The Joint Symposium of Seismic Hazard Assessment
June 17, 2013, Trust City Conference, Sendai, Japan

Lessons learned from the 2011 Tohoku earthquake for reducing earthquake disasters

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Earthquake Disaster Prevention in Europe

The 14th century Assisi earthquake
"Earthquake" by Giotto

Giotto

Earthquake Disaster Prevention in Japan

Pictures of the 1855 Edo (Tokyo) Ansei Earthquake (M6.9)

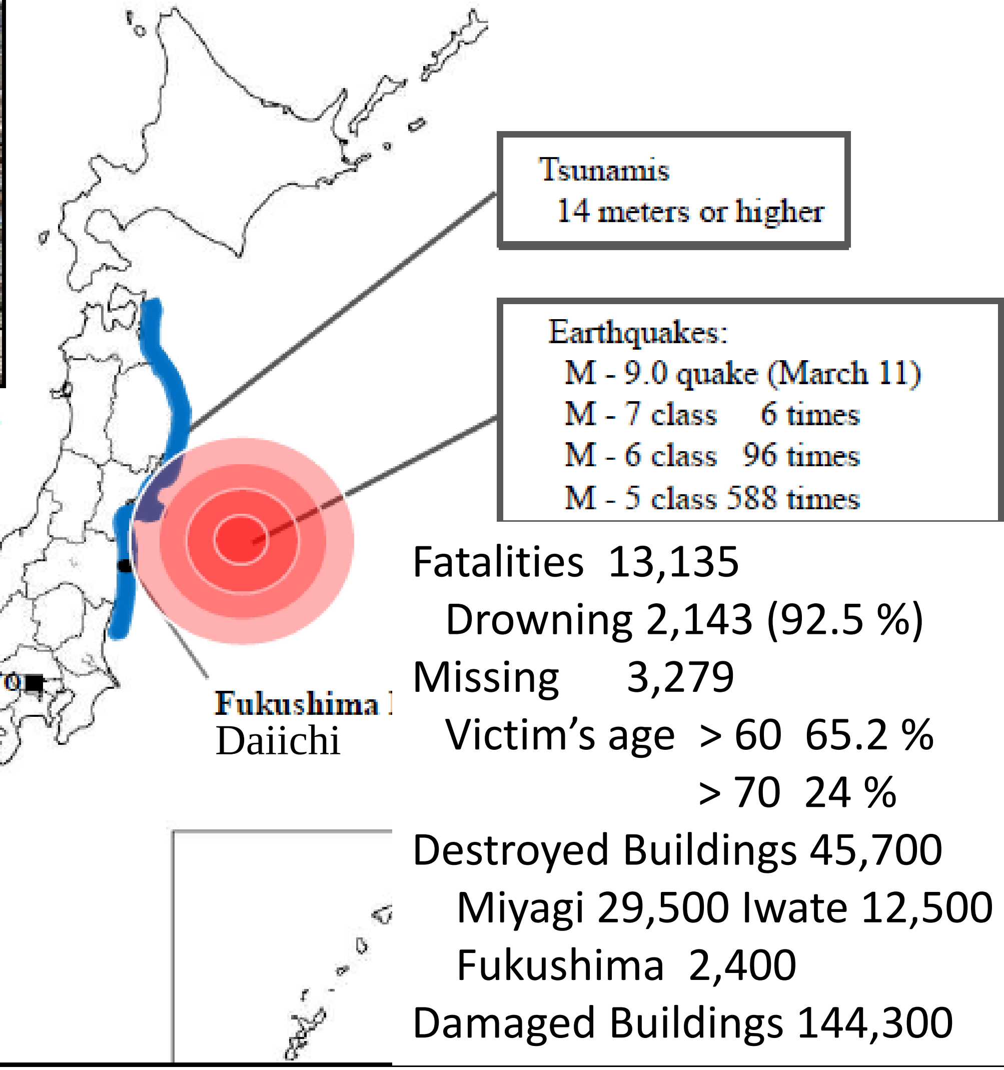
- Battles against underground catfishes -

Today's Topics

1. Outline of damage during the 11 March 2011 Mw 9.0 Tohoku, Japan earthquake
2. National seismic hazard in Japan before and after the earthquake
3. Early Warning of Strong Shaking and Tsunami by JMA
4. Short-period source model of the 11 March 2011 Mw 9.0 Tohoku earthquake estimated from strong motion data
5. Period-dependence of rupture processes
6. Recipe of predicting strong ground motions for subduction megathrust earthquakes
7. Summary

1. Outline of damage during the 11 March 2011 Mw 9.0 Tohoku, Japan earthquake

KYODO NEWS



Fatalities 13,135
  Drowning 2,143 (92.5 %)
Missing 3,279
  Victim's age > 60 65.2 %
  > 70 24 %
Destroyed Buildings 45,700
  Miyagi 29,500 Iwate 12,500
  Fukushima 2,400
Damaged Buildings 144,300

After "Japan's Challenge Towards Recovery", March 2012, METI

March 11, 2011 tsunami

Satake (2012)

Miyako, Iwate pref.
~30 min after the eq.

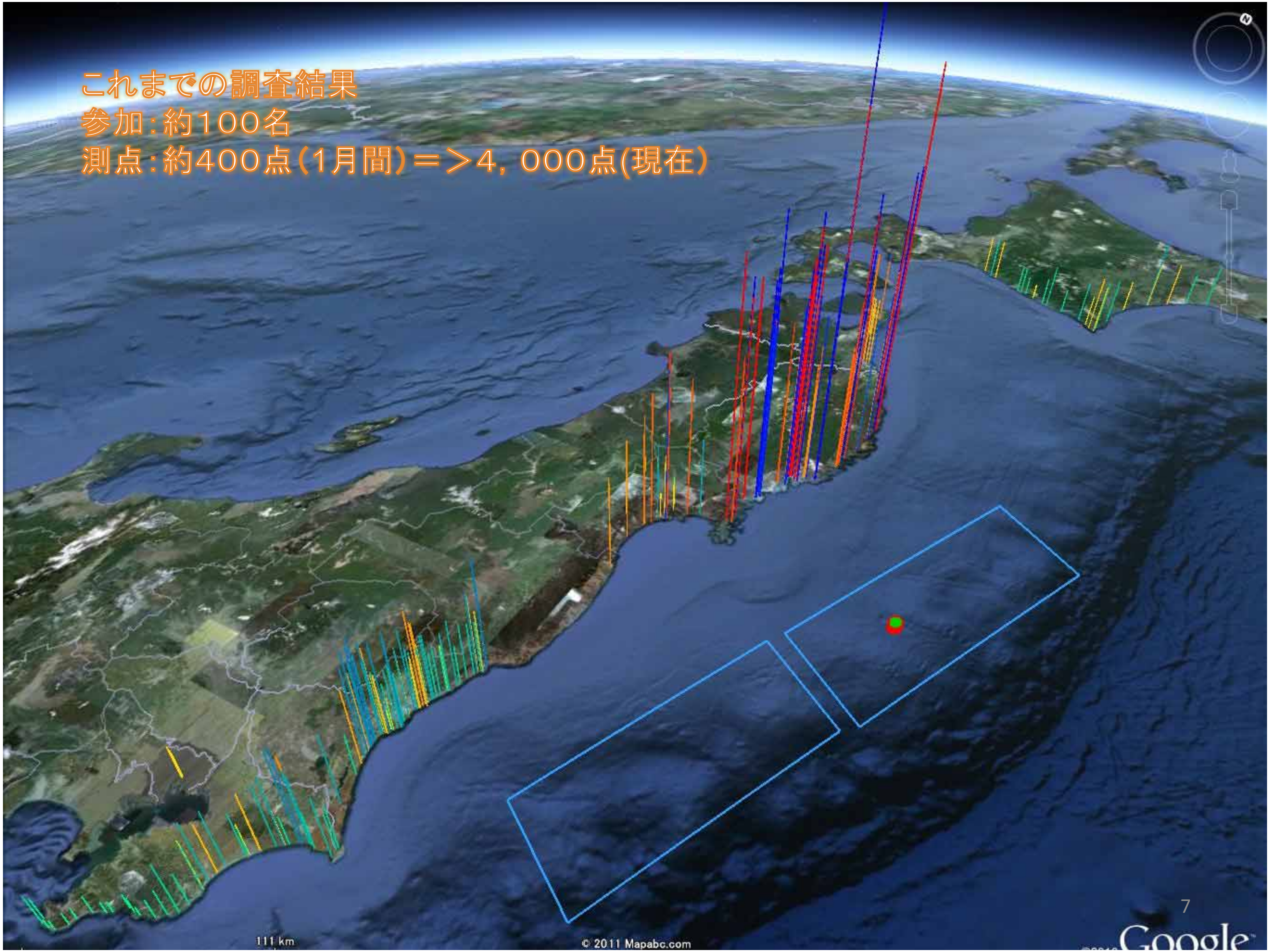
Large (~ 30 m) tsunami height along Sanriku coast

Mainichi Newspaper

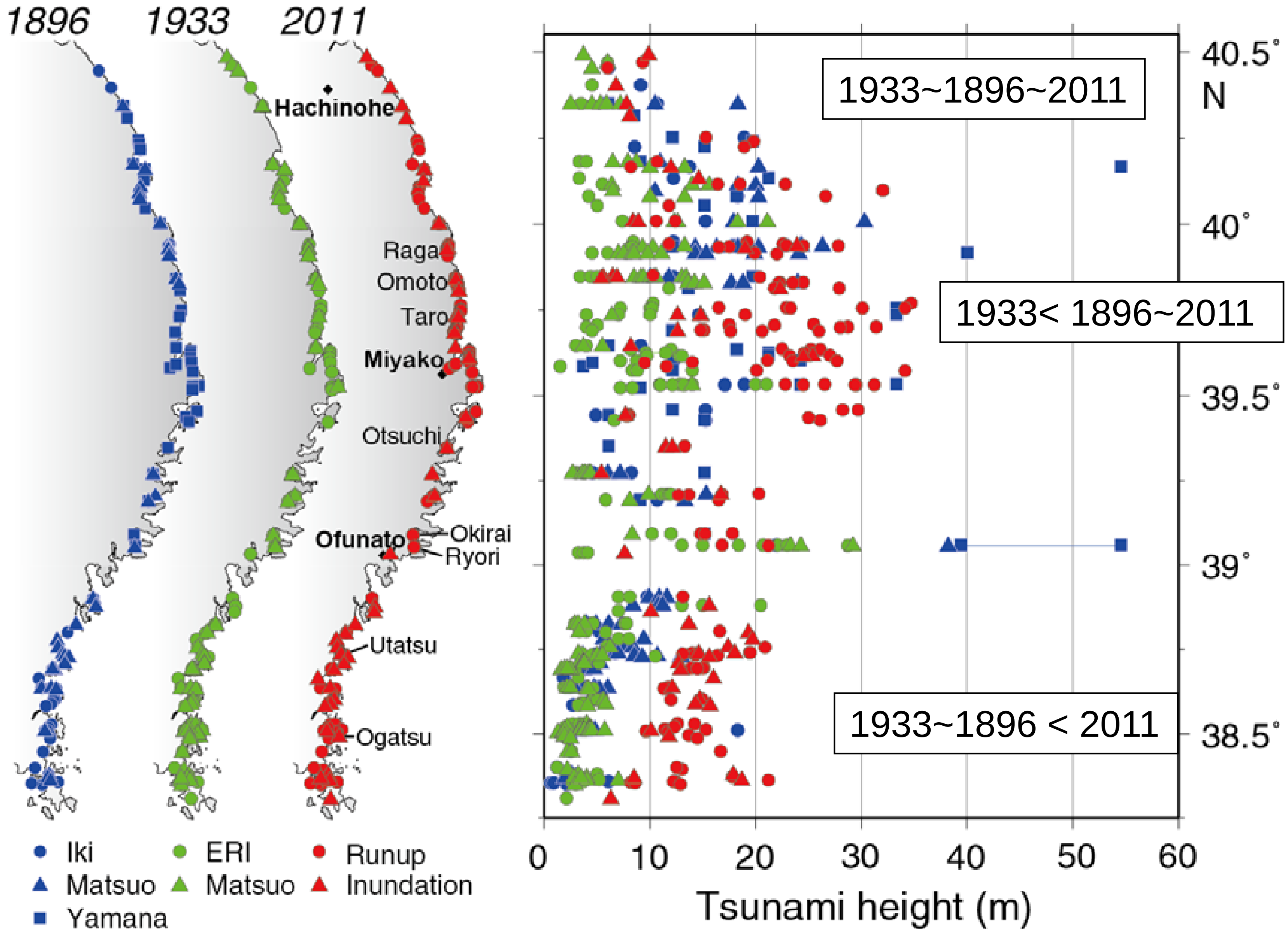
Natori, Miyagi pref.
~ 1 hour after the eq.

Long (~5 km) inundation in Sendai plain

AP


これまでの調査結果
参加:約100名
測点:約400点(1月間)=>4,000点(現在)
111 km
© 2011 Mapabc.com
Google

Comparison of 2011 Tohoku with Past Tsunami



After Satake (2012)

NPPs in Eastern Coast of Japan

Onagawa (Tohoku)

Unit1: 524 MW, 1984-
Unit2: 825 MW, 1995-
Unit3: 825 MW, 2002-

Fukushima Daiichi * (TEPCO)

Unit1: 460 MW, 1971-
Unit2: 784 MW, 1974-
Unit3: 784 MW, 1976-
Unit4: 784 MW, 1978-
Unit5: 784 MW, 1978-
Unit6: 1,100 MW, 1979-

Fukushima Daini (TEPCO)

Unit1: 1,100 MW, 1982-
Unit2: 1,100 MW, 1984-
Unit3: 1,100 MW, 1985-
Unit4: 1,100 MW, 1987-

Tokai-2 (JAPCO)

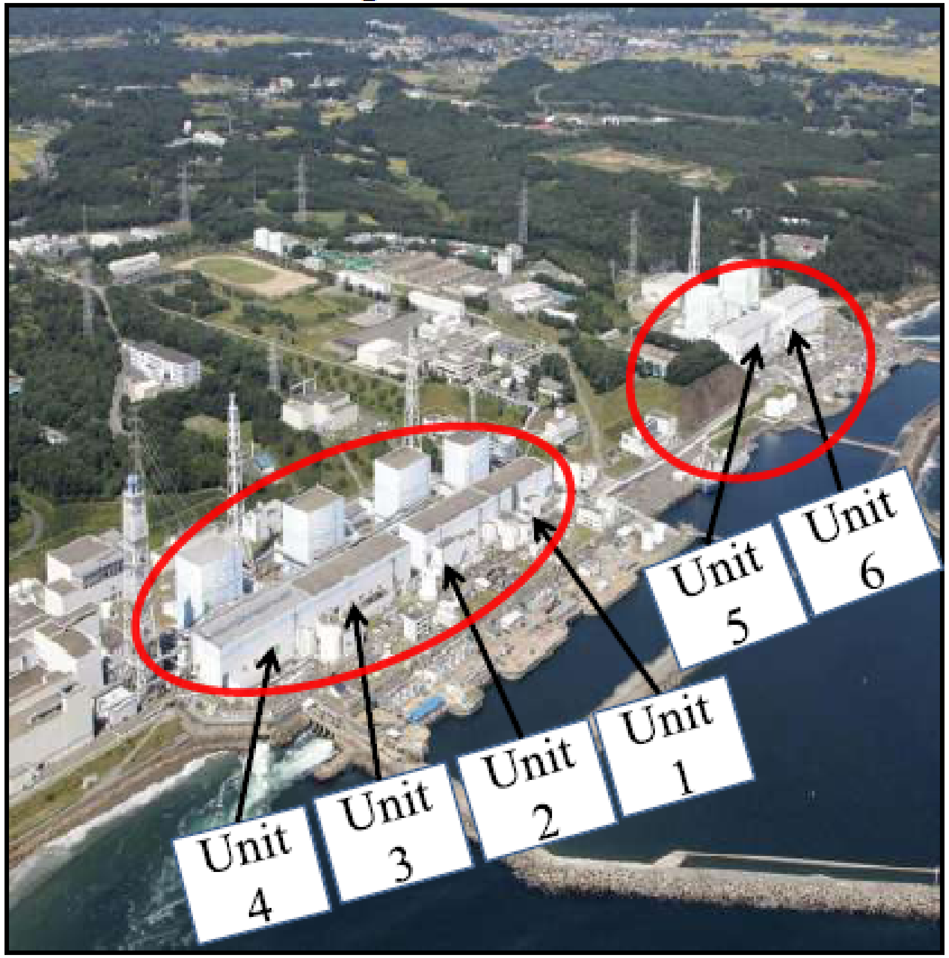
1,100 MW, 1978-)

**** Fukushima Daiichi locates approximately 230 km north of Tokyo***

Onagawa Nuclear Power Station
(very little damage by tsunami)

Accident at Fukushima Nuclear Power Station

Before the Earthquake and Tsunamis



TEPCO

After the Earthquake and Tsunamis

Air Photo Service Inc (Myoko, Niigata Japan)

2. National seismic hazard before and after the 2011 Tohoku earthquake

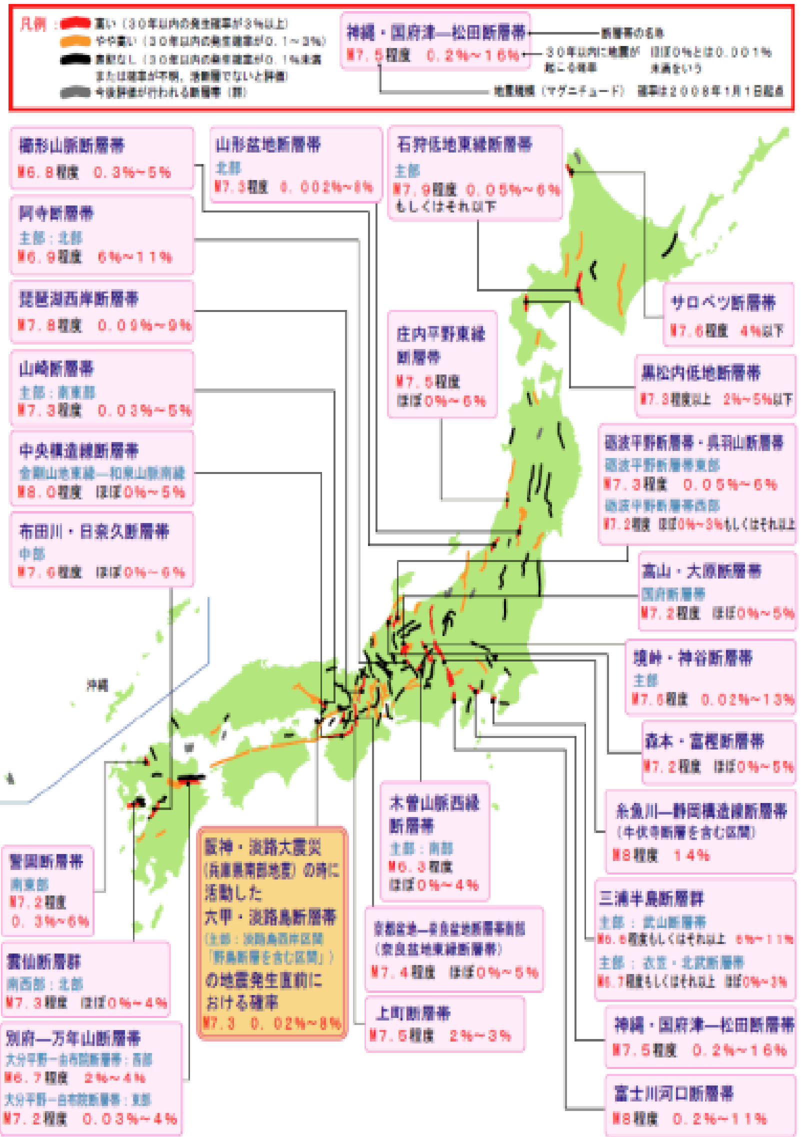
"National Hazard Maps" in Japan have been published by the Headquarter of Earthquake Research Promotion since 2005.

- Long-term evaluation of earthquake occurrence has been made nation-wide for inland crustal earthquakes, subduction earthquakes and intraslab earthquakes including the source region of the 2011 Toh0ku earth.
- Strong ground motion evaluation has been made using prpbabilistic and deterministic approaches.

Tsunami assessments have been made for specific past disastrous earthquakes by Central Disaster Management Council.

