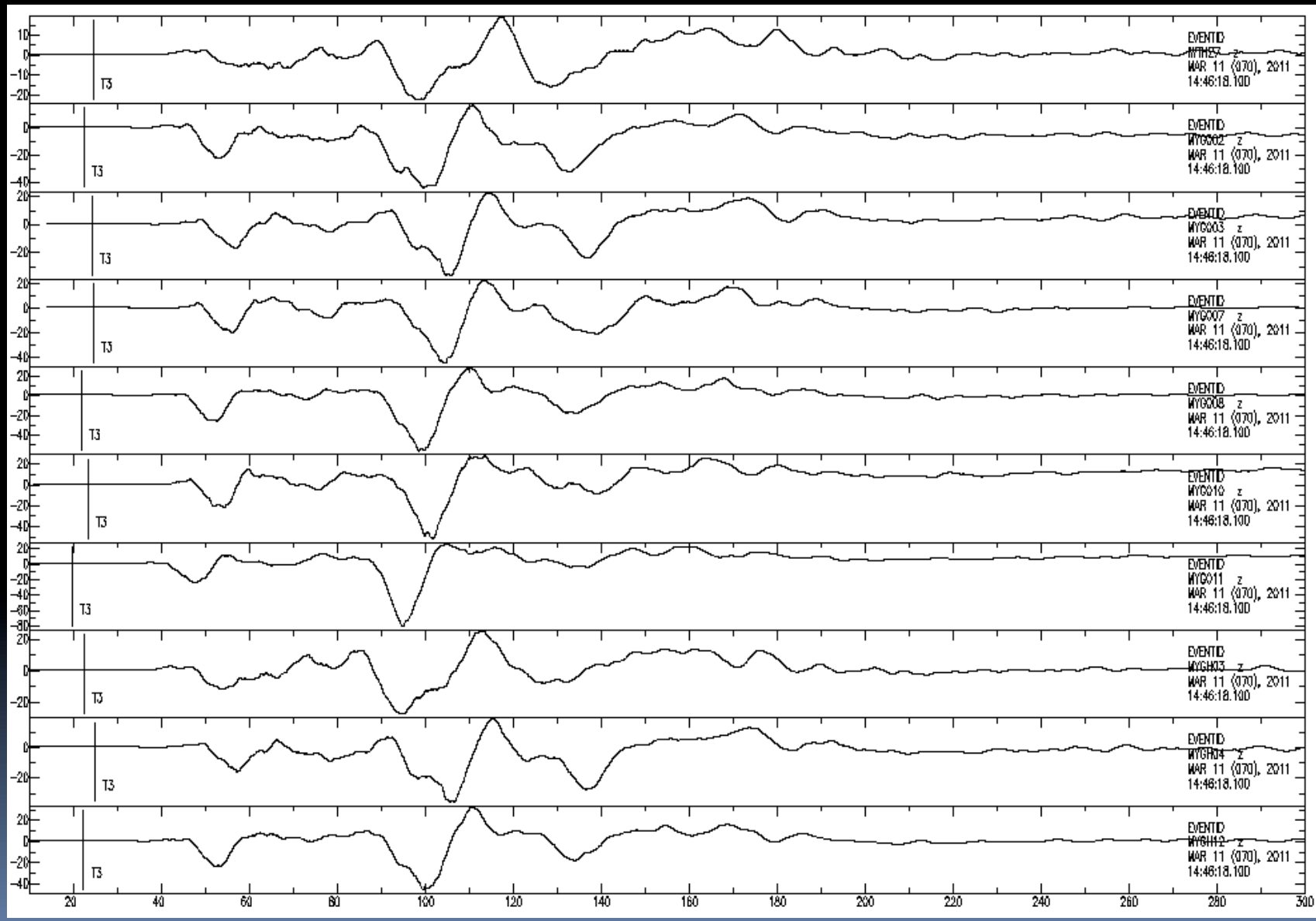


Observed Intensity



Predicted Intensity

Displacement at 10 close stations (cm)



Early Warning for 2011 Tohoku Earthquake

- Early warning was provided for entire Tohoku region before the S-wave arrival.