Probability of Earthquake Occurrence in 30 years

Inland Crustal-Earthquakes

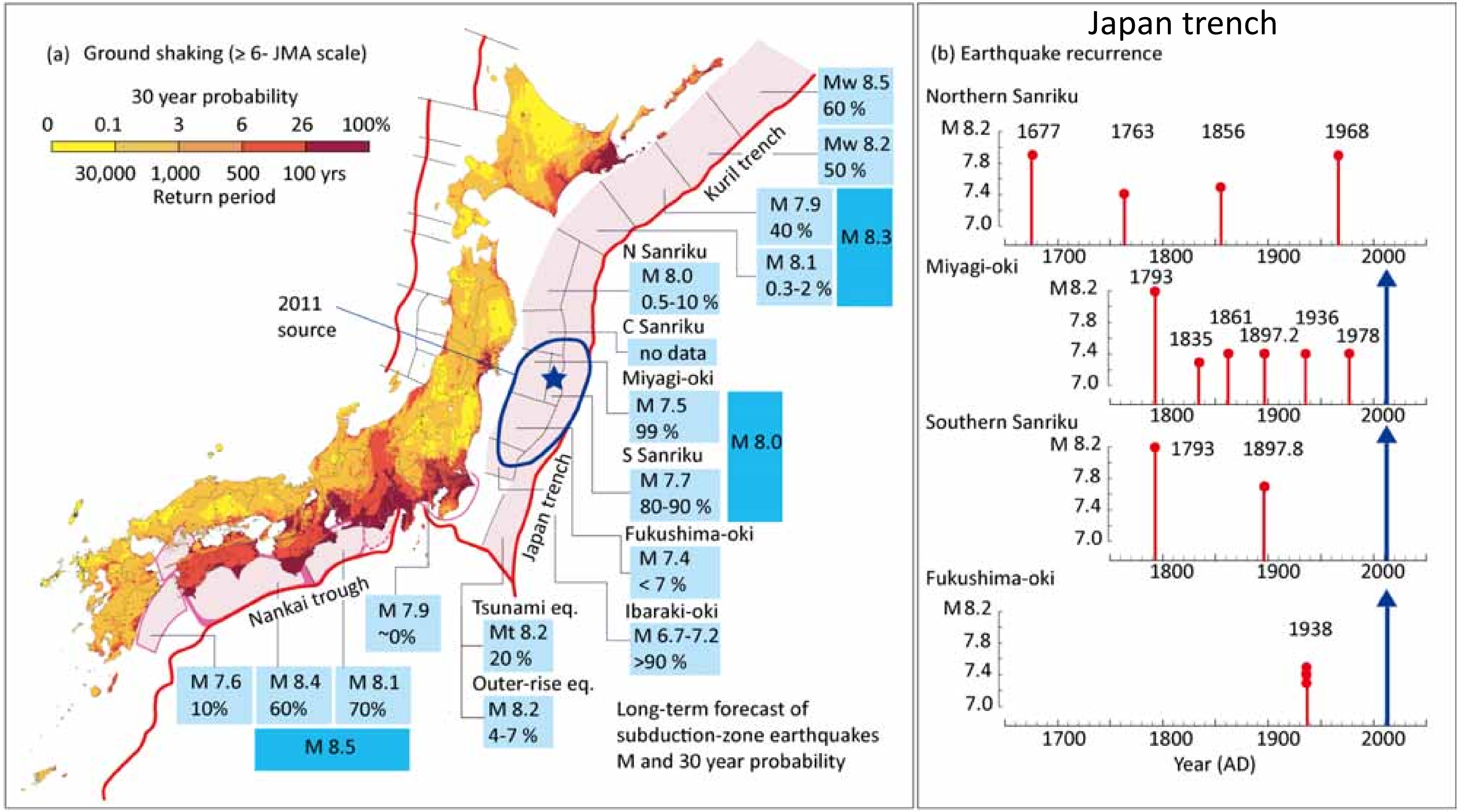


Subduction Earthquakes

Headquarter of Earthquake Research Promotion (2010)

National Seismic Hazard Map for Japan and Regions for Long-term Forecast along Subduction Zone

Recurrence of large earthquakes along Japan trench



NIED (2011)

Revision of long-term evaluation of seismic activity for the region from the off Sanriku to the off Boso ,

(Earthquake Research Committee , 25 Nov. , 2011)

Earthquakes with the same type as **the 2011 off the Pacific coast of Tohoku Earthquake**

■Past Activity

5 times for past 2,500 years

- 2011 M 9.0 earthquake
- 15 century from Tsunami deposits
- 869 (the Jogan earthquake) from a history book
- 4 to 5 centuries from Tsunami deposits
- 3 to 4 centuries B.C. from Tsunami deposits

■ Return periods

400 – 800 years

average period 600 years

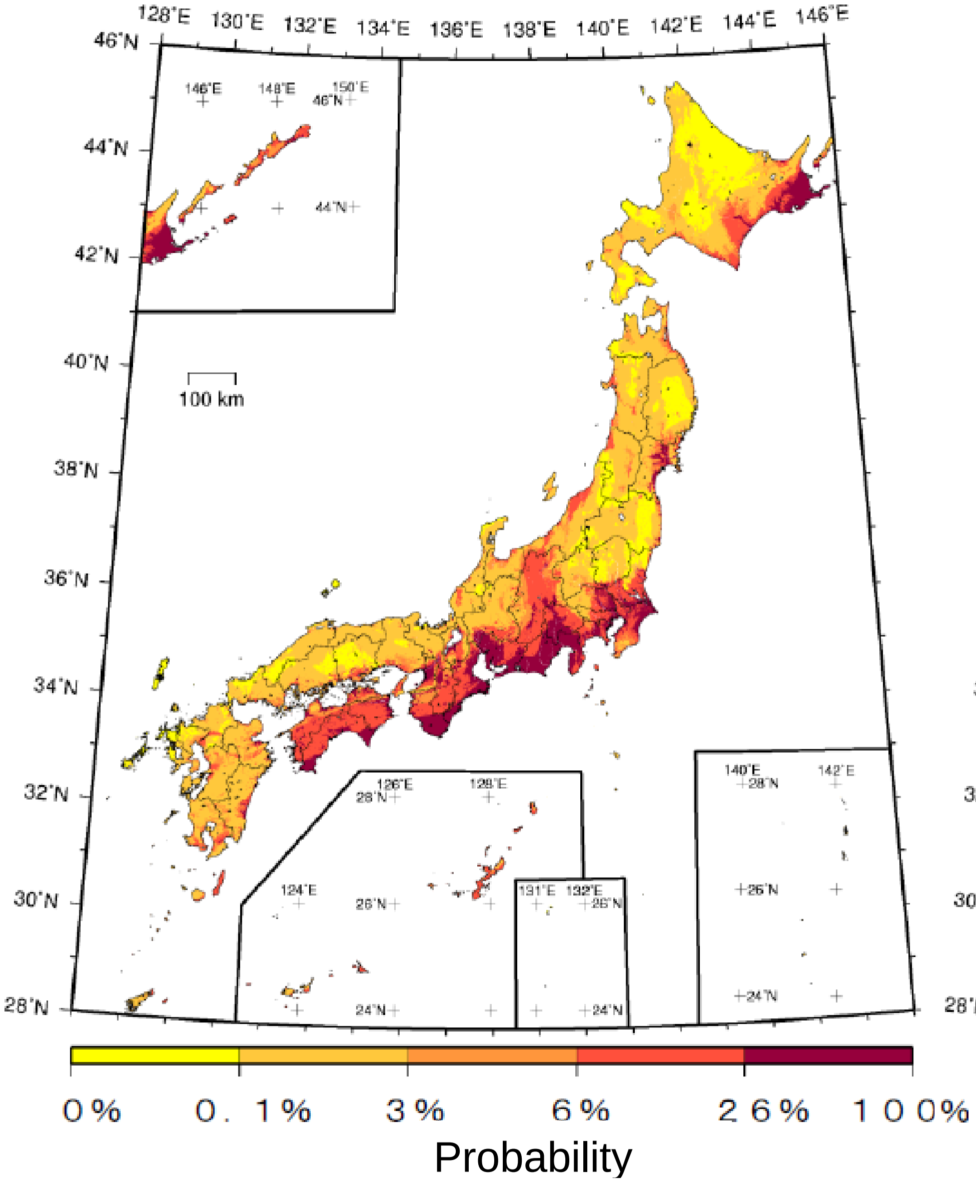
■ Probability of earthquake occurrence before the 2011 earthquake

10 – 20 % in 30 years

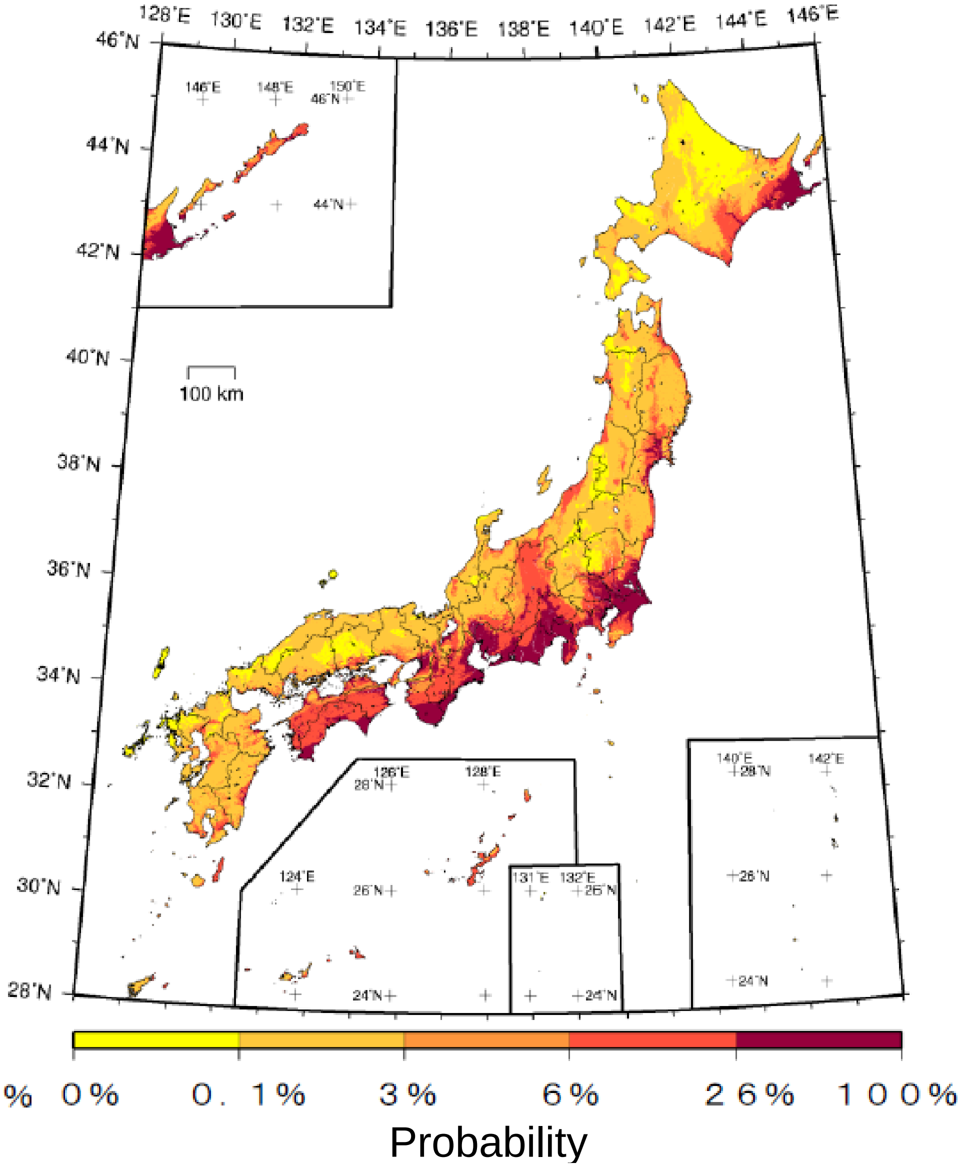
Probabilistic Seismic Hazard Map in 2011 (HERP, 2012)

Probability of ground motions more than JMA intensity 6-lower within 30 years

Without Mw 9 earthquake

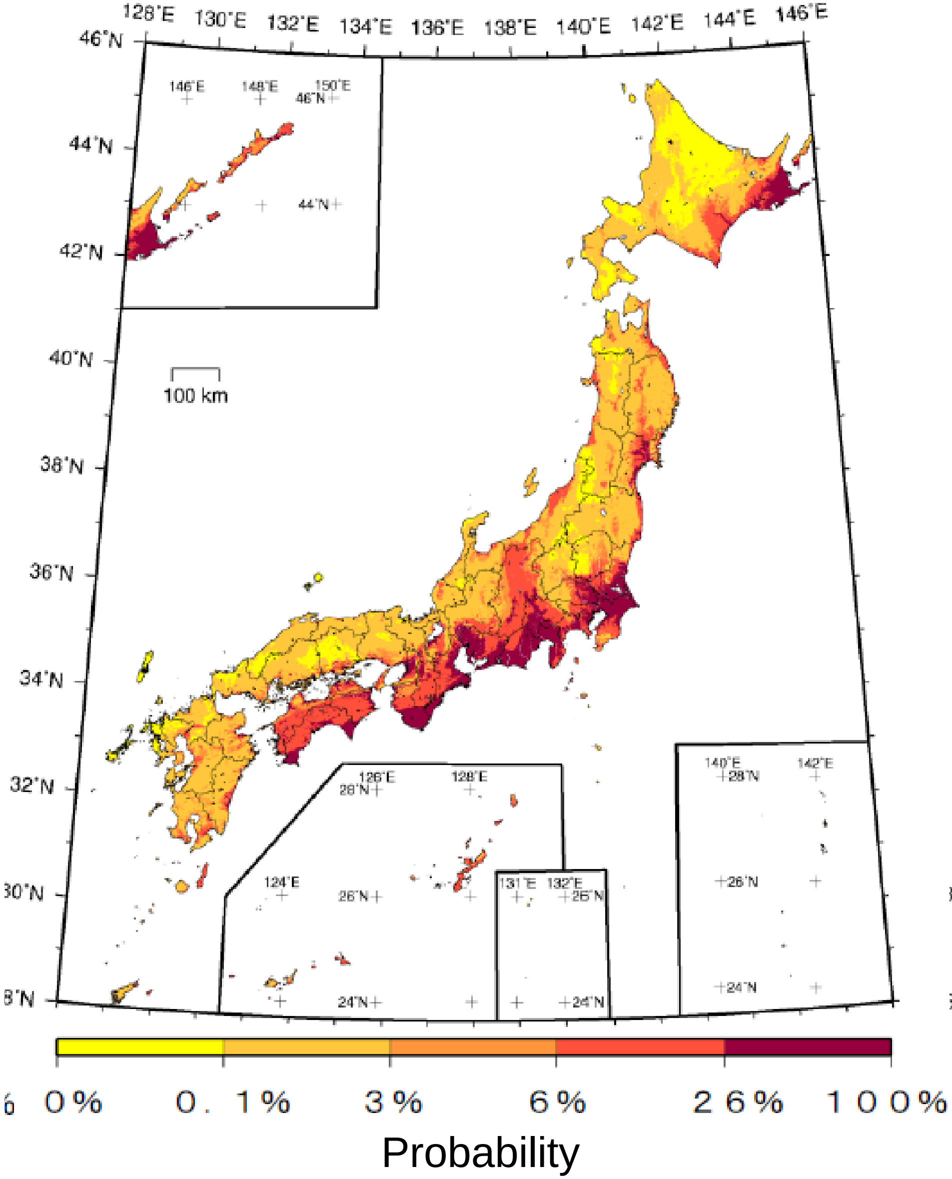


With Mw 9 earthquake

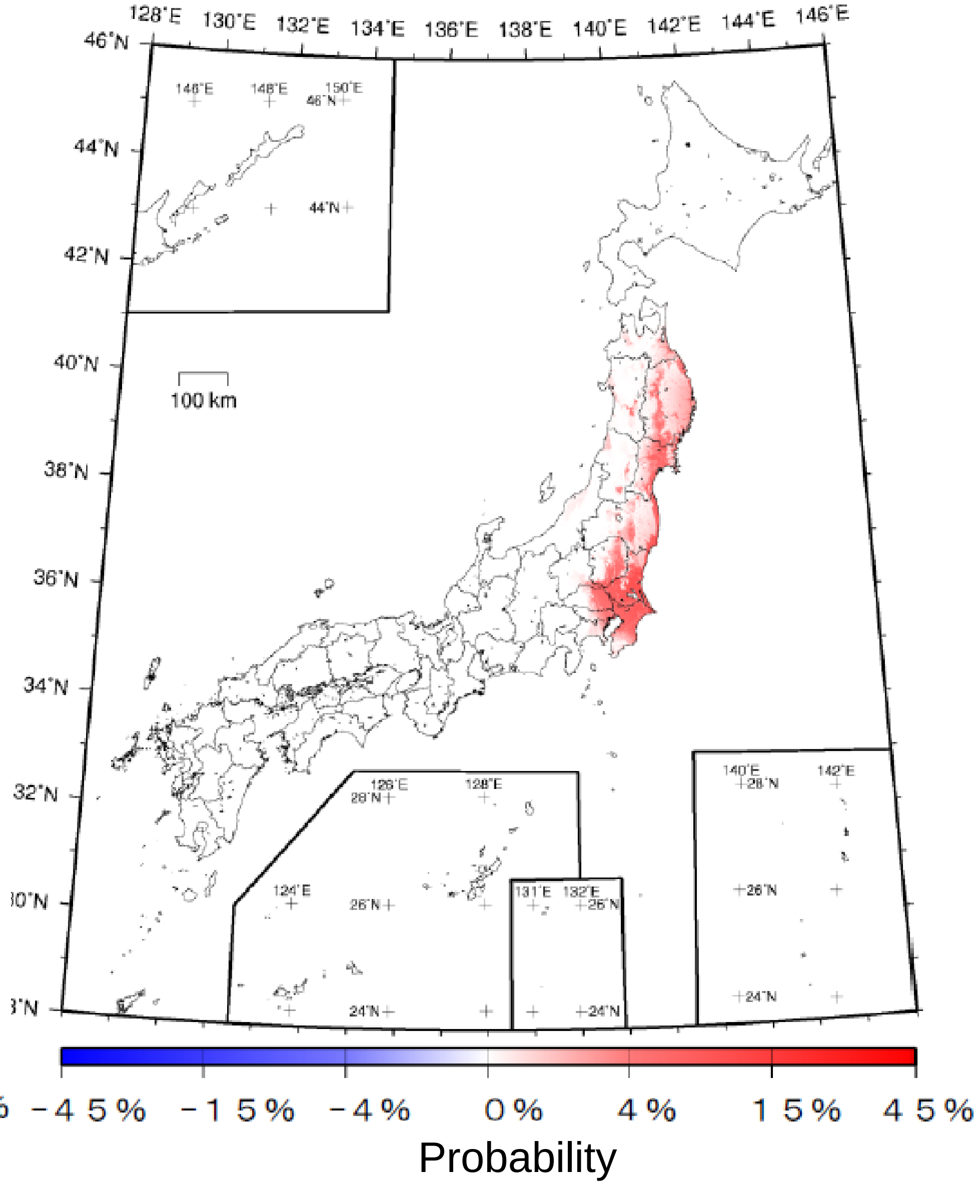


Influence of Mw 9.0 earthquake on Probabilistic Seismic Hazard Map in 2011

With M9.0 earthquake



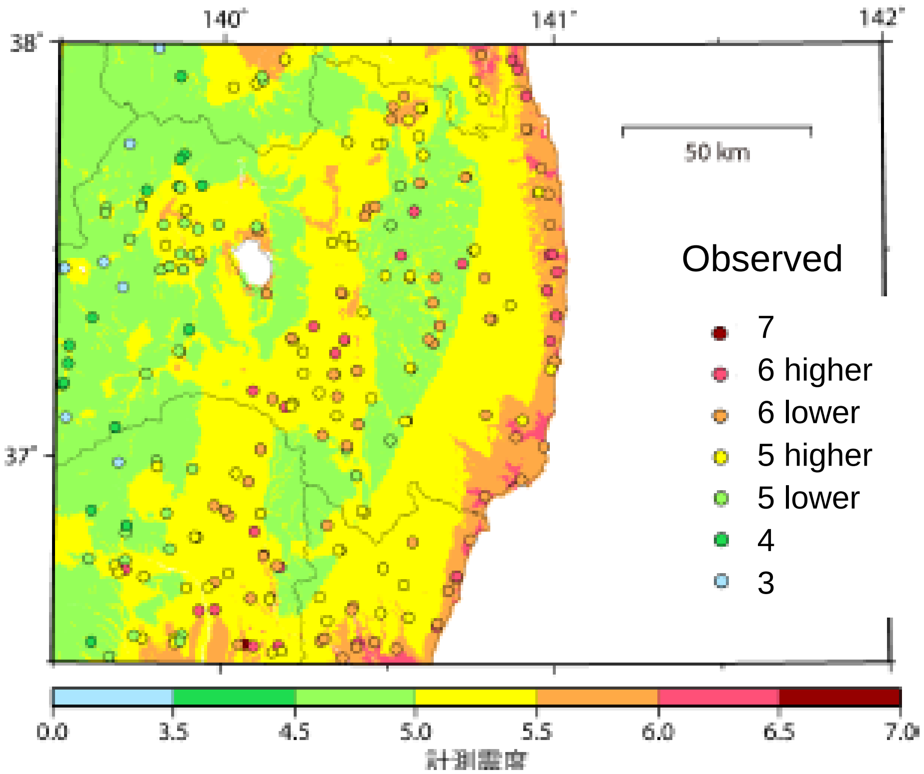
Difference between PSHM with M 9.0 and that without M 9.0



Maximum JMA intensity with more than 2 % probability within 50 years in 2011

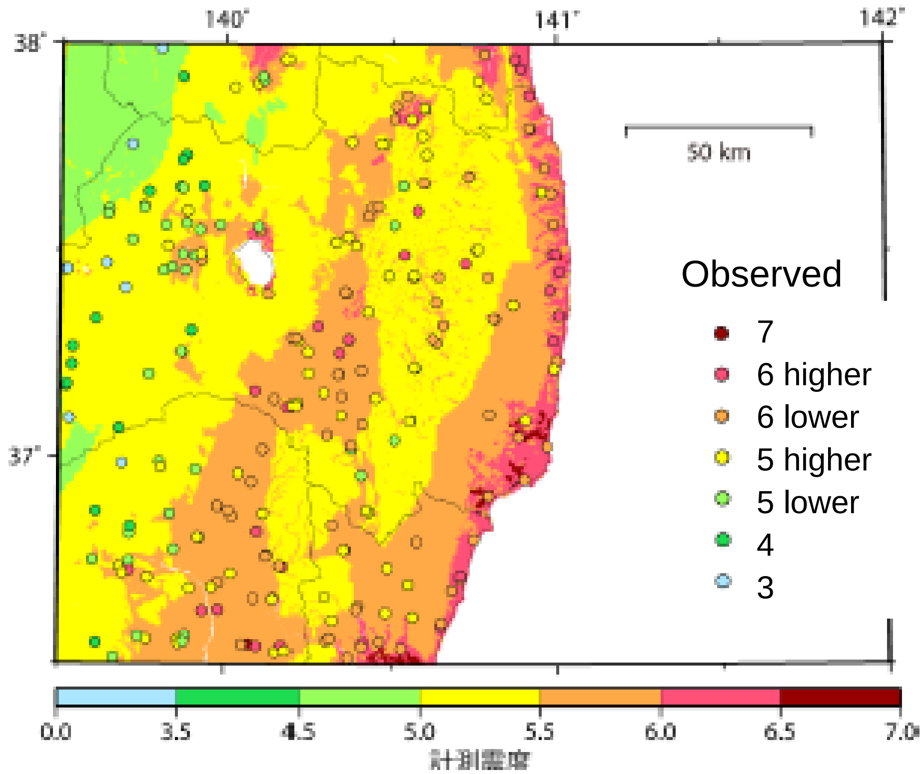
Comparison between estimated ones and observed ones during the 2011 Tohoku earthquake

Without M 9.0 earthquake



JMA intensity

With M 9.0 earthquake



JMA intensity

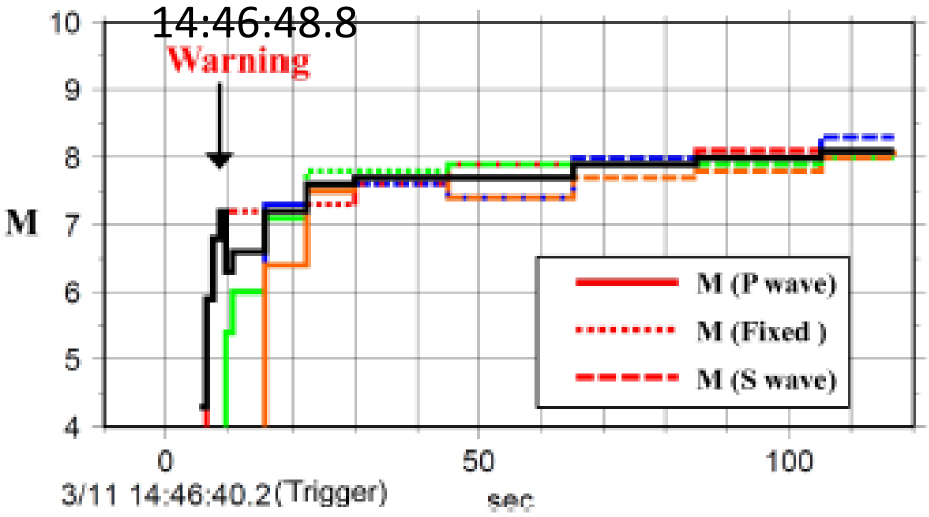
3. Early Warning of Strong Shaking and Tsunami by JMA

Japan Meteorological Agency is in charge of issuing warning information about strong shaking and tsunami as quickly as possiblehave whenever an earthquake occurs.

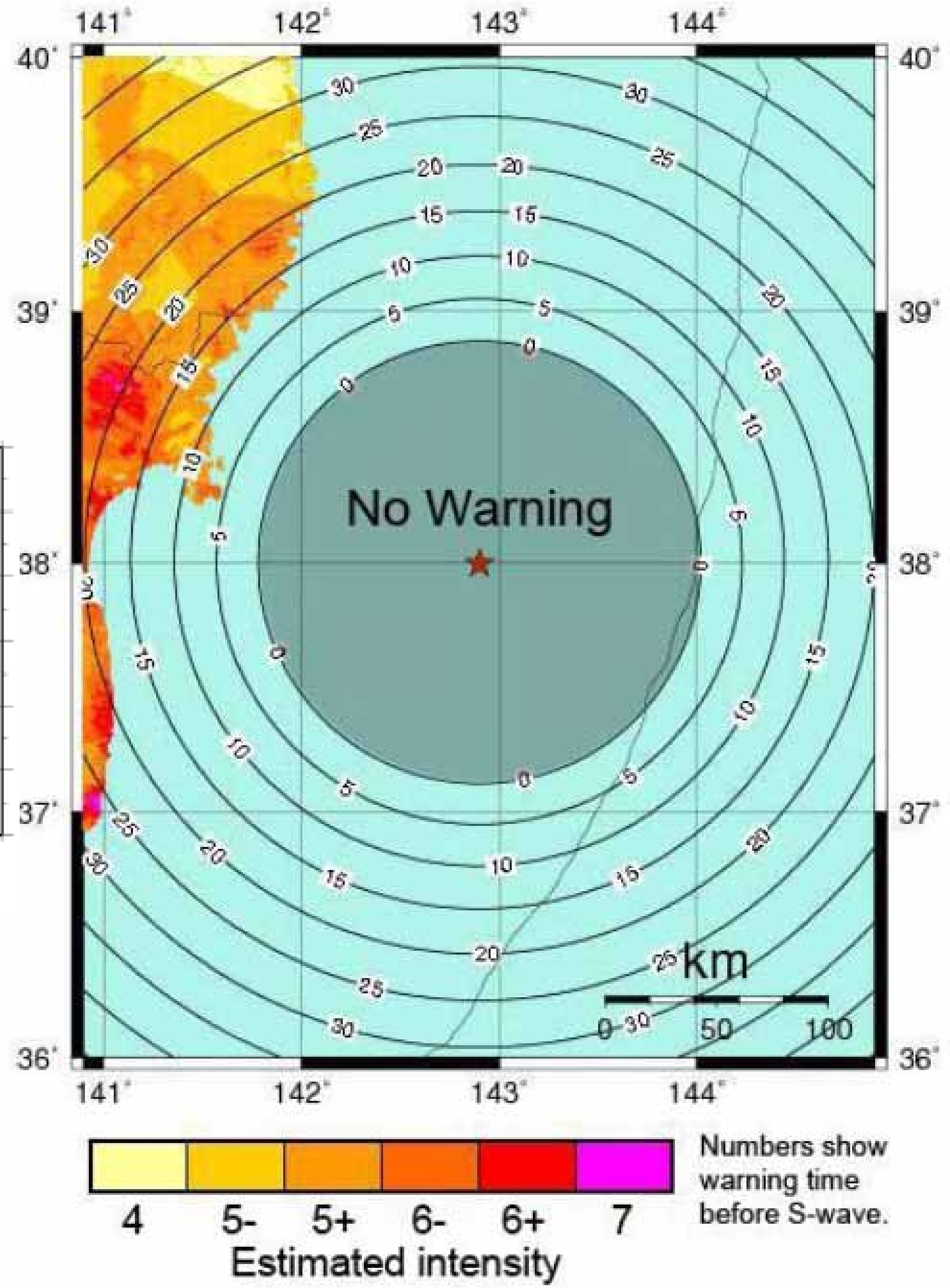
- Earthquake Early Warning System
- Tsunami Warning and Evacuation

Earthquake Early Warning from JMA during the 2011 Tohoku earthquake

Sequence of determining magnitude in the JMA FEW



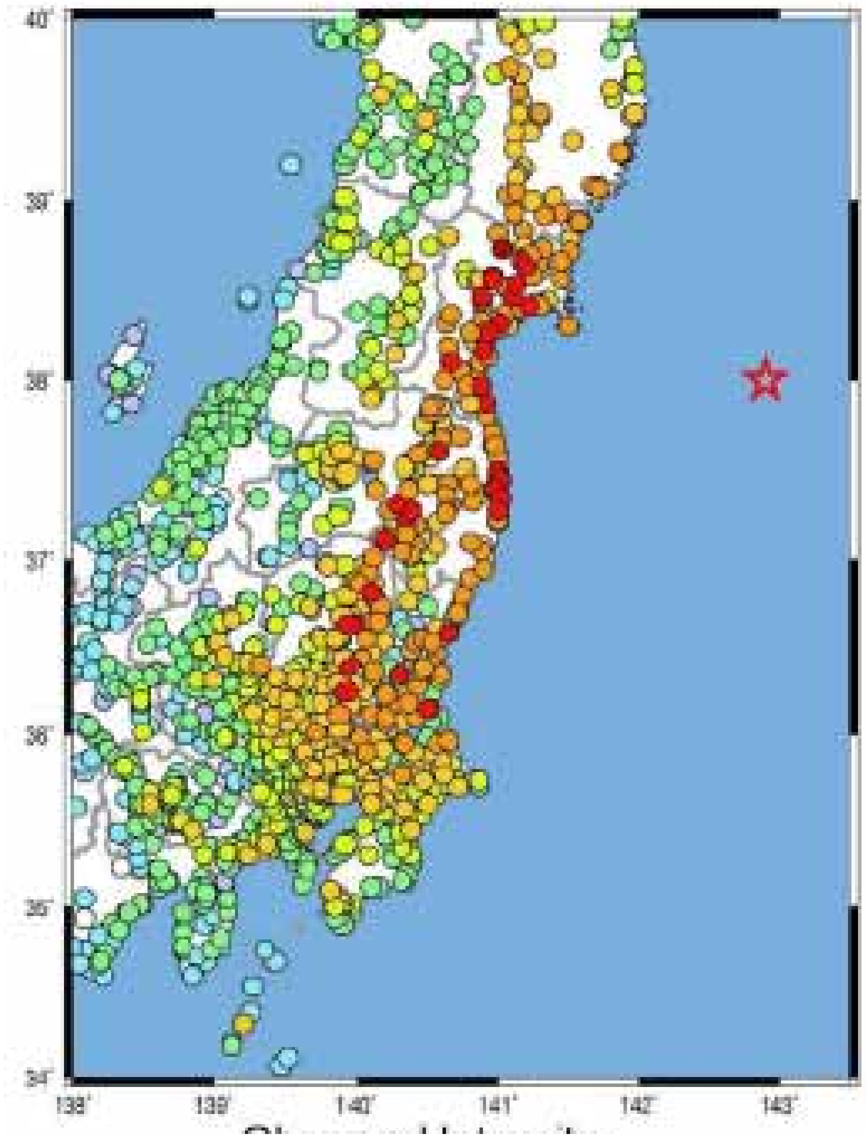
Origin time: 14:46:23



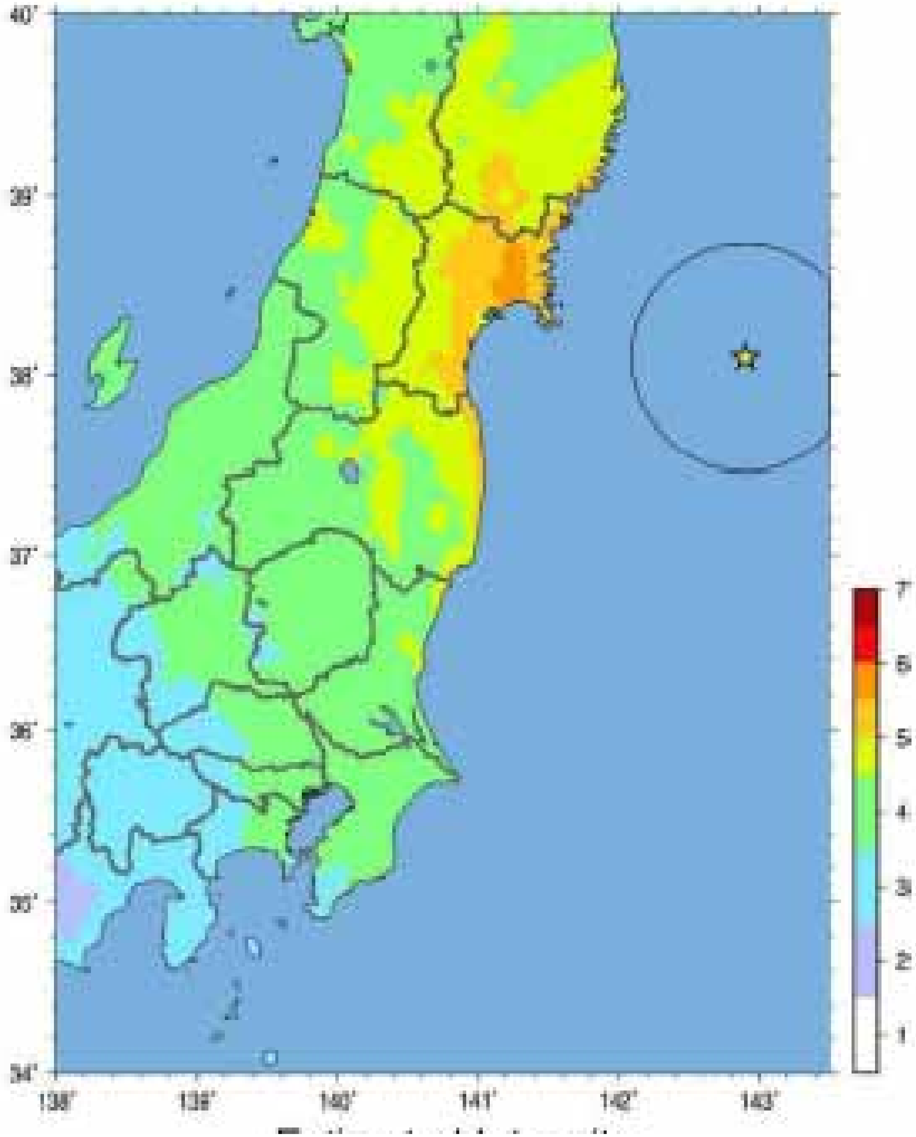
Earthquake Early Warning from JMA during the 2011 Tohoku earthquake

Final warning M 8.1
105.0 sec after first P-wave detection

Observed Intensity (JMA)



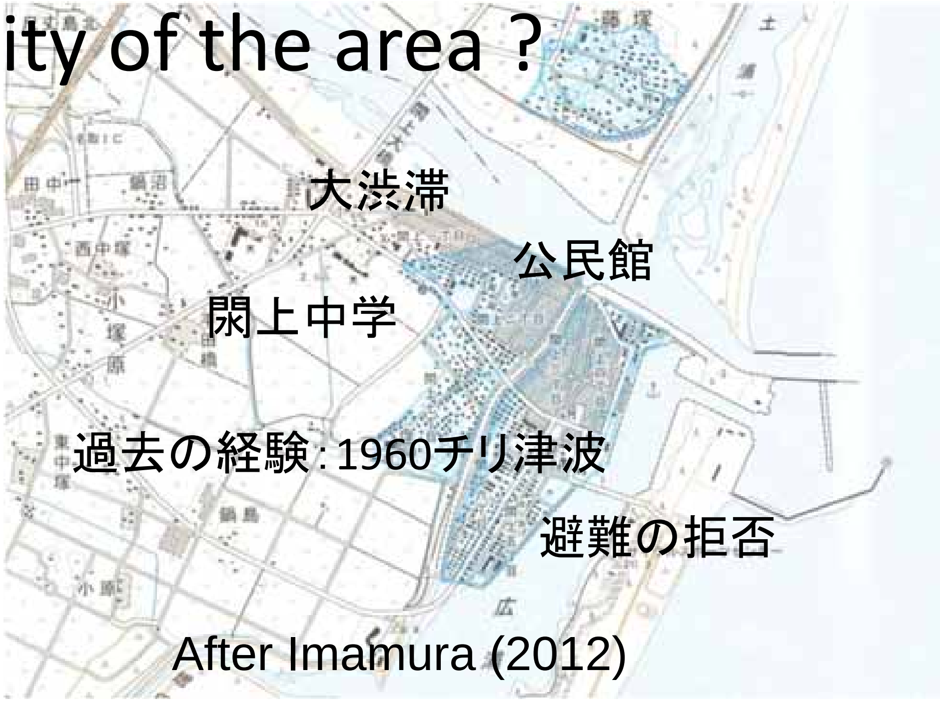
Estimated Intensity (JMA)



Why were people not able to evacuate for devastating tsunamis ?

What problems did the JMA tsunami warning system have?

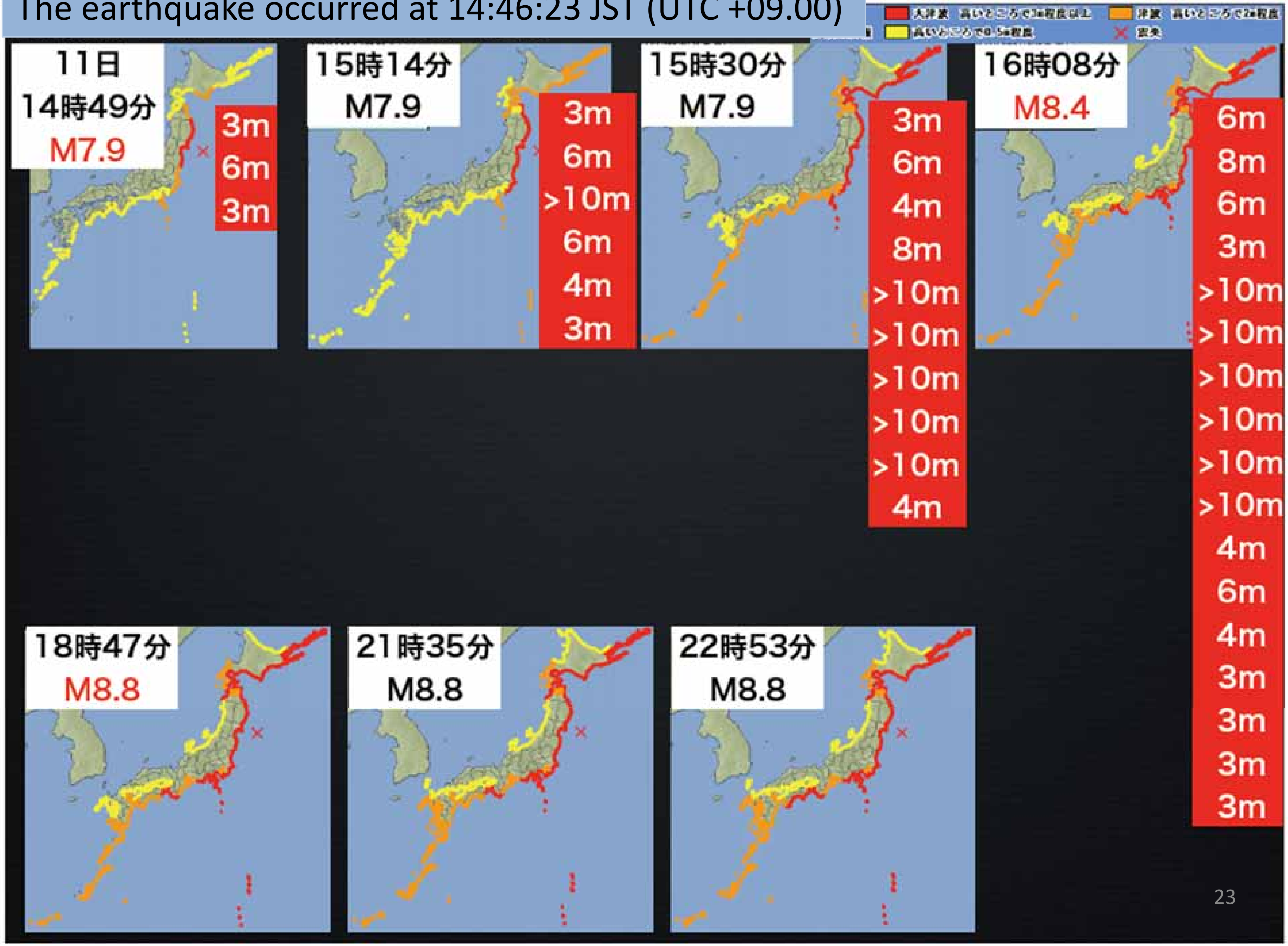
What unrecognized factors contributed to the high vulnerability of the area ?



After Imamura (2012)

Sequence of the tsunami warning after the Tohoku earthquake

The earthquake occurred at 14:46:23 JST (UTC +09.00)



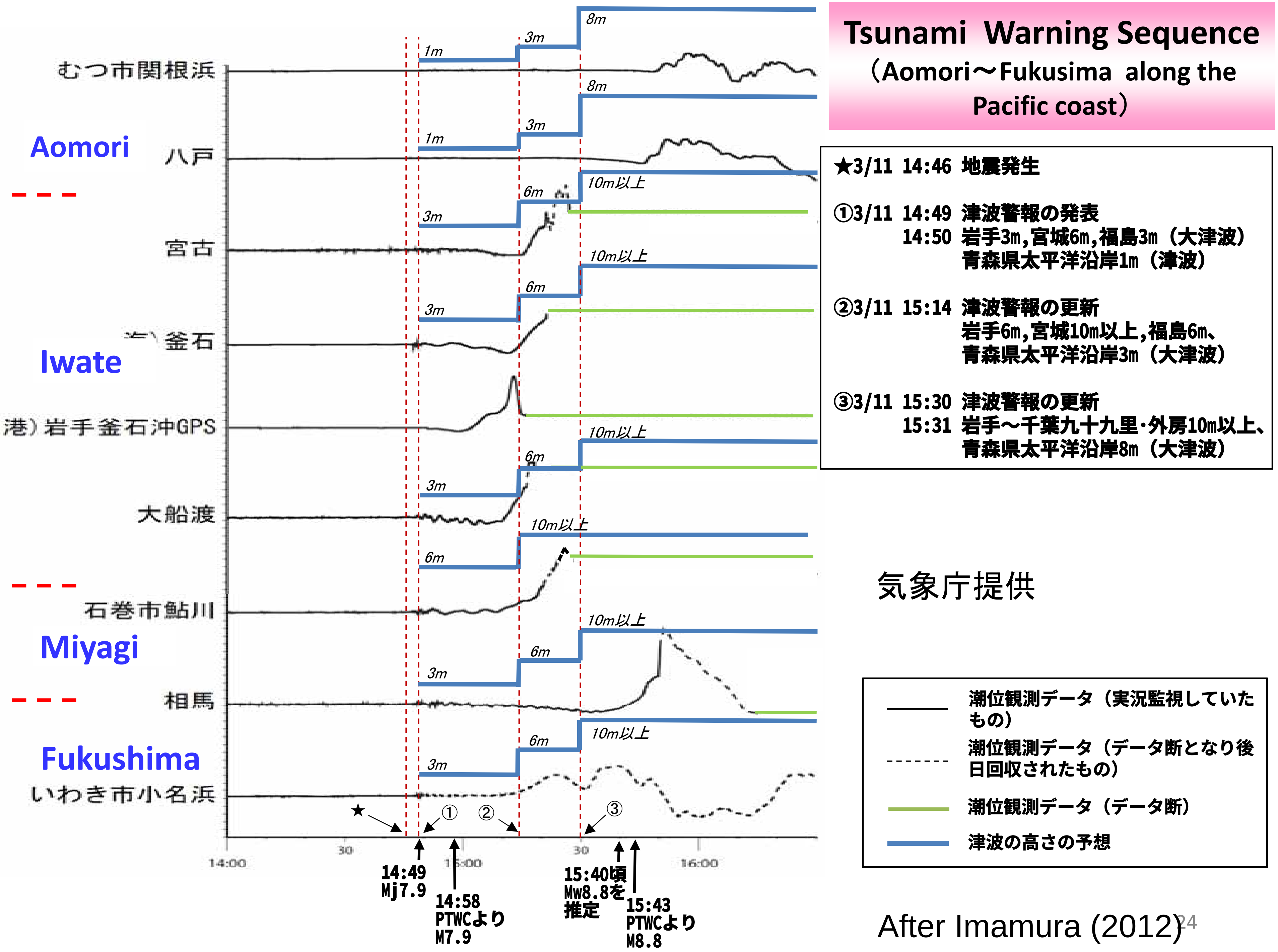
Tsunami Warning Sequence
（Aomori～Fukusima along the Pacific coast）

★3/11 14:46 地震発生

①3/11 14:49 津波警報の発表
14:50 岩手3m,宮城6m,福島3m（大津波）
青森県太平洋沿岸1m（津波）

②3/11 15:14 津波警報の更新
岩手6m,宮城10m以上,福島6m、
青森県太平洋沿岸3m（大津波）

③3/11 15:30 津波警報の更新
15:31 岩手～千葉九十九里･外房10m以上、
青森県太平洋沿岸8m（大津波）



気象庁提供

After Imamura (2012)