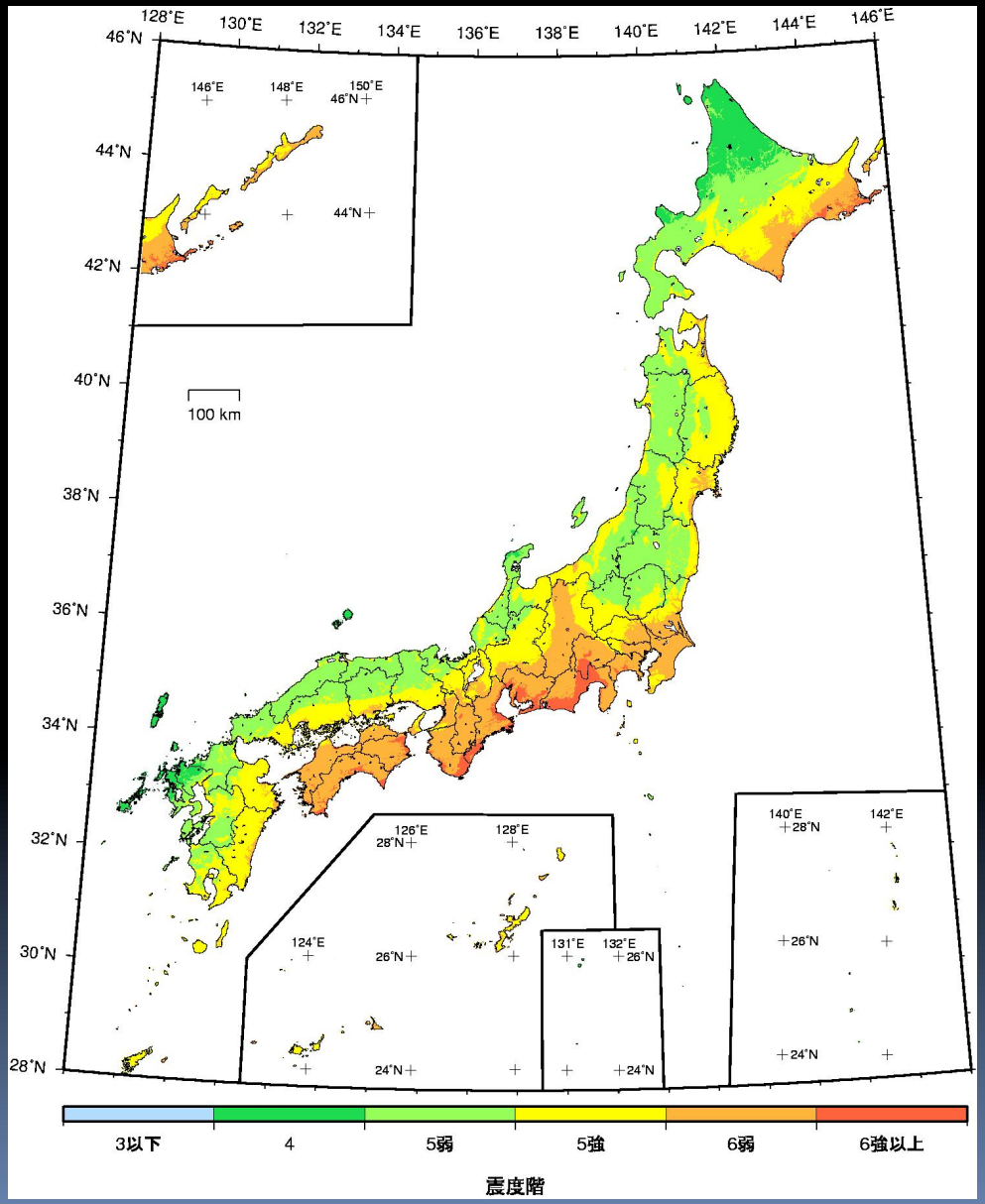
- Warning was not provided in Kanto region for the mainshock.
  → Need estimate of fault dimension in real-time.

- Warning did not always work properly for aftershocks because of mislocations.
  → Need better realtime locations during complex aftershock sequences

What are some low probability events that can damage a nuclear power plant?

1943 eruption of Parcutin in Michocan, Mexico appeared in a cornfield

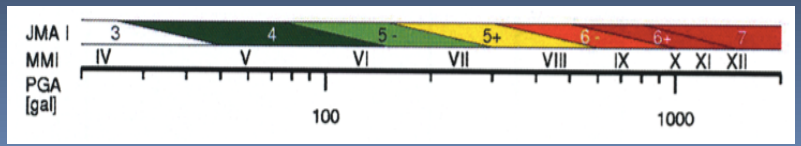
Probabilistic Seismic Hazard Map (PSHM)



10% probability of exceedance in 50 years

~ 25,000 people killed by earthquakes in 50 years (0.02 %)

~ 500,000 people killed in traffic accidents in 50 years (0.5%)



If we could accurately estimate the probability of failure of a nuclear power plant,

How many people would be in favor of maintaining nuclear power ?