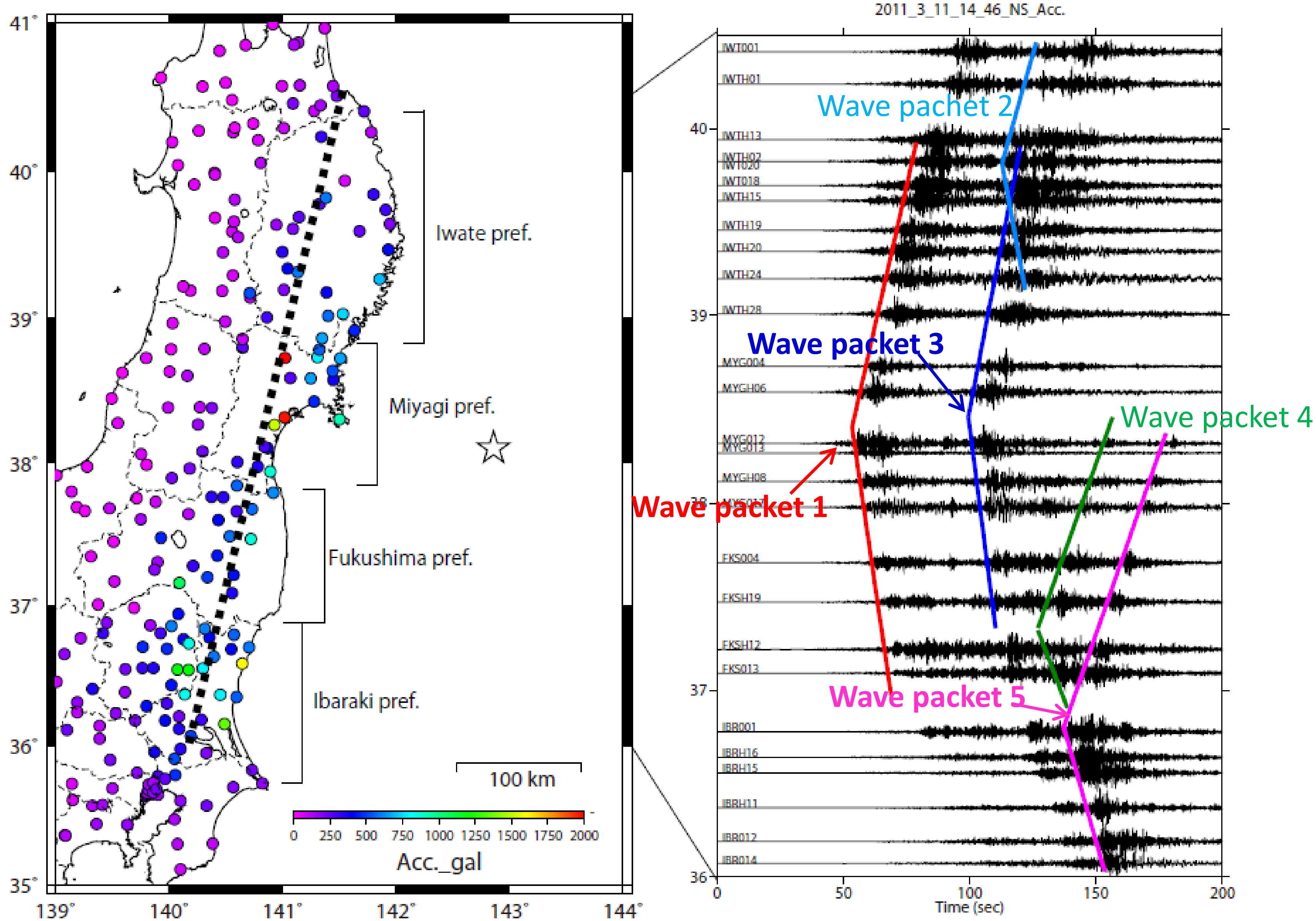
4. Short-period source model of the 11 March 2011 Mw 9.0 Tohoku earthquake estimated from strong motion data

■ Five distinctive wavapackets were detected on strong motion sesimograms at stations near the source fault.

■ The arrival azimuths of those wavepackets were estimated using the semblance analysis in several small arrays.

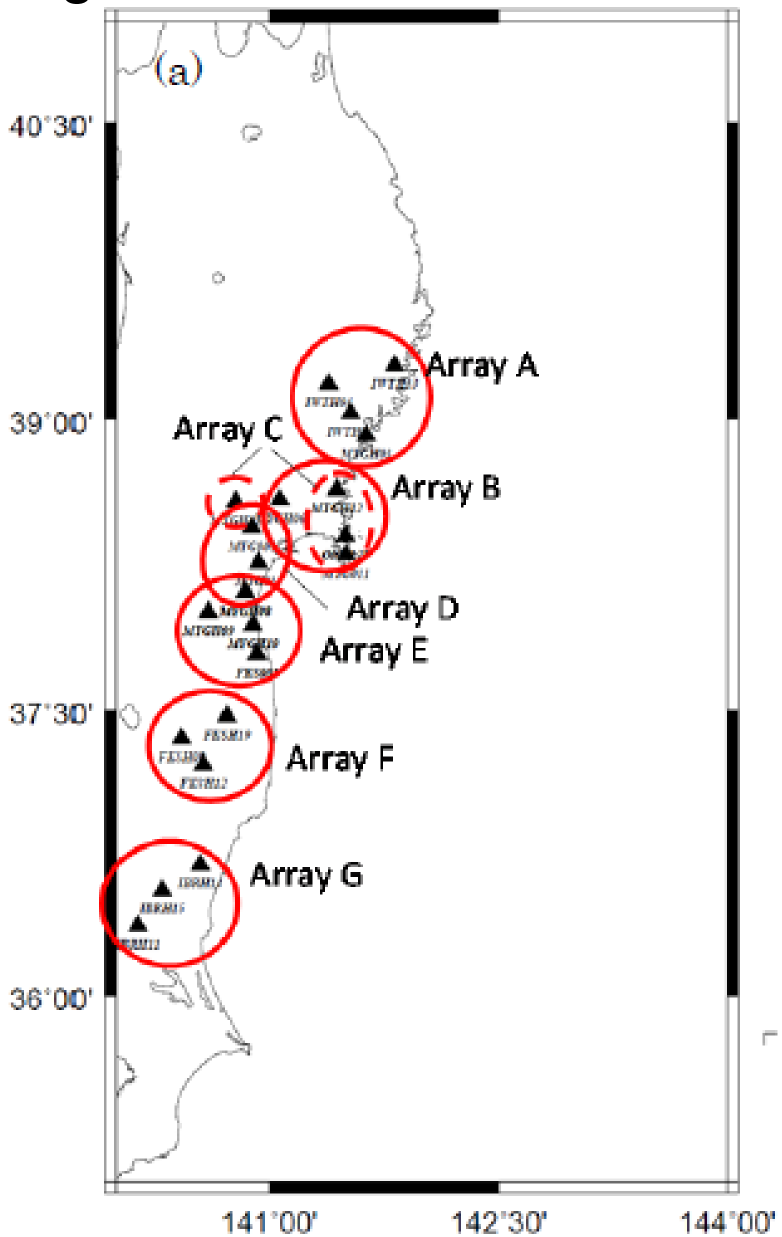
■The locations of strong motion generation areas (SMGAs) are coincident with the origins of those wavepackets.

Re-estimation of Locations of SMGAs from Semblance Analysis of Wave-Packets seen in Short-Period Seismograms

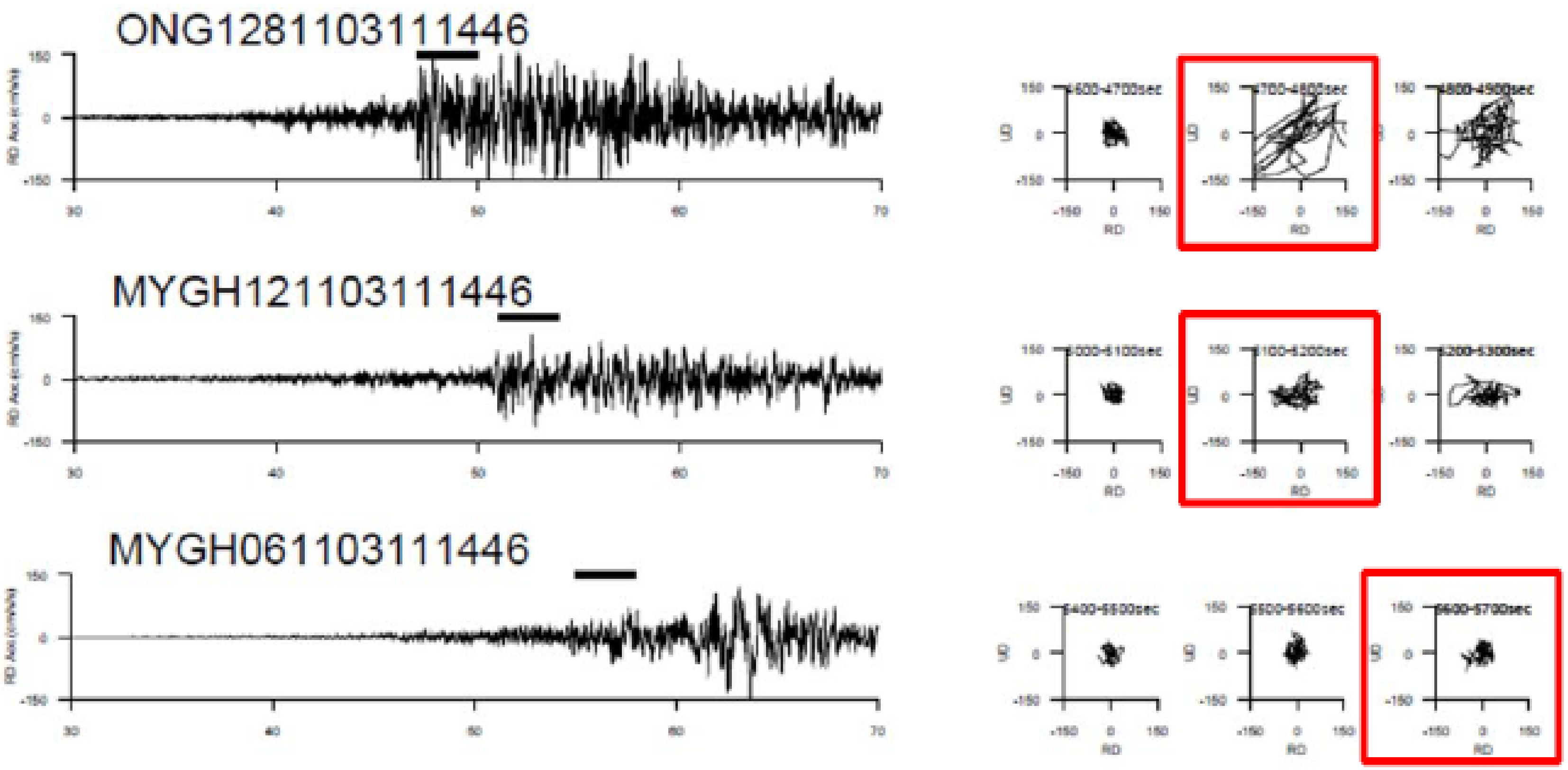


After Irikura and Kurahashi (2011)

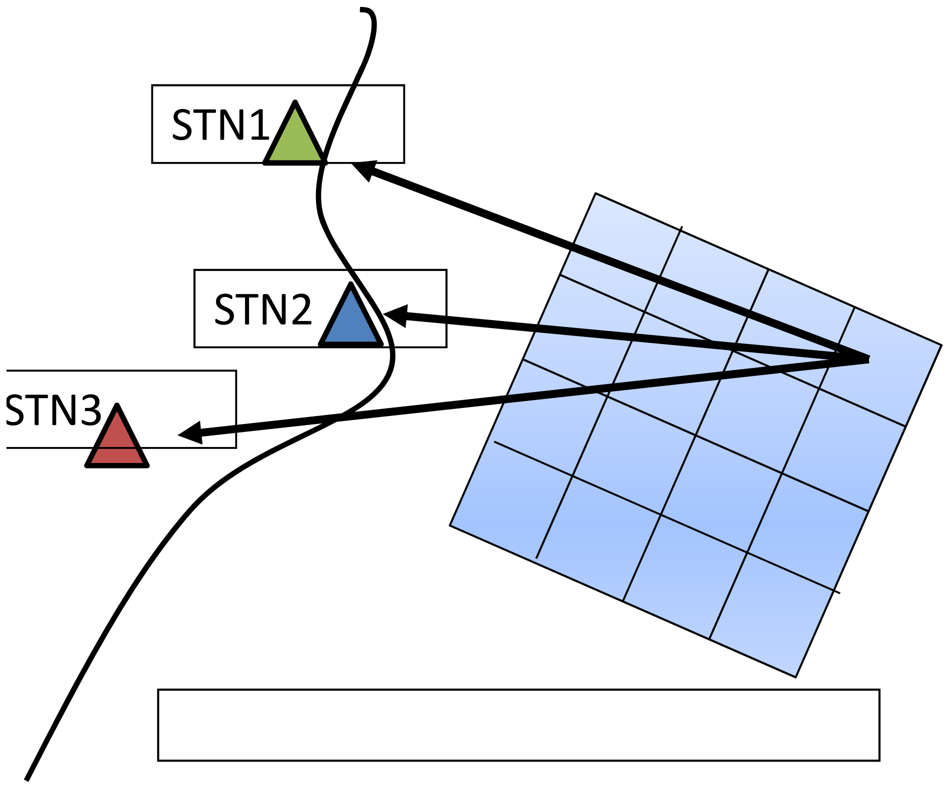
Mini-arrays (A, B, C, D, E, F, and G) for estimating arrival azimuths of wave-packets

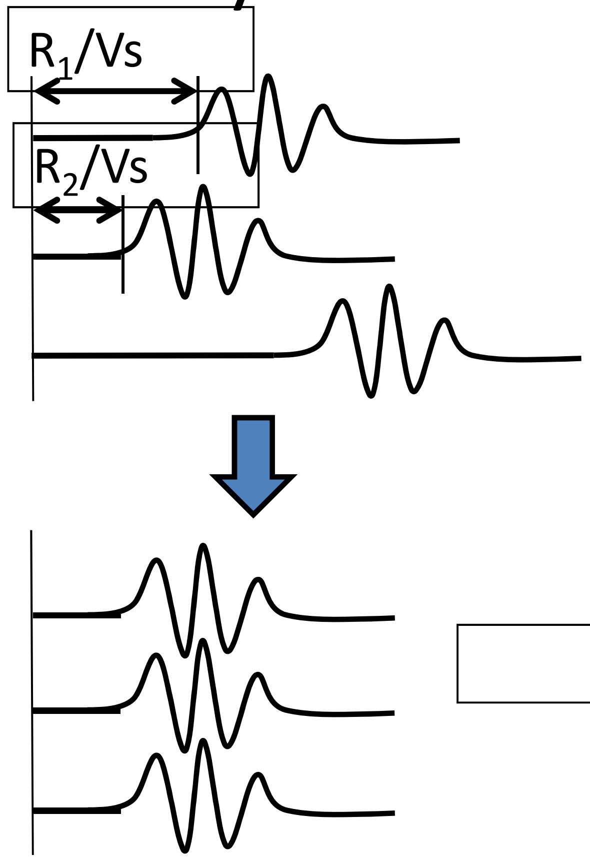


Particle Motion Diagrams (Vertical) of WP1 at 3 Stations in Array B



Semblance Analysis for Wave Packets using Local Arrays





$$S_e(\boldsymbol{s}) = \frac{1}{N}\frac{\sum_{k=1}^{M}\left[\sum_{i=1}^{N}\boldsymbol{u}(\boldsymbol{x}_i, \boldsymbol{t}_k + \boldsymbol{s}\cdot\boldsymbol{x}_i)\right]^2}{\sum_{k=1}^{M}\sum_{i=1}^{N}\boldsymbol{u}(\boldsymbol{x}_i, \boldsymbol{t}_k)^2}$$

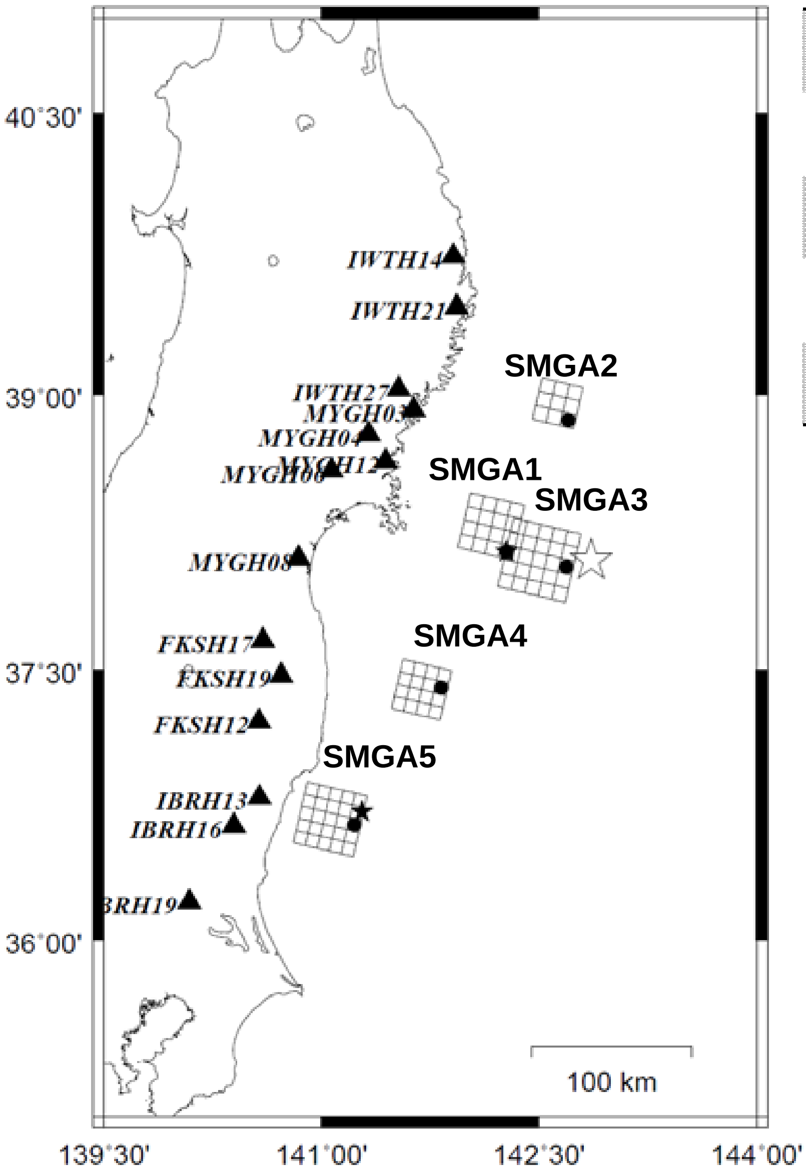
Simulation of Strong Ground Motions during the 2011 Tohoku Earthquake Using the Empirical Green's Function Method

■ Strong Motion Generation Areas are relocated using the semblance analysis of the wave-packets in small arrays.

■ The observed data from medium-sized earthquakes occurring near each strong motion generation area are adopted as the empirical Green's functions.

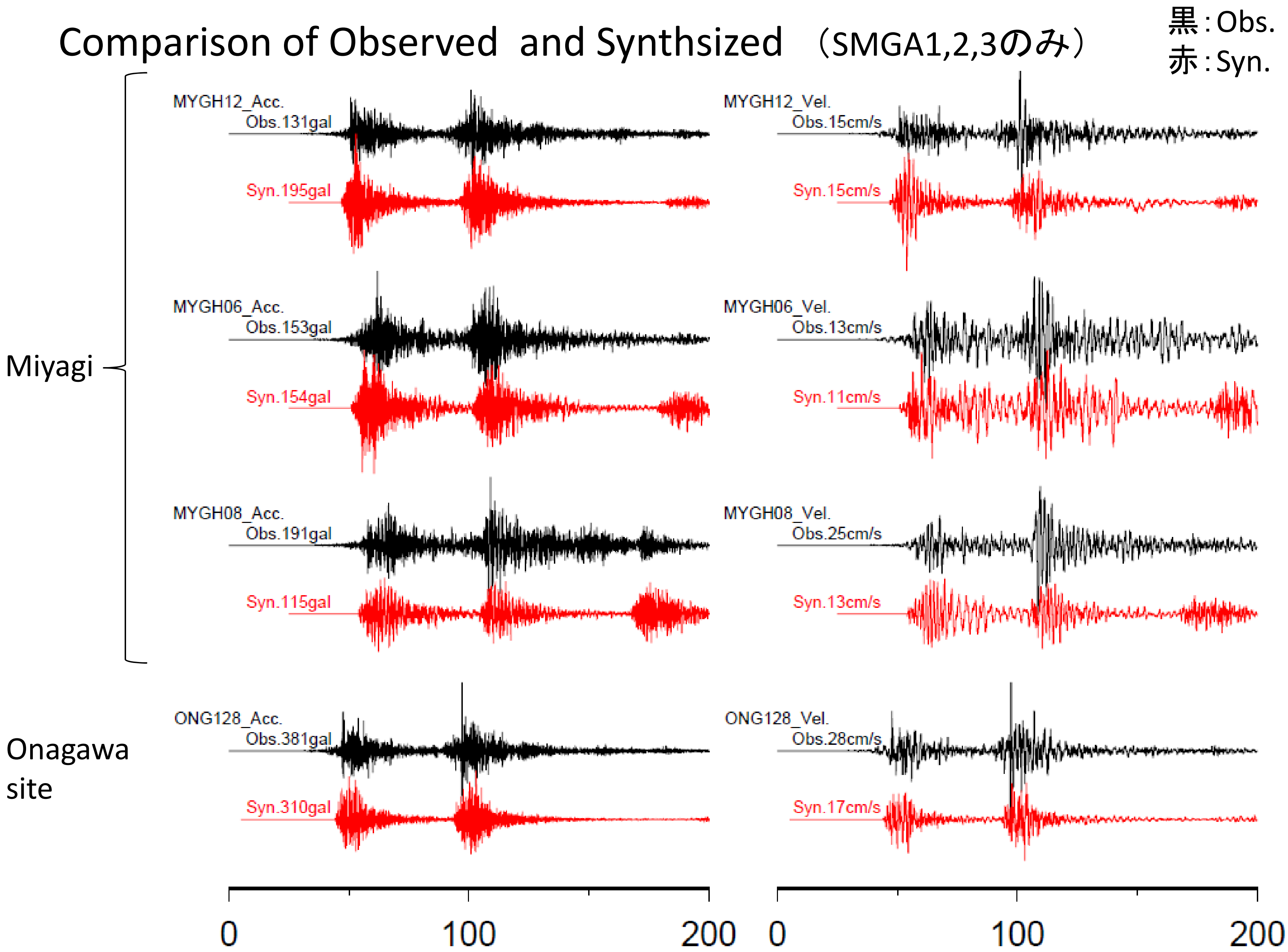
■ Strong motion records of the 2005 Miyagi-Oki earthquake (Mw 7.2) are used as the empirical Green's functions for SMGA1 (WP1) and SPGA3 (WP2).

Revised Model

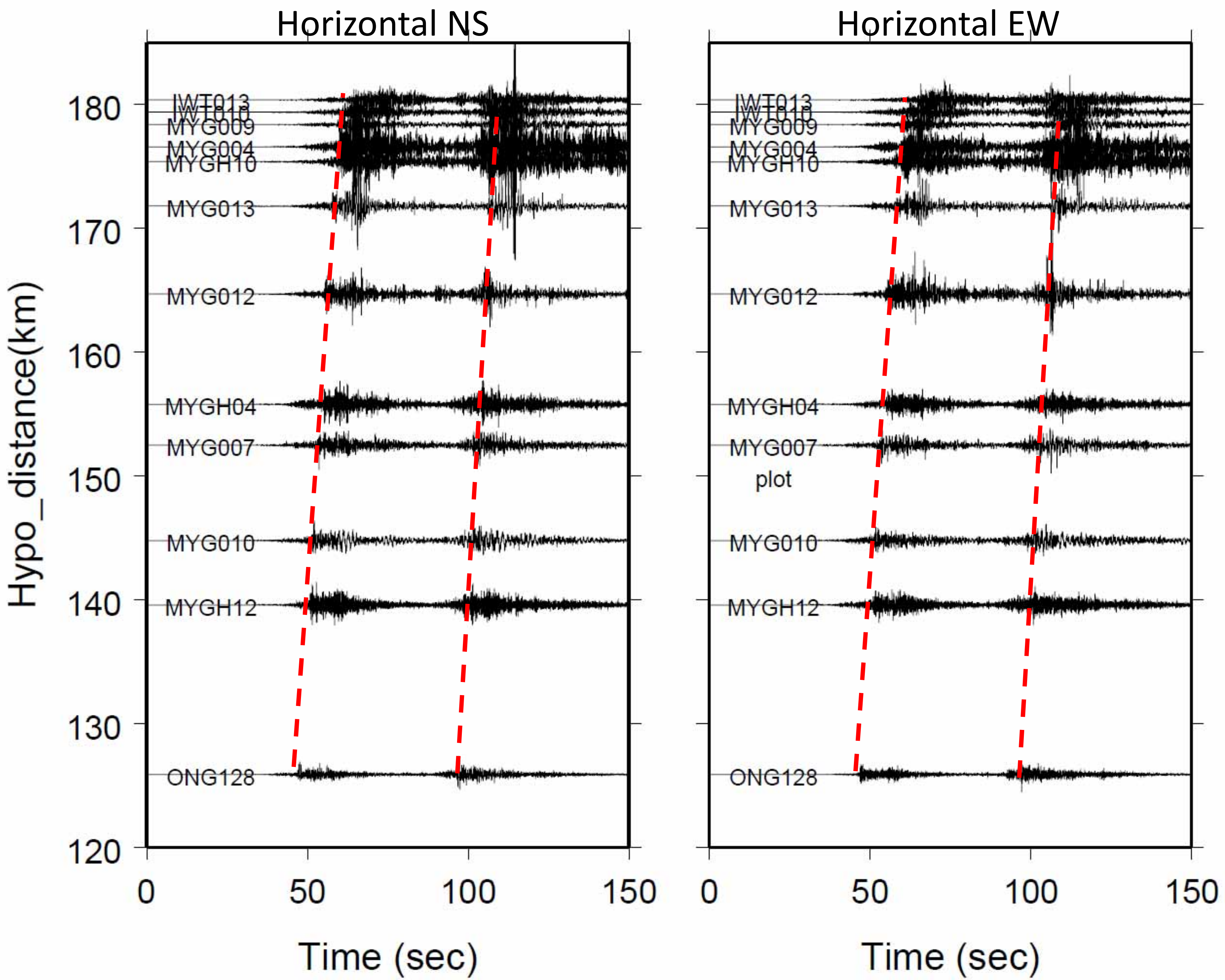


	L,W	Mo	Stress drop
SMGA1	34 × 34	2.68E+20	16
SMGA2	23.1 × 23.1	1.41E+20	20
SMGA3	42.5 × 42.5	6.54E+20	20
SMGA4	25.5 × 25.5	1.24E+20	25.2
SMGA5	38.5 × 38.5	5.75E+20	25.2

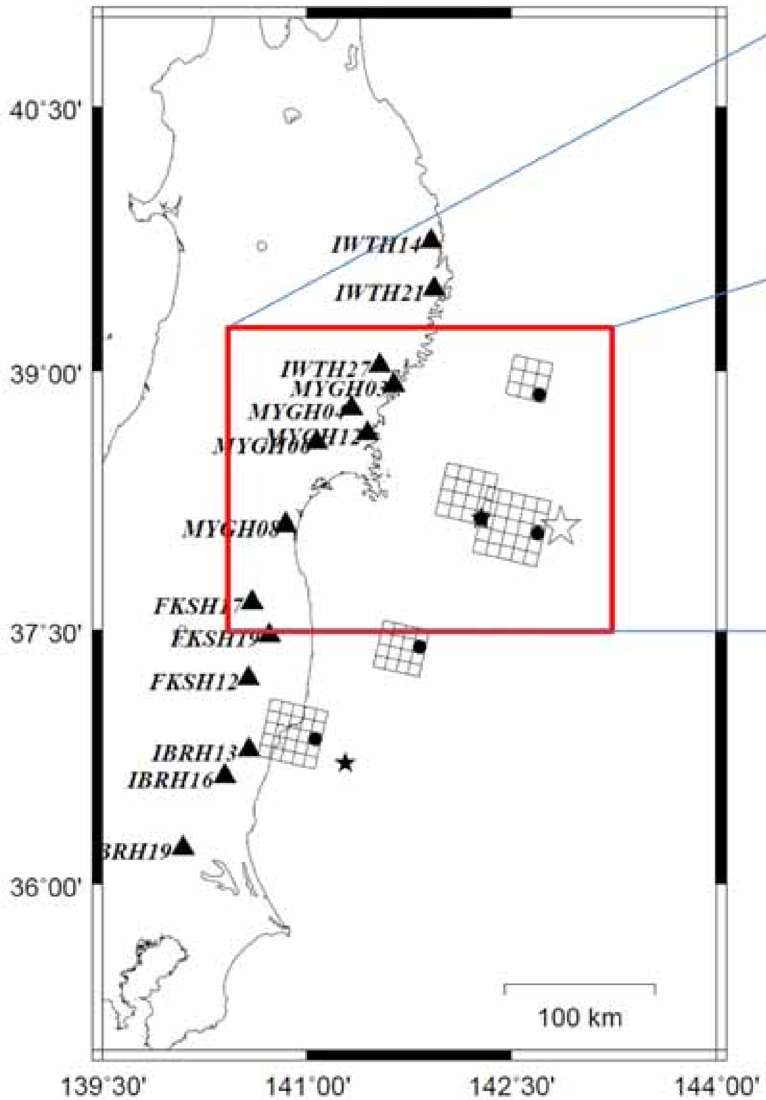
Comparison of Observed and Synthsized （SMGA1,2,3のみ）

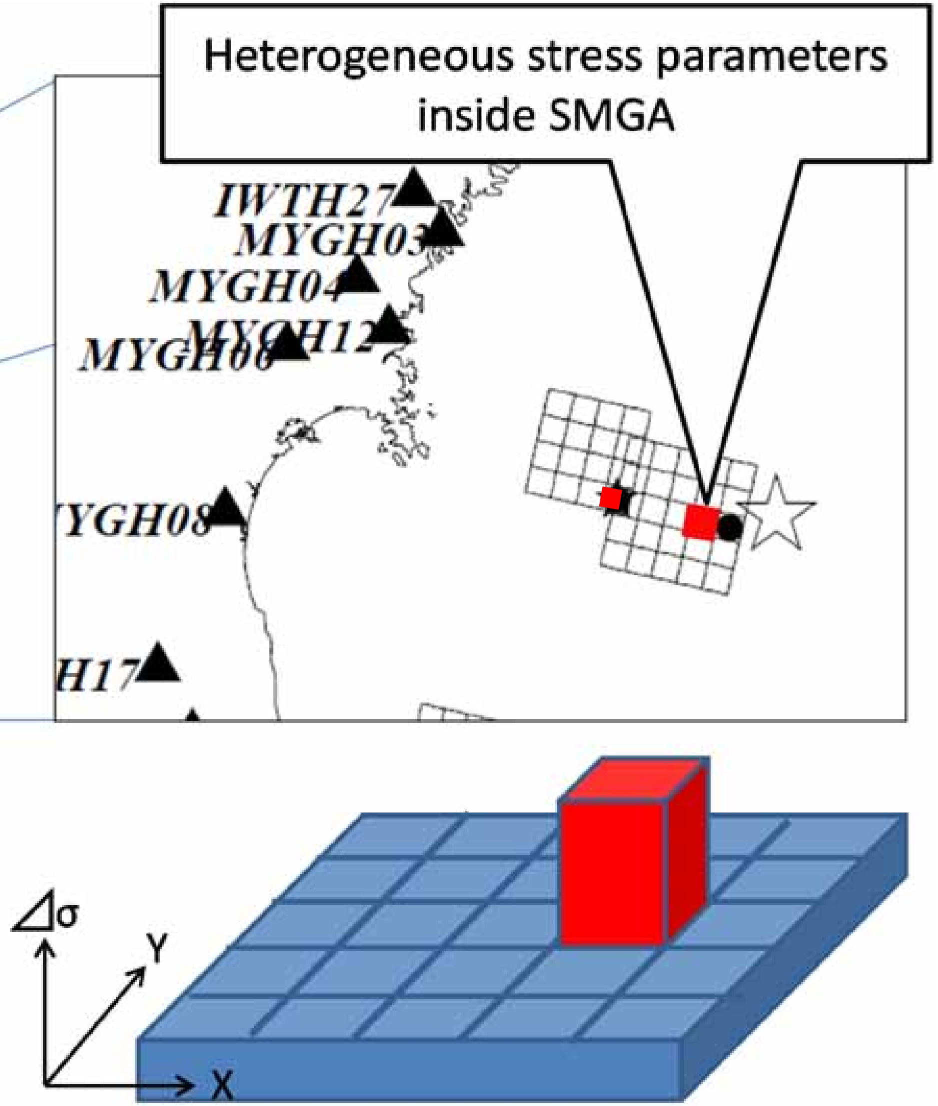


Acceleration Records with remarkable distictive pulses

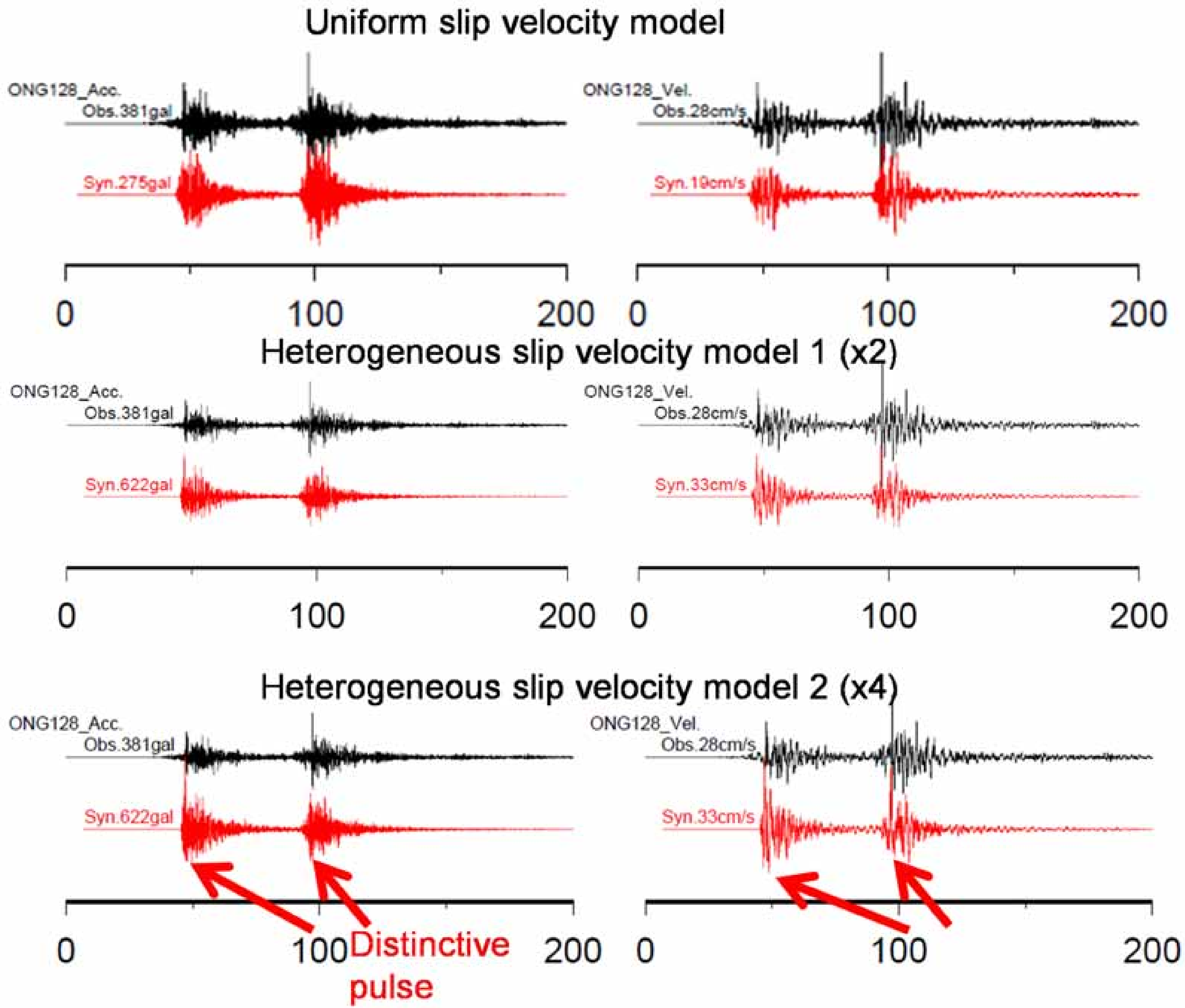


Heterogeneity of stress parameters inside SMGA





Matsushima and Kawase (2006)


Uniform slip velocity model
ONG128_Acc.
Obs.381gal
Syn.275gal
0
100
200
ONG128_Vel.
Obs.28cm/s
Syn.19cm/s
0
100
200
Heterogeneous slip velocity model 1 (x2)
ONG128_Acc.
Obs.381gal
Syn.622gal
0
100
200
ONG128_Vel.
Obs.28cm/s
Syn.33cm/s
0
100
200
Heterogeneous slip velocity model 2 (x4)
ONG128_Acc.
Obs.381gal
Syn.622gal
0
100
200
Distinctive pulse
ONG128_Vel.
Obs.28cm/s
Syn.33cm/s
0
100
200

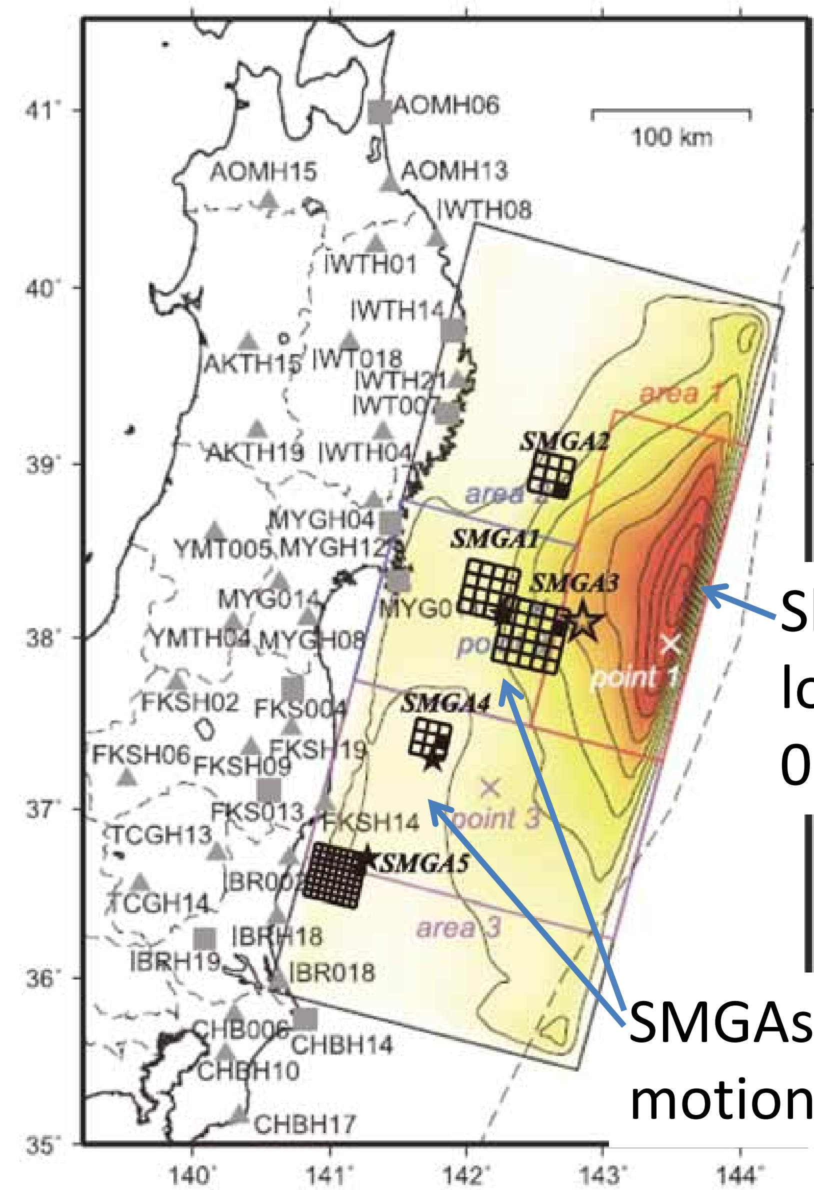
Period range of ground motions generated from the SMGAs

- Longer-period motions from the Strong Motion Generation Areas (SMGAs) are estimated using numerical Green's functions: the Discrete Wavenumber method (Bouchon, 1981) and the Reflection/Transmission coefficient matrix method (Kennet, 1983) using a stratified medium.

- Effective period range of ground motions generated from the SMGAs are confirmed by comparing simulated motions with observed motions.

- Verification of the fault parameters are made, mainly inner fault parameters of Strong Motion Generation Areas (SMGAs) estimated using the empirical Green's function method

Comparison between slip distribution using long-period motions (Suzuki et al, 2011) and SMGAs in this study



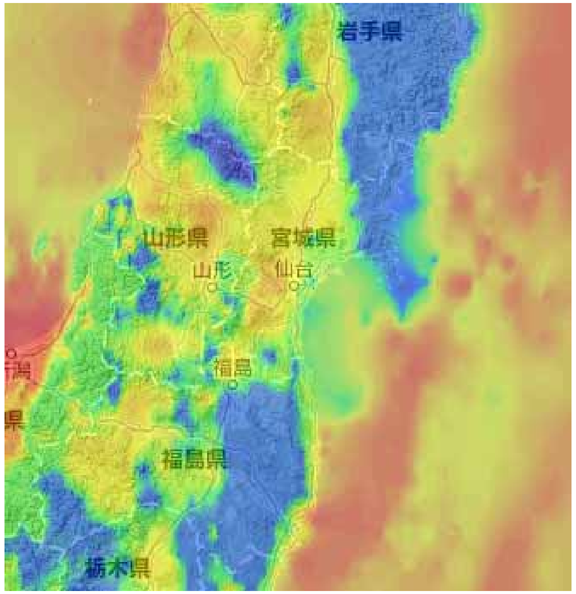
Slip distribution inverted from long-period motions filtered 0.01-125Hz (100 – 8 s)

SMGAs estimated from short-period motions filtered 0.15-10Hz (6.6 – 0.1 s)

Initial models of velocity structures

- Surface layers models: P-S logging data in boreholes (Kik-net and K-NET)
- Shallow layers model less than 5 km: Velocity structure models determined by NIED.
- Deeper layers model more than 5 km: Velocity structure model by Wu et al.(2008)

Velocity structure model in shallow layers (Kik net)



Velocity structure model in deeper layers

Table 3. Velocity Model in the Crust and Upper Mantle

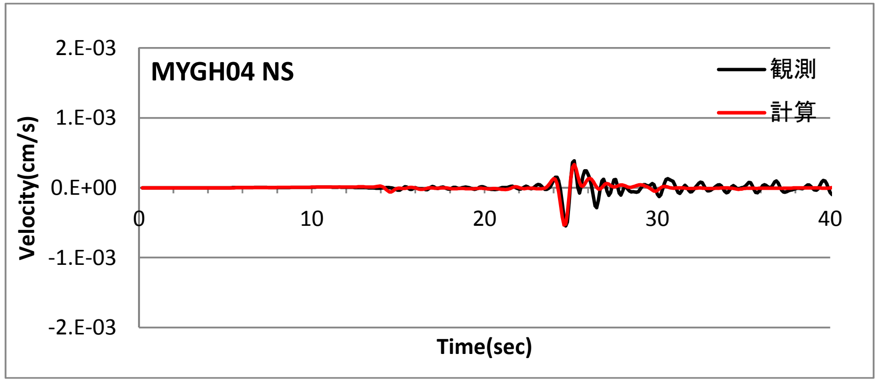
Vp, km/s	Vs, km/s	Density, g/cm^3	Depth, km	Qp	Qs
6.08	3.50	2.64	5.0	340.0	170.0
6.23	3.60	2.65	13.0	360.0	180.0
6.35	3.64	2.70	21.0	400.0	250.0
6.55	3.68	2.75	27.0	450.0	350.0
6.95	3.96	2.90	32.0	600.0	350.0
7.60	4.29	3.10	40.0	700.0	400.0
7.69	4.31	3.15	65.0	1000.0	500.0
7.73	4.34	3.20	90.0	1000.0	500.0
8.27	4.56	3.30	120.0	1000.0	500.0
8.37	4.61	3.35	150.0	1000.0	500.0

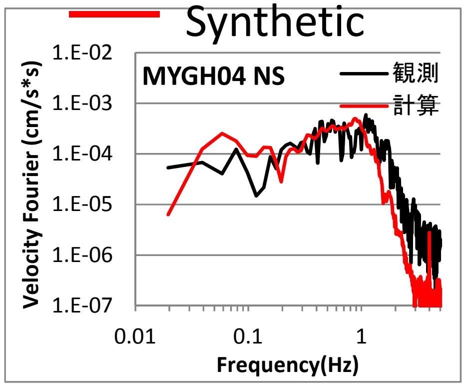
Identification of Velocity Structure Model

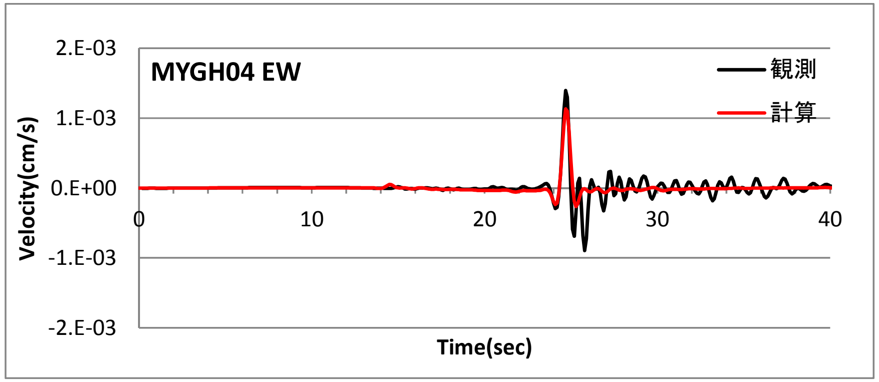
Frequency Range
0.05-1Hz

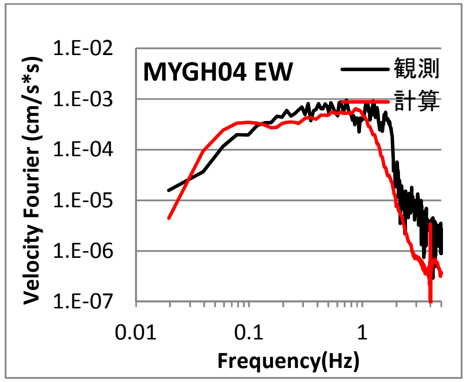
Fitting Observed to Calculated Motions from Small Events

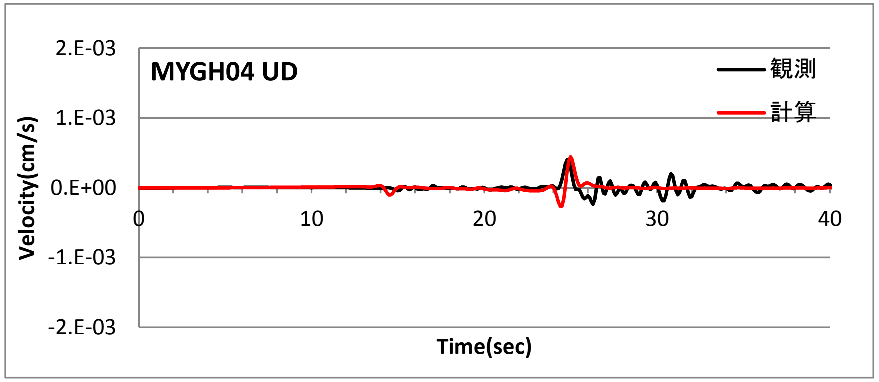
Observed
Synthetic

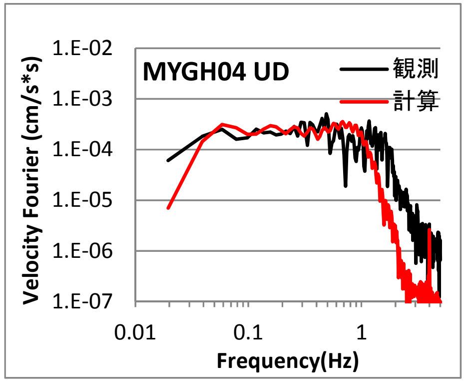






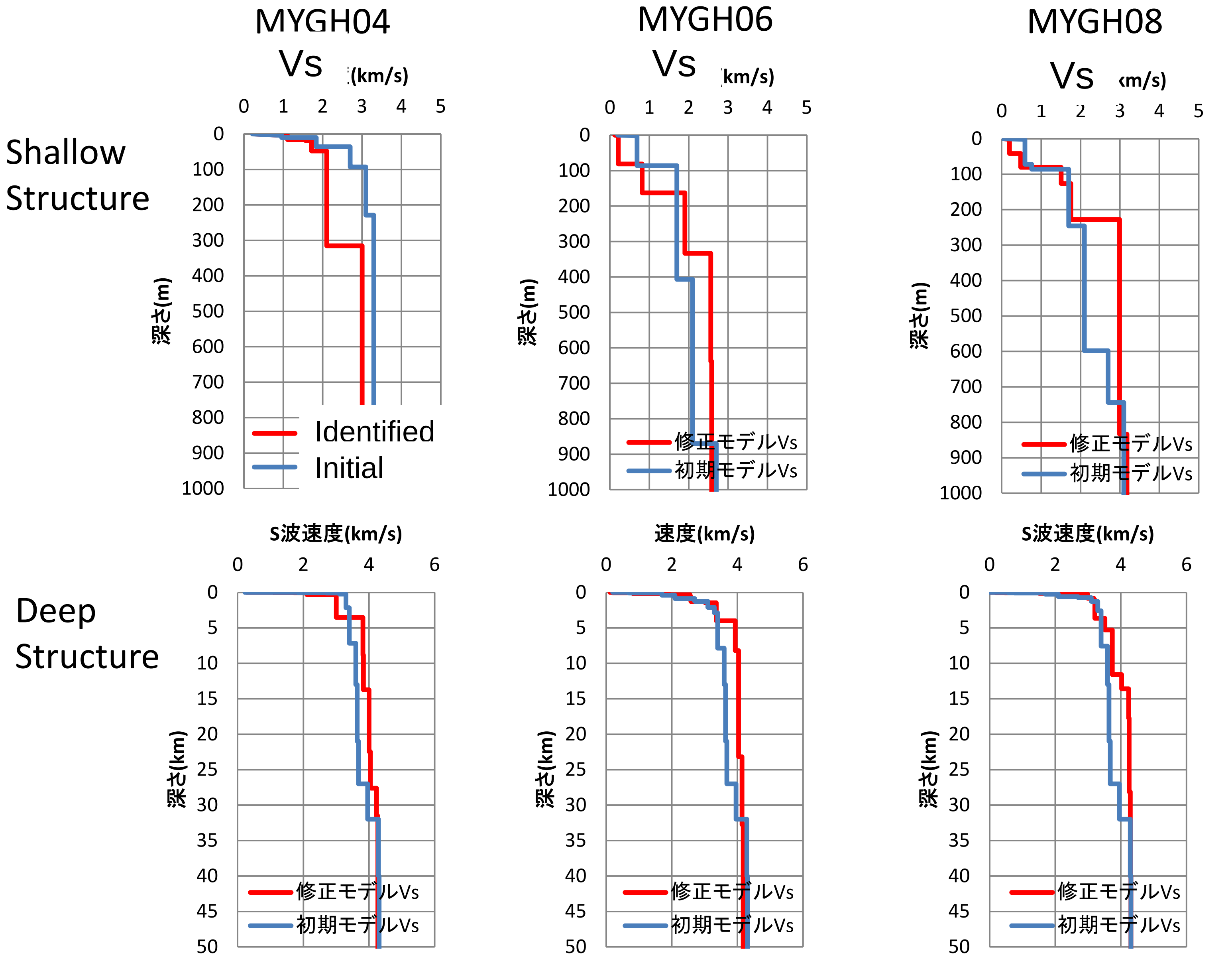






Velocity Structure Models (Vs）

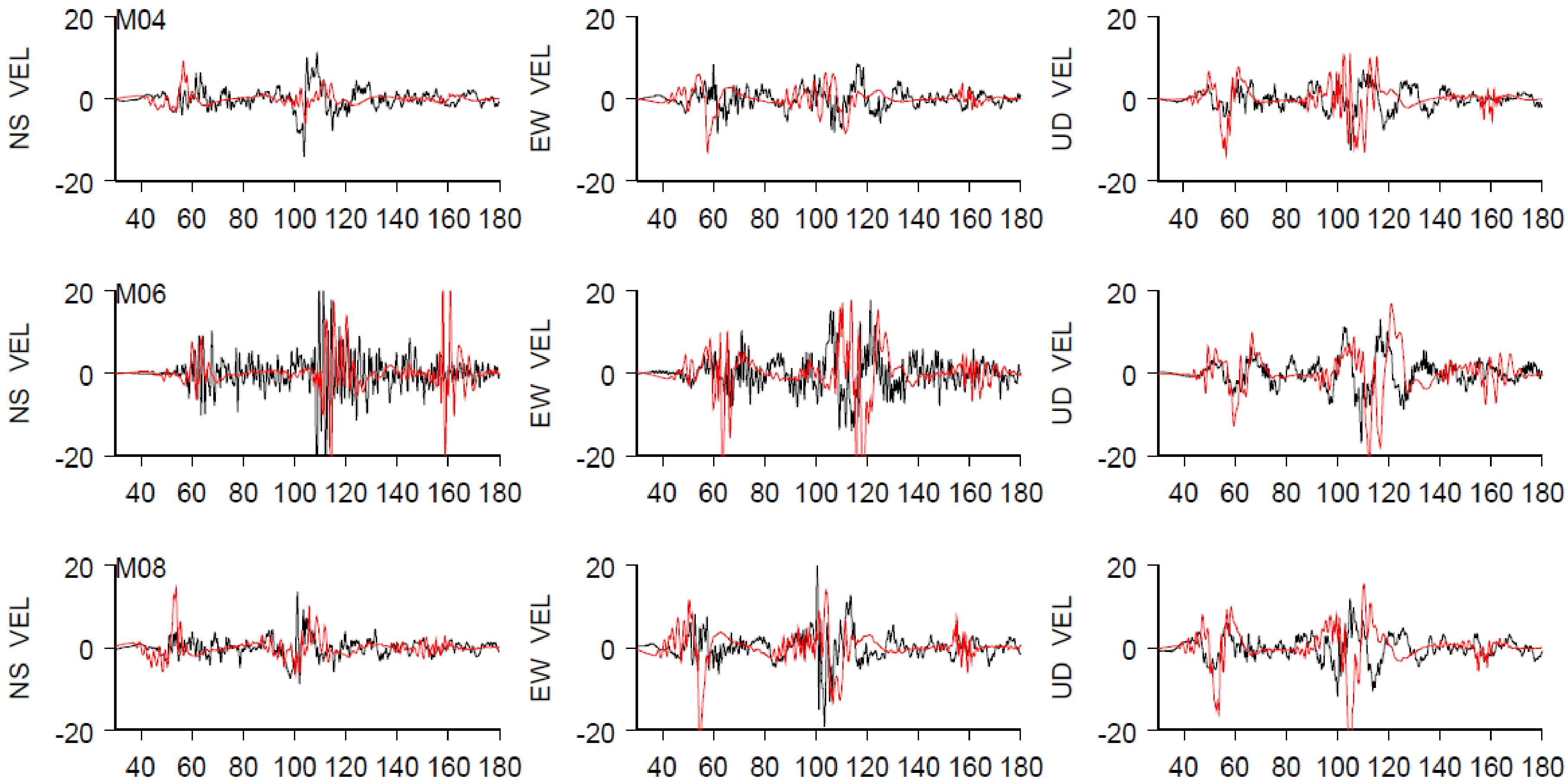
1-D velocity structures from stations to source are modeled comparing synthetic motions with observed ones from small events.



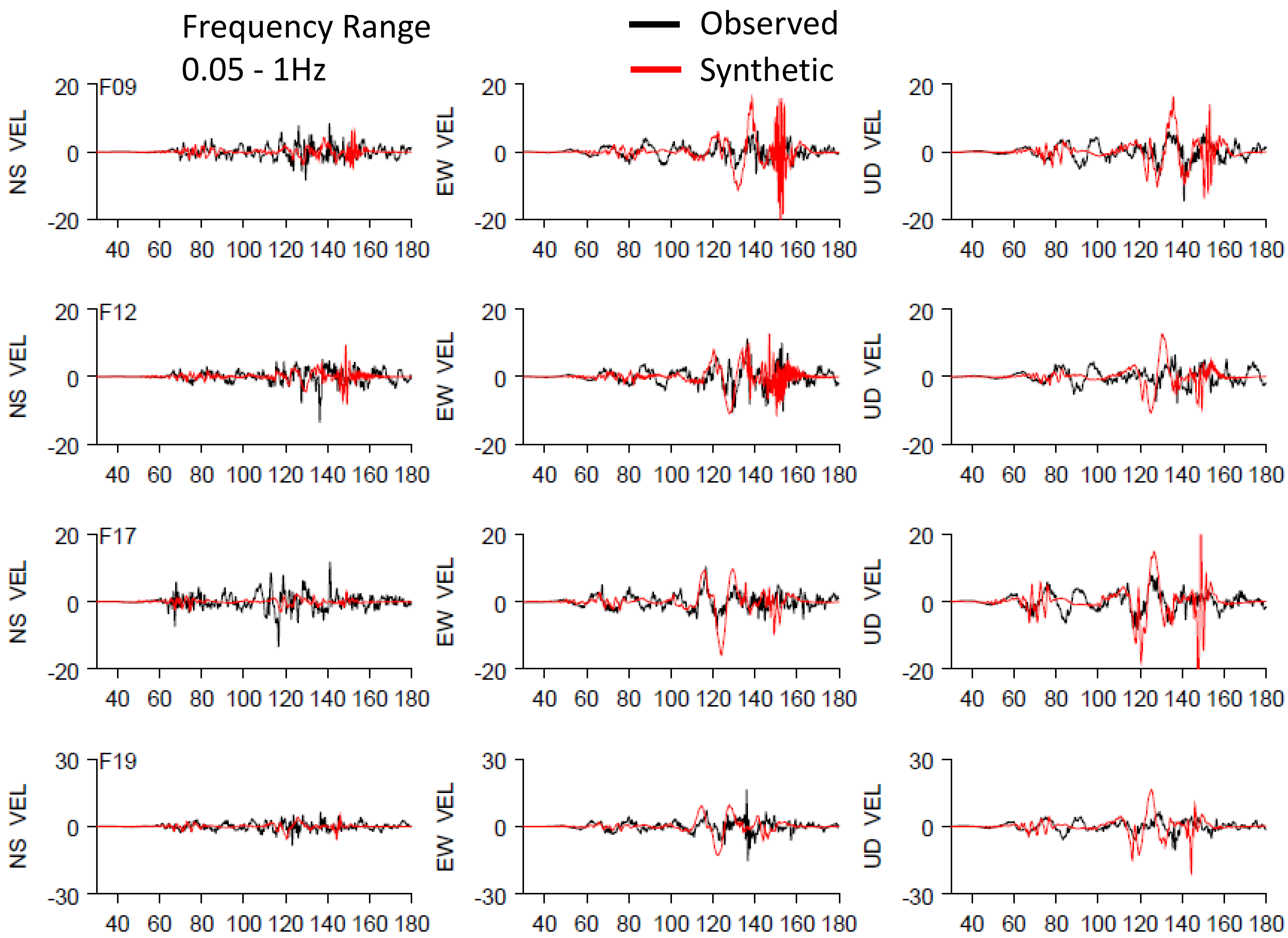
Comparison between Observed and Synthetic Motions in Miyagi Prefecture

Frequency Range
0.05 – 1.0 Hz

Observed
Synthetic



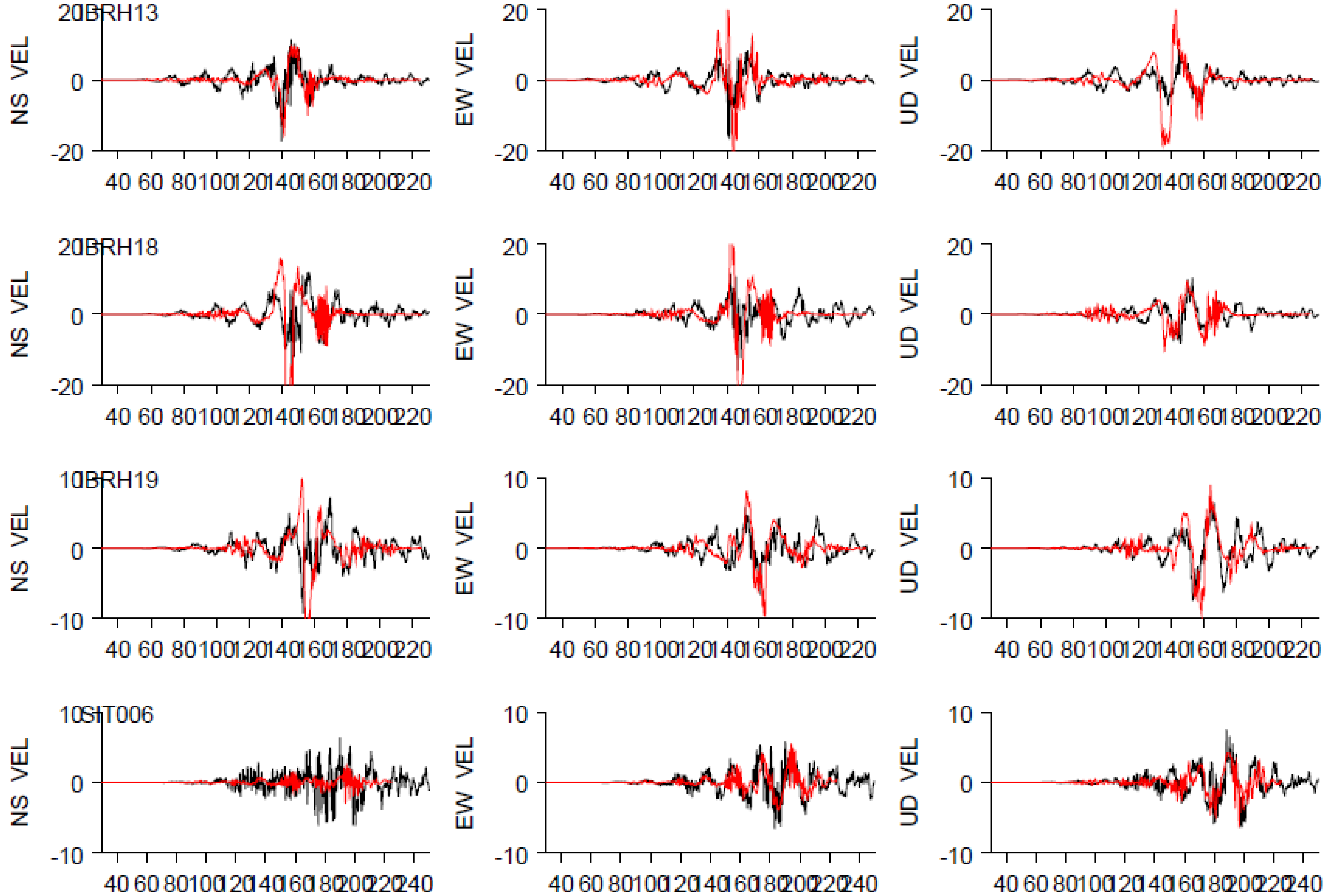
Comparison between Observed and Synthetic Motions in Fukushima Prefecture



Comparison between Observed and Synthetic Motions in Kanto Region

Frequency Range
0.05 - 1Hz

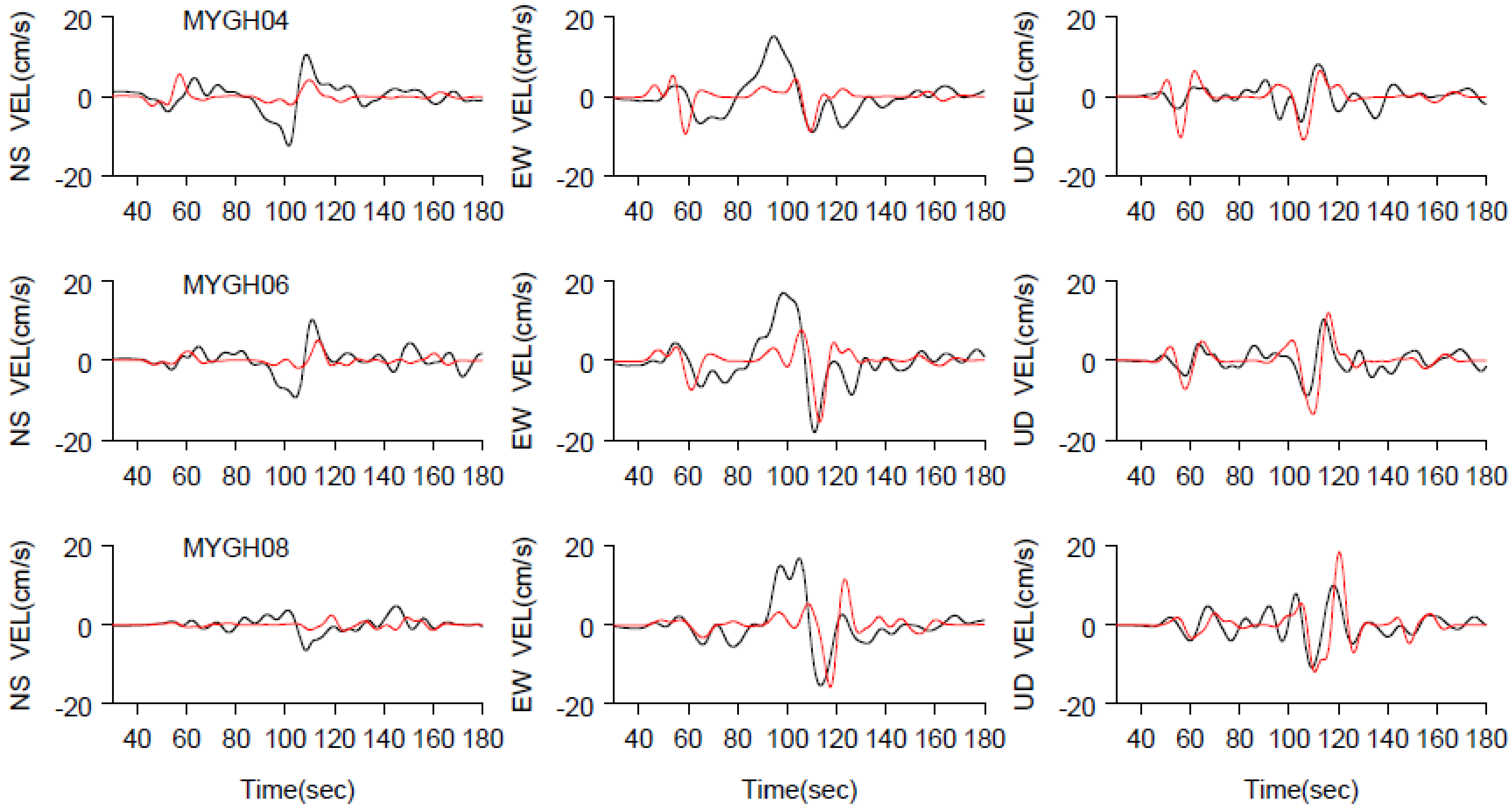
Observed
Calculated



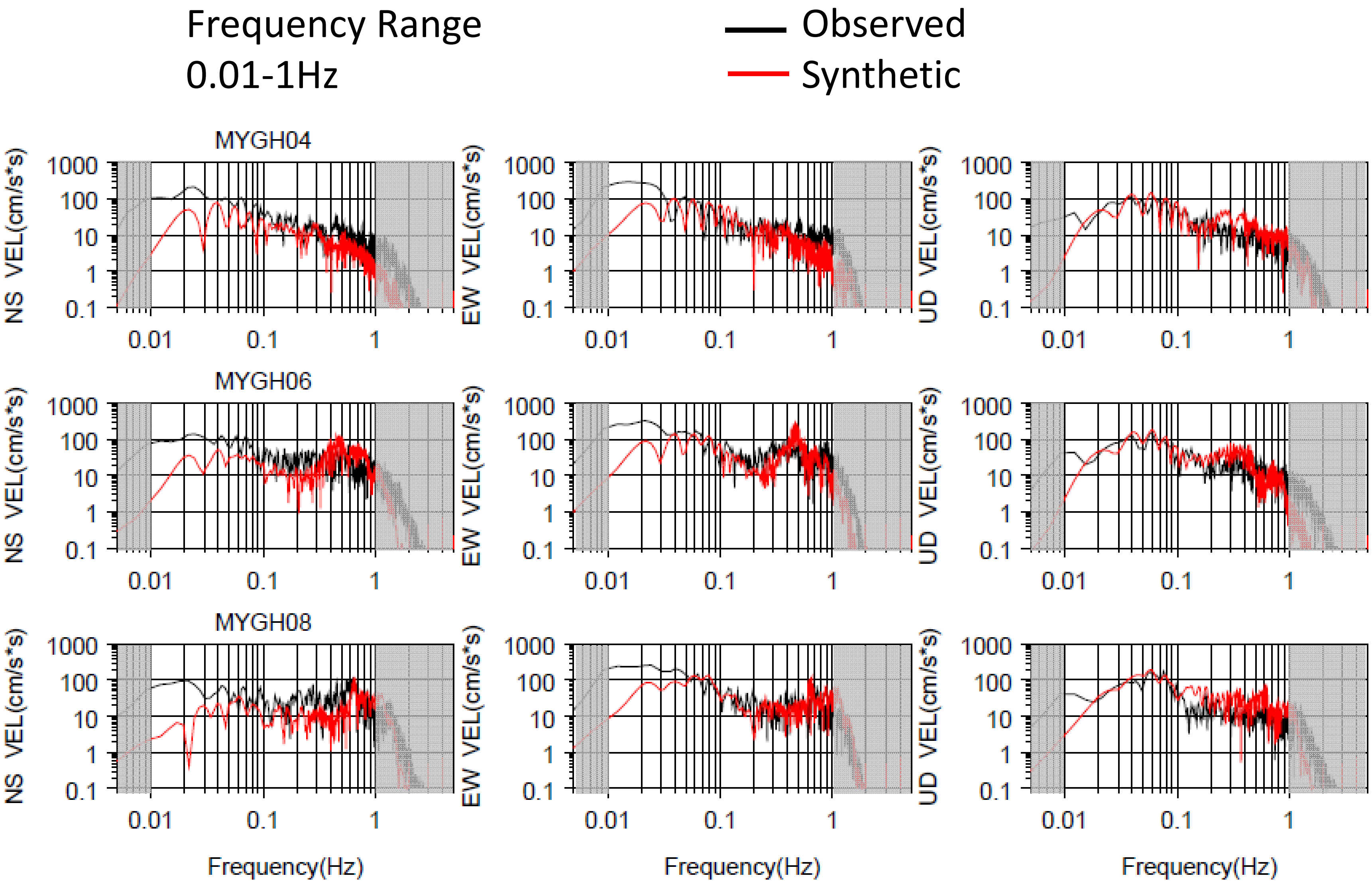
Comparison between Observed and Synthetic Motions in Miyagi Prefecture

Frequency Range
0.01 - 0.1Hz

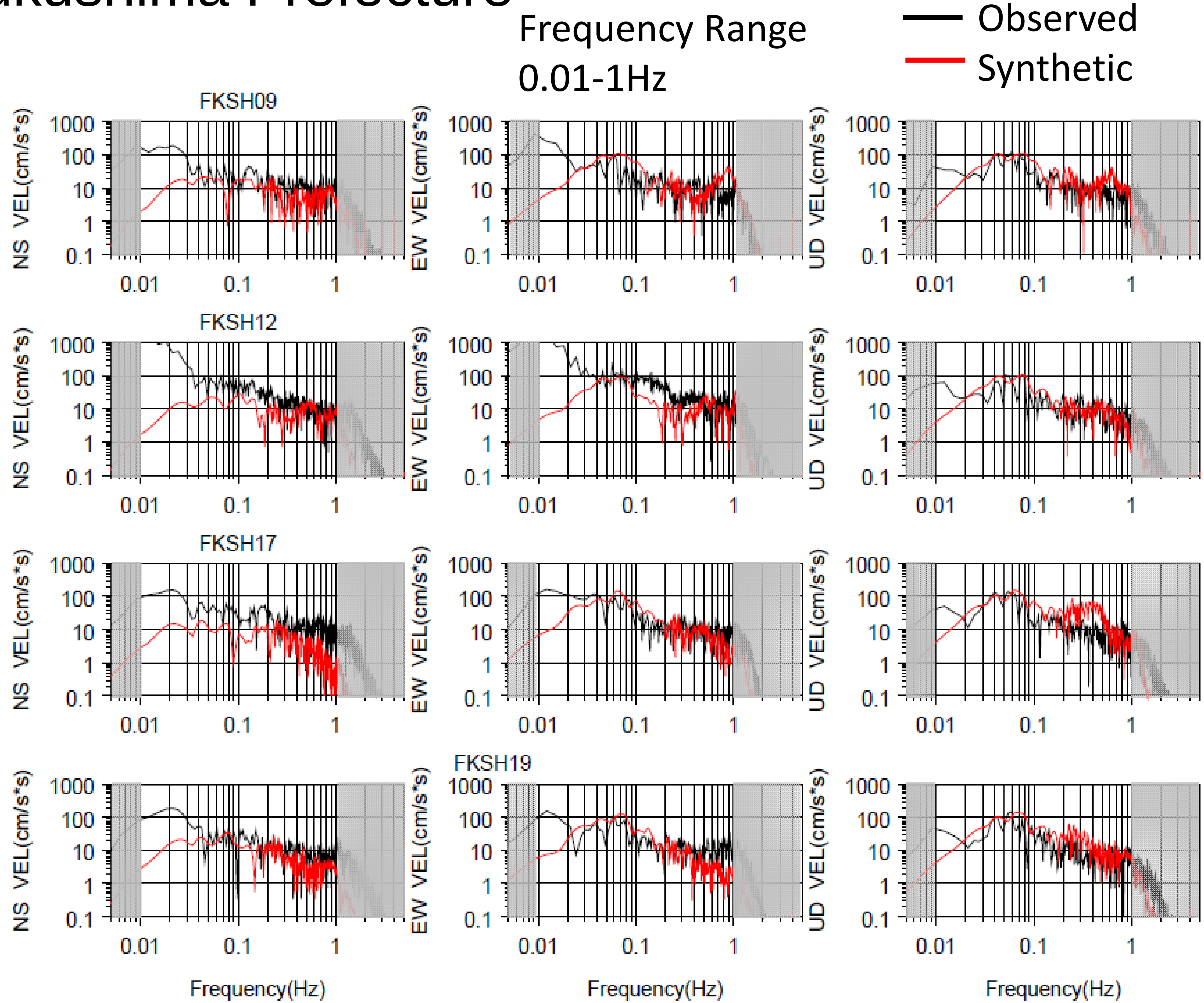
Observed
Calculated



Comparison between Observed and Synthetic Motions in Miyagi Prefecture



Comparison between Observed and Synthetic Motions in Fukushima Prefecture



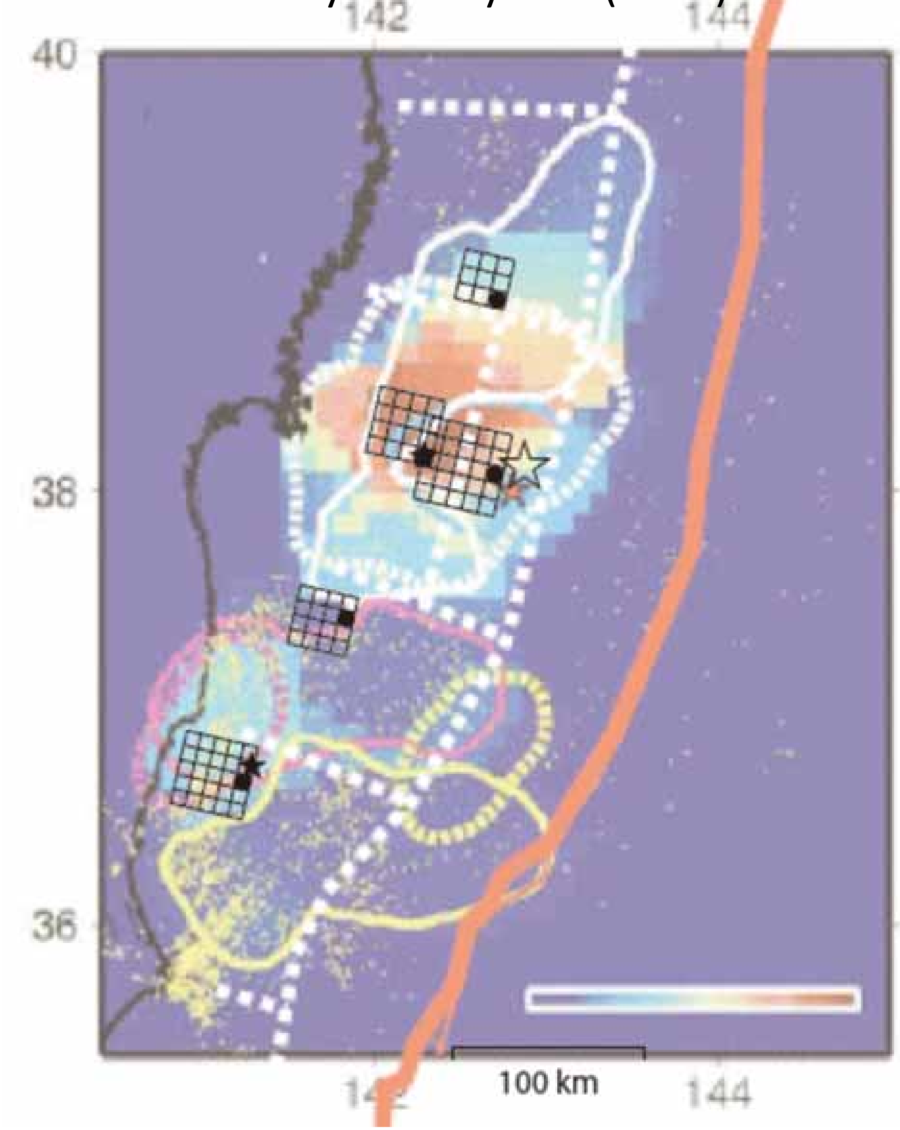
5. Period-dependence of rupture processes
– comparison of short-period source model and long-period source models inverted long-period strong motion data, tsunami waveforms, geodetic data -

■ Short-period source models using backprojection of teleseismic short-period P-waves

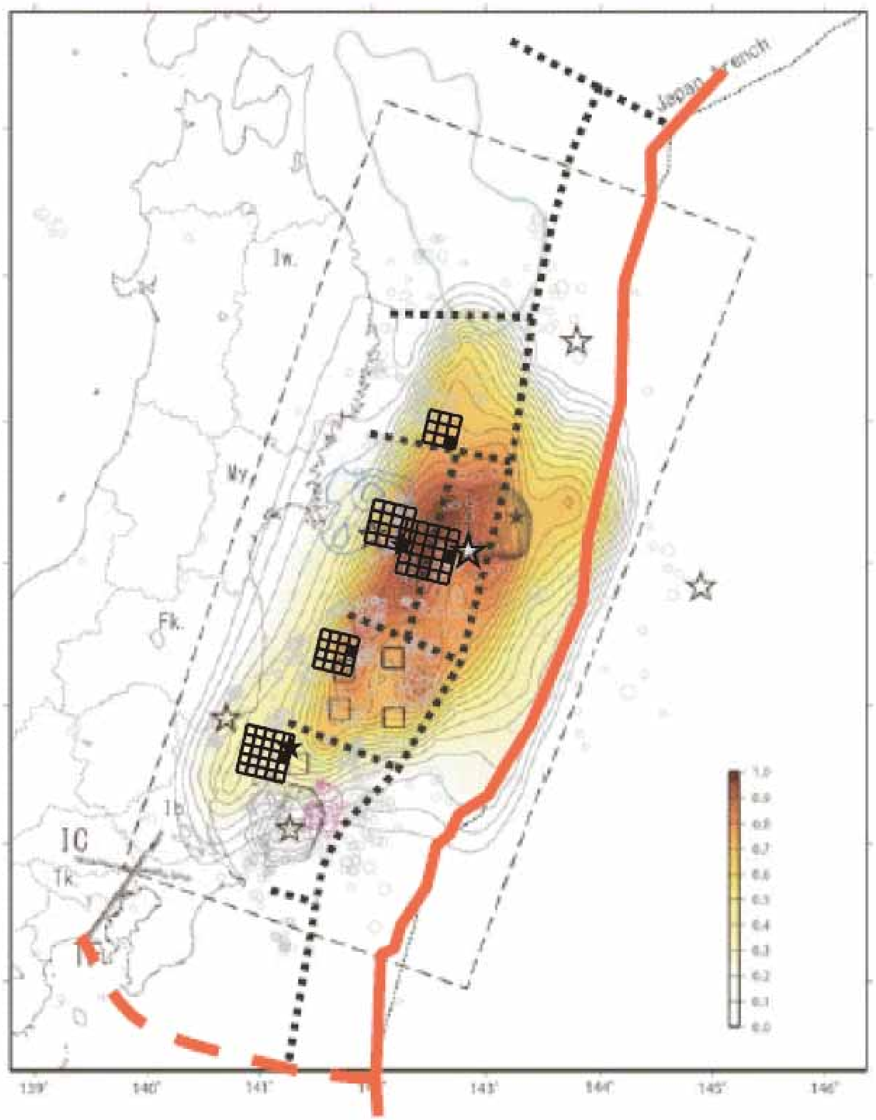
■ Long-period source models inverted from tsunami data (Fujii et al., 2012) , geodetic data (Iinuma et al., 2012) and joint data (Yokota et al.)

Comparison of Short-Period Source Model in This Study with Short-Period Released Energy by the back-projevtion method

US Array Data by Ishii (2011)



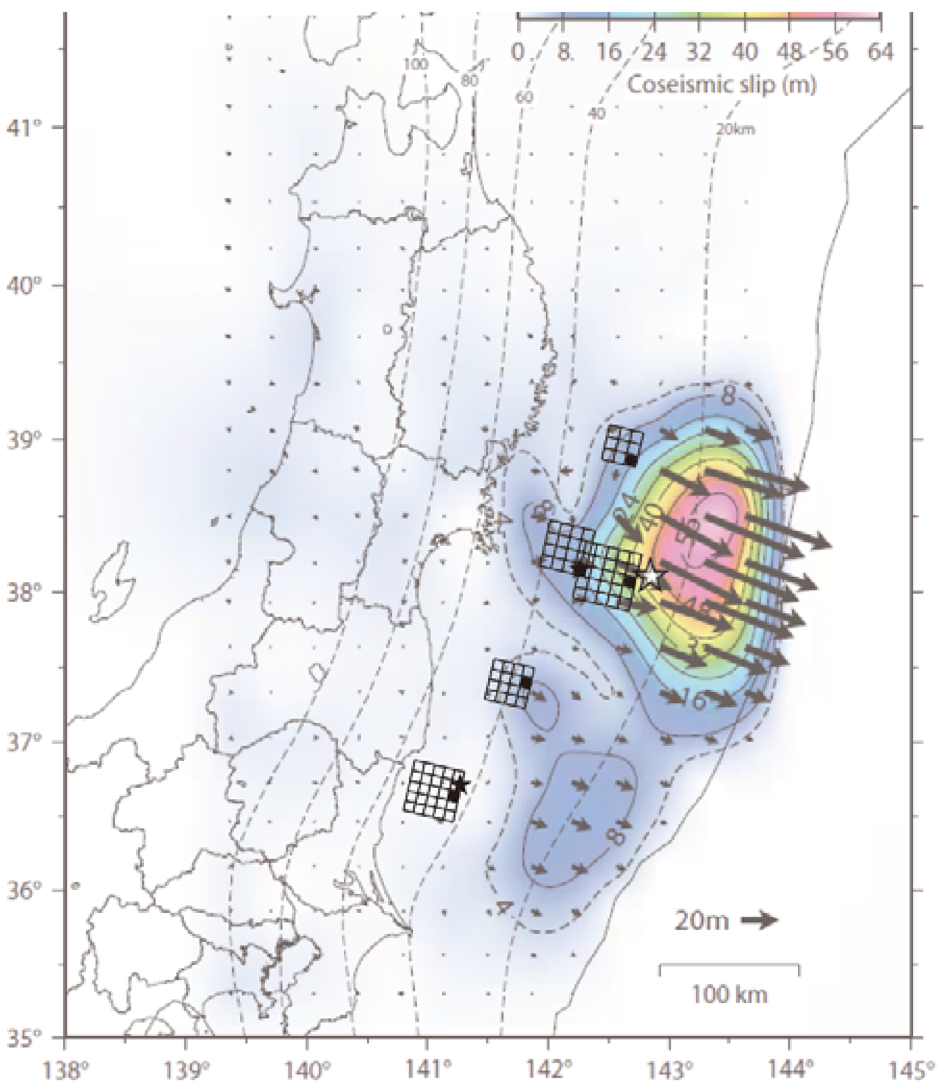
Kanto Array Data by Hoda et al, (2011)



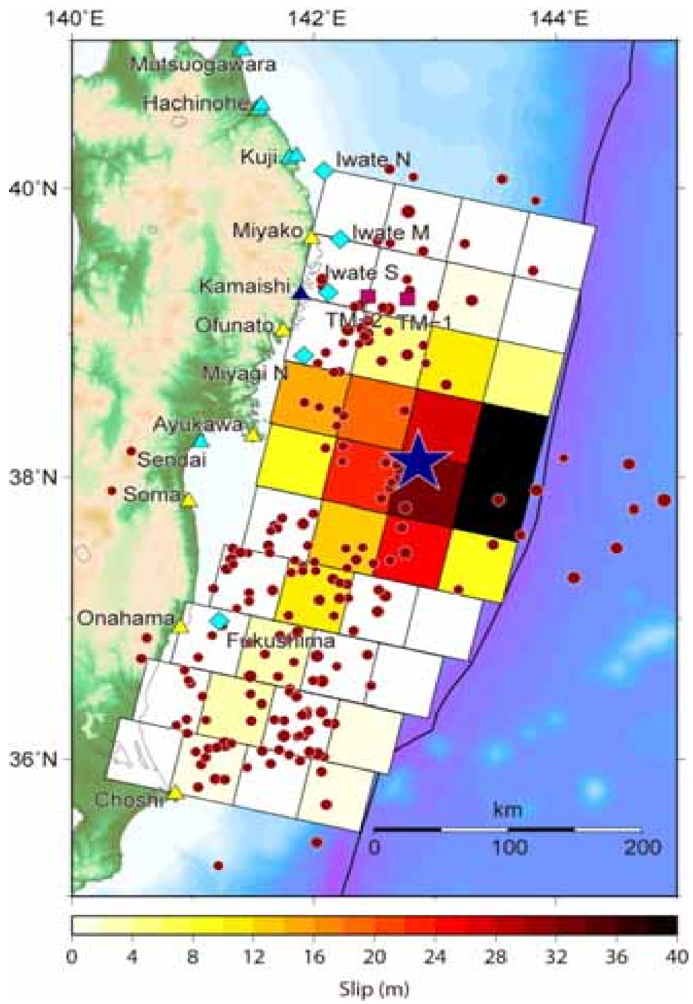
Slip Distribution of the 2011 Tohoku Earthquake

DPS data including inland and off-shore observation

Tsunami Waveform Data

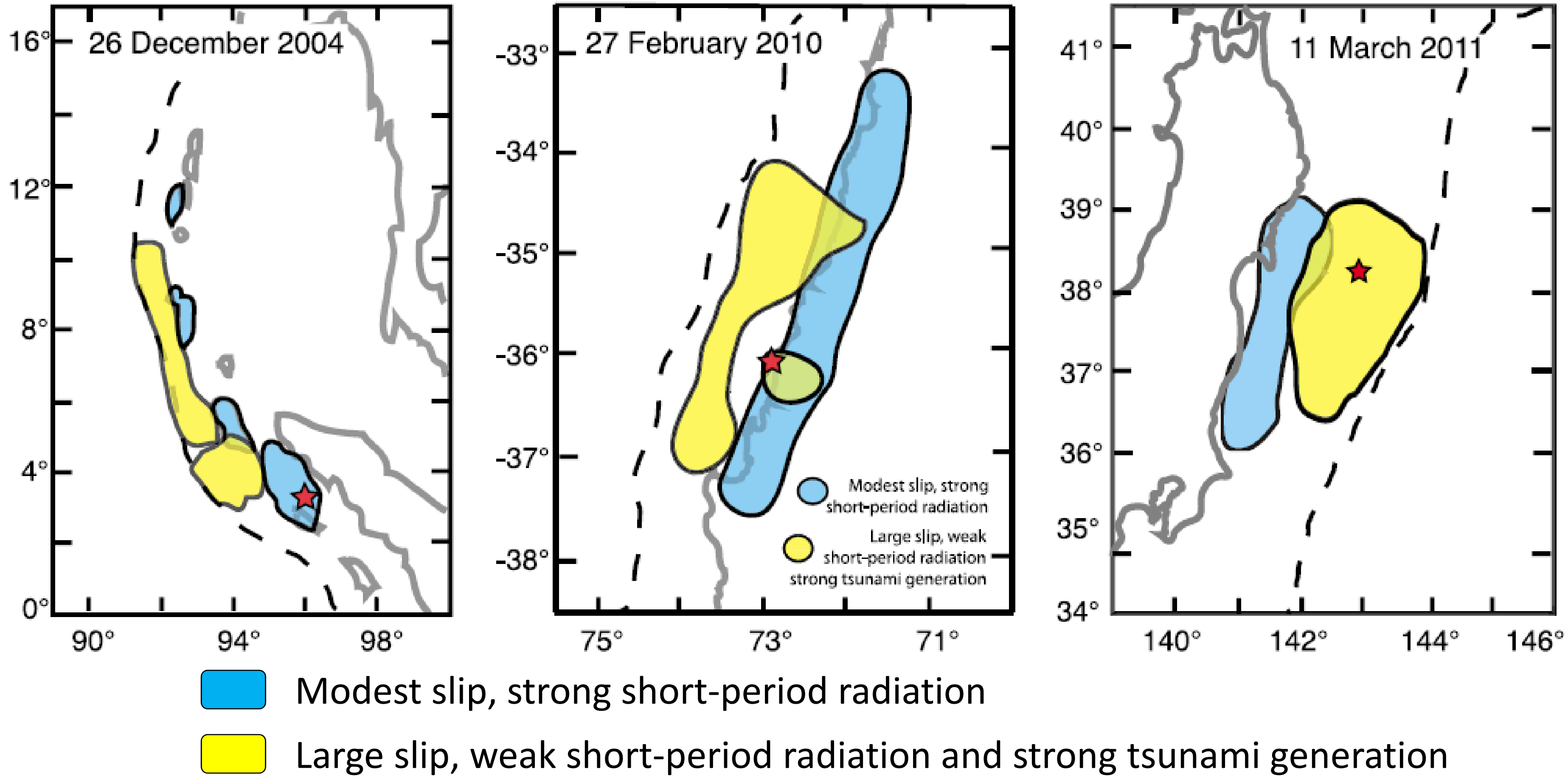


Geographical Institute (2011)



Fujii and Satake (2011)

Patterns of Coherent Short-period radiation and Large Slip Regions for Mega-thrust Earthquakes



Lay, et al. JGR(2012)

6. Recipe of predicting strong ground motions for subduction-zone megathrust earthquakes

■ Rupture process of subduction-zone megathrust earthquakes show period-dependence.

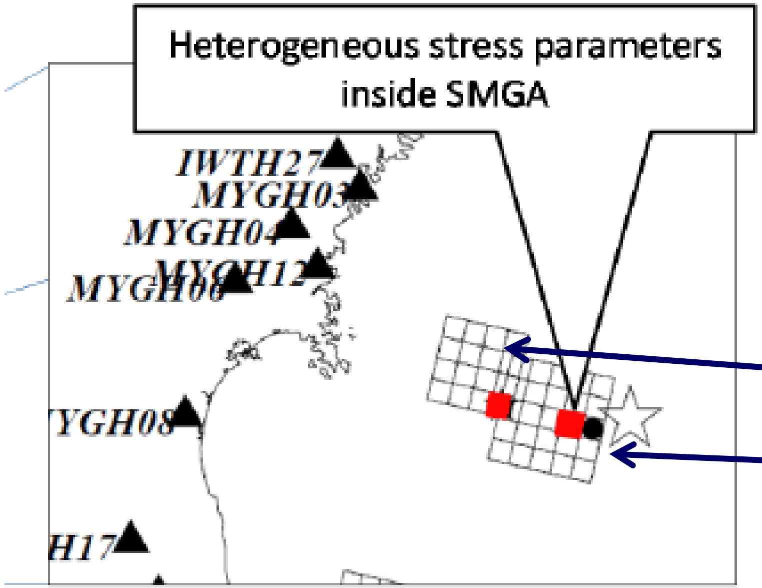
■ New source image for period-dependent source process is expressed as multi-step heterogeneous-source-model.

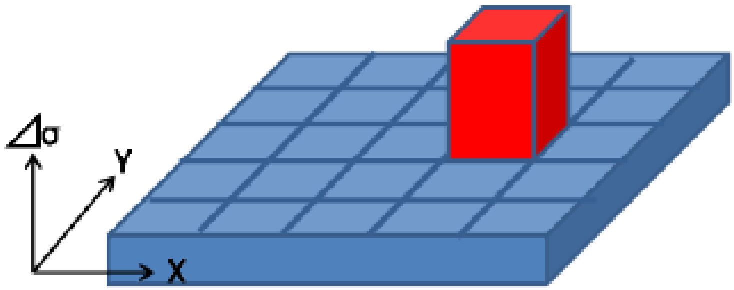
■ Strong ground motions of engineering interest in the period-range from 0.1 to 10 sec are estimated using the basic characteristic source model with outer-fault parameters and inner fault parameters, that is, just one step heterogeneity source model.

Multi-Step Heterogeneous Source Model - 1

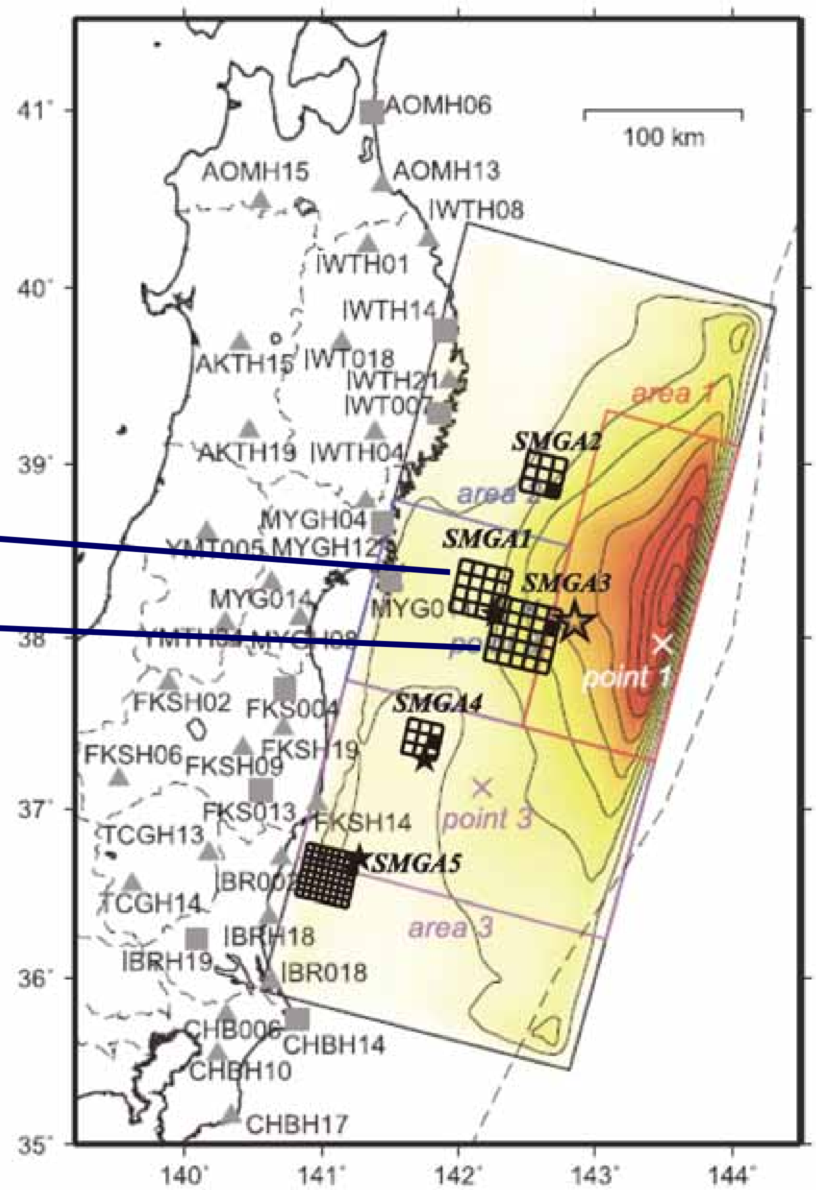
First step: Heterogeneity model for short periods 0.1 – 20 s

Second step: Heterogeneity model for very short-periods 0.05 – 0.2 s

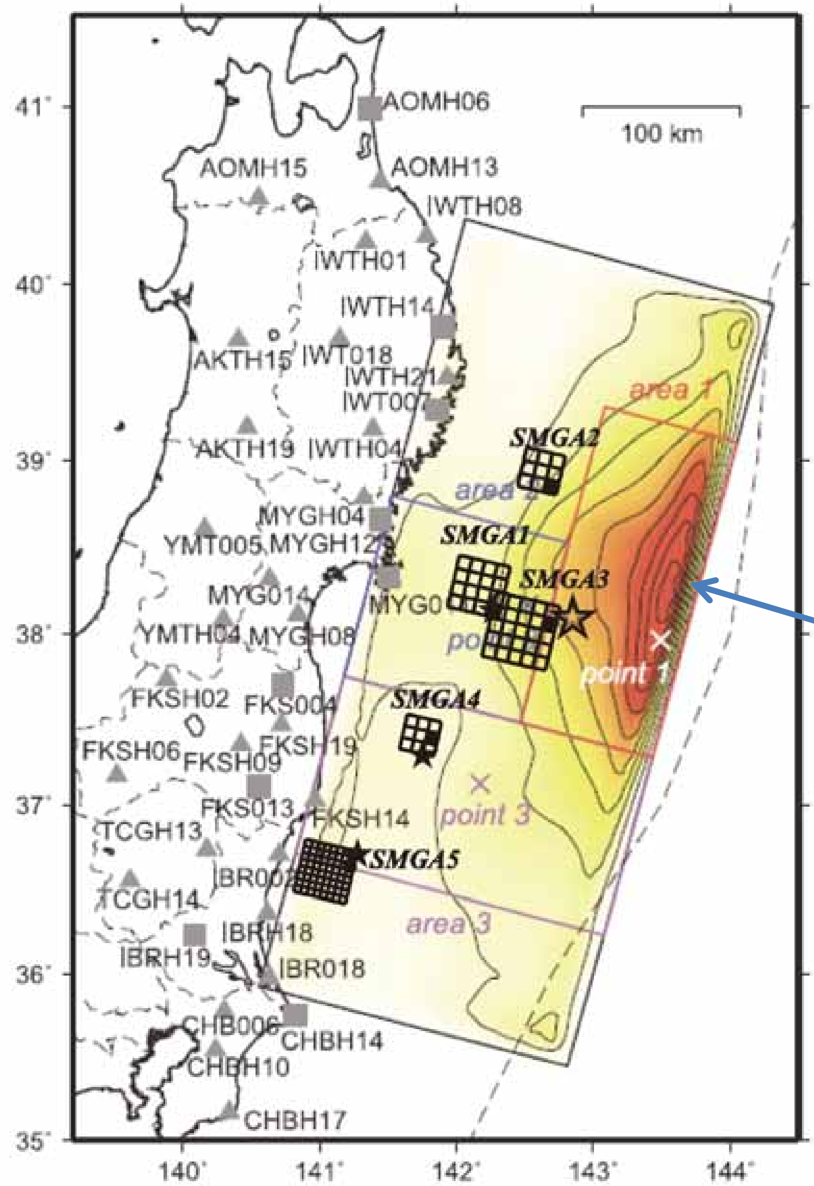




Matsushima and Kawase (2006)



Multi-Step Heterogeneous Source Model - 2

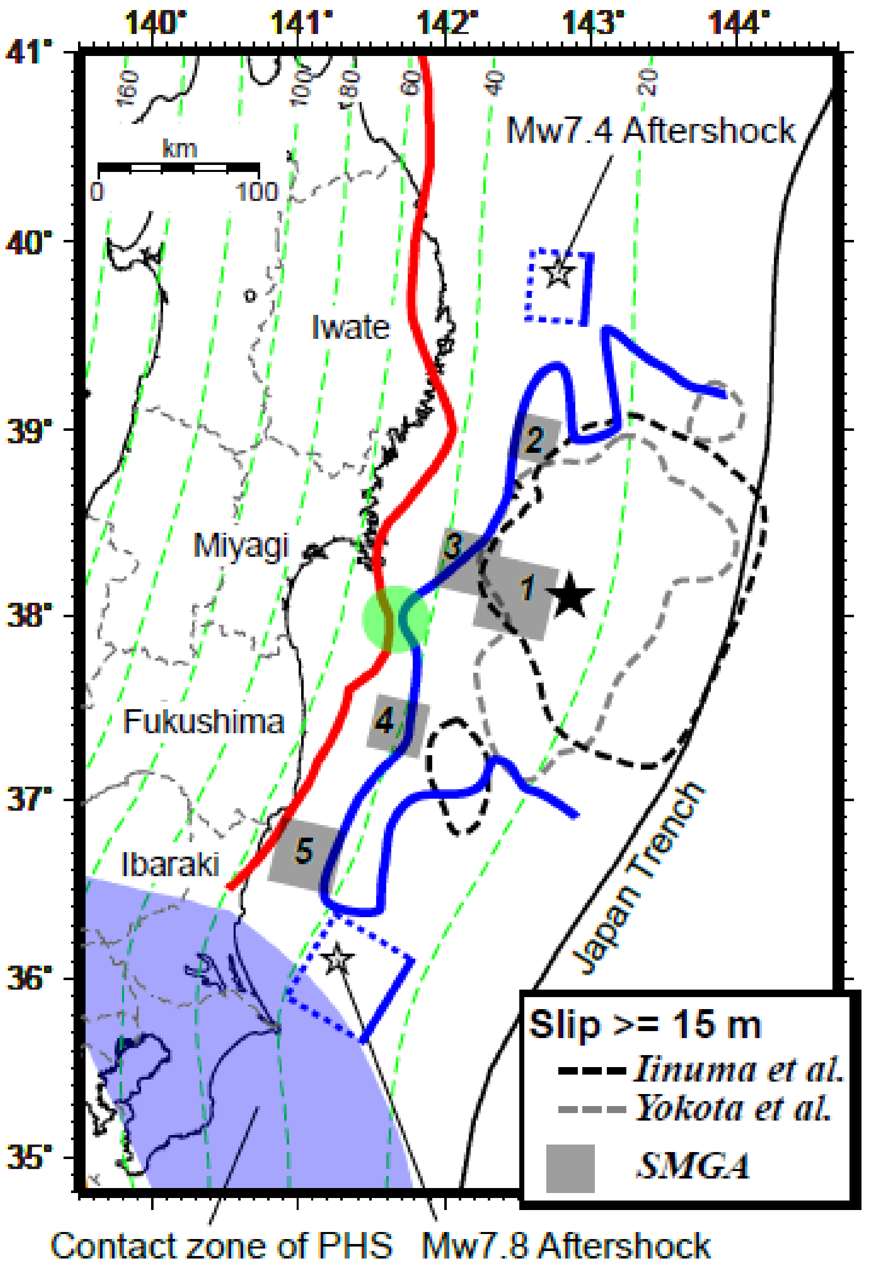


Third step: Heterogeneity model for long periods 10 – 100 s

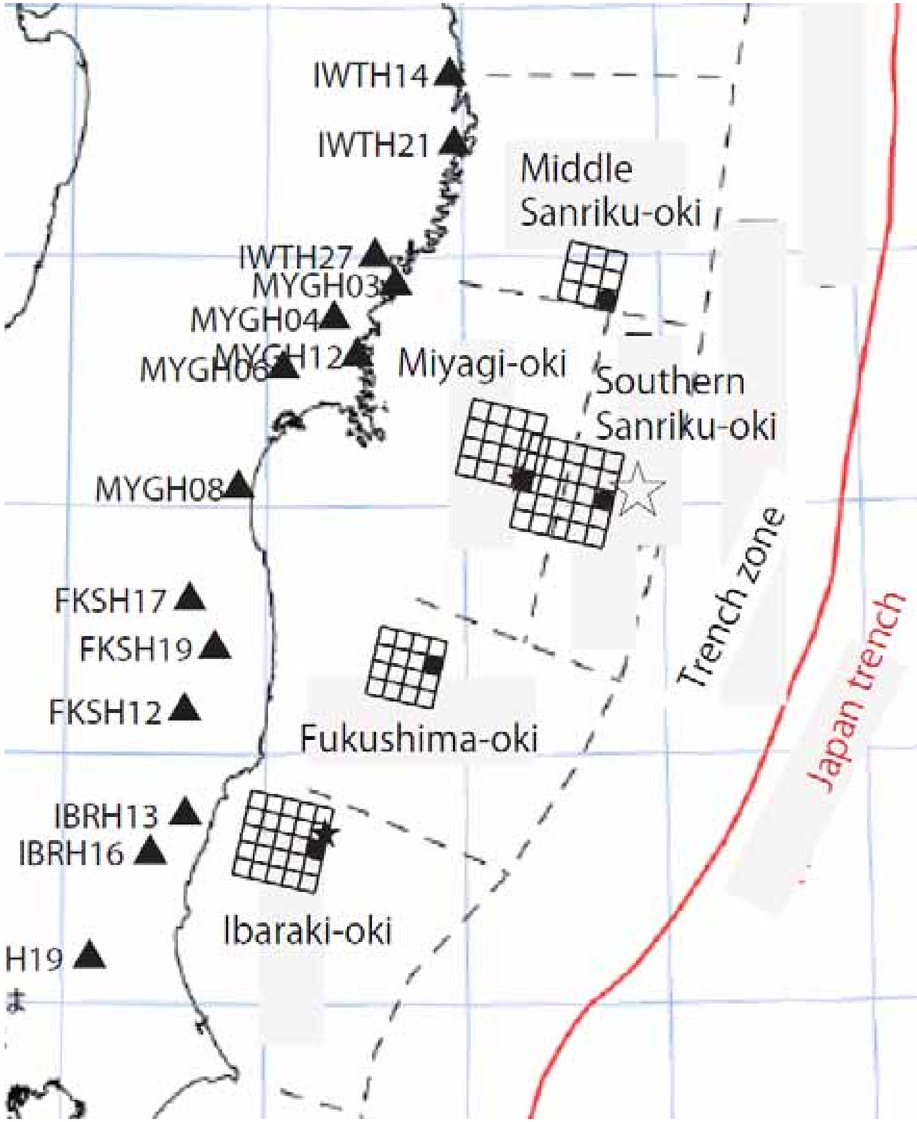
Suzuki et al. (2011)

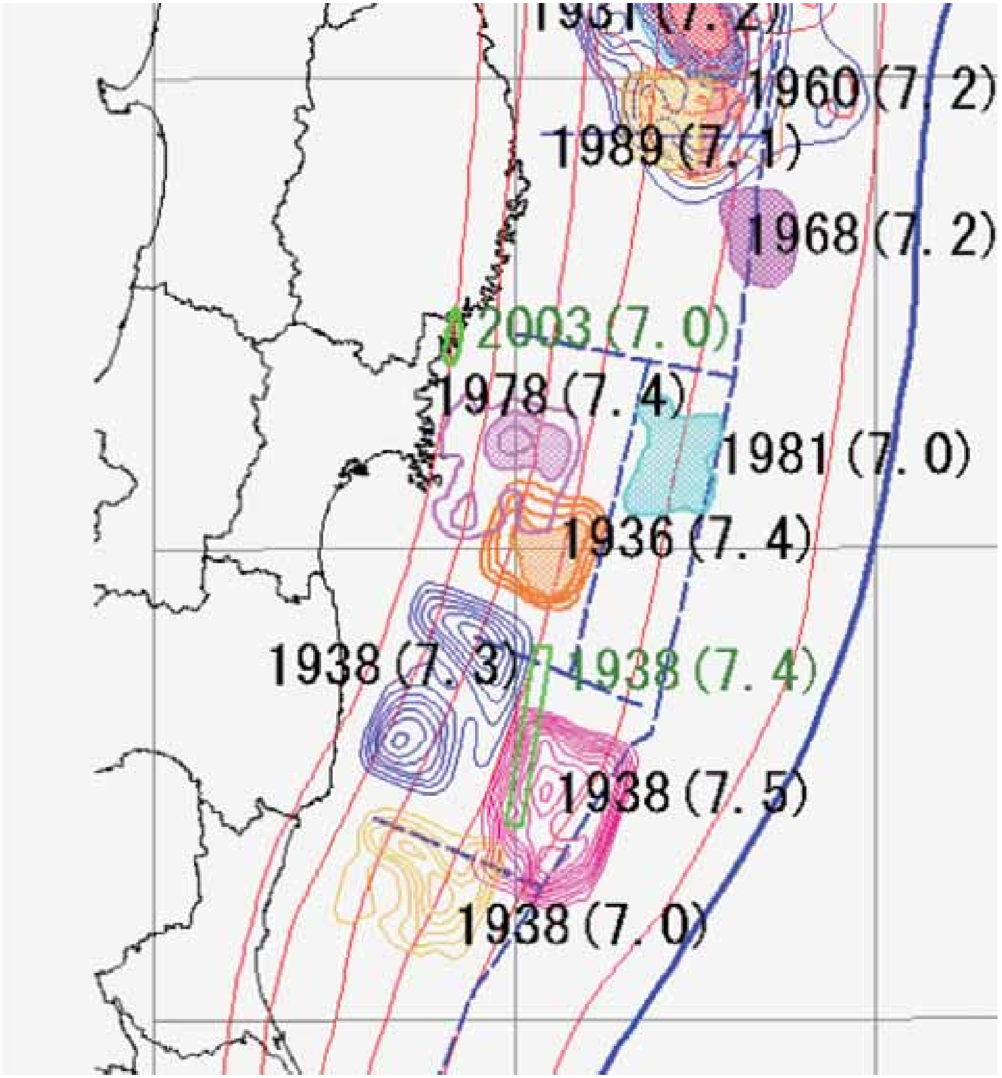
Heterogeneous Model for Broad-band Motions from 0.1 to 10 s

The SMGAs are located along outer edge of the large slip delineated based on the seismicity rate (Kato and Igarashi, 2012)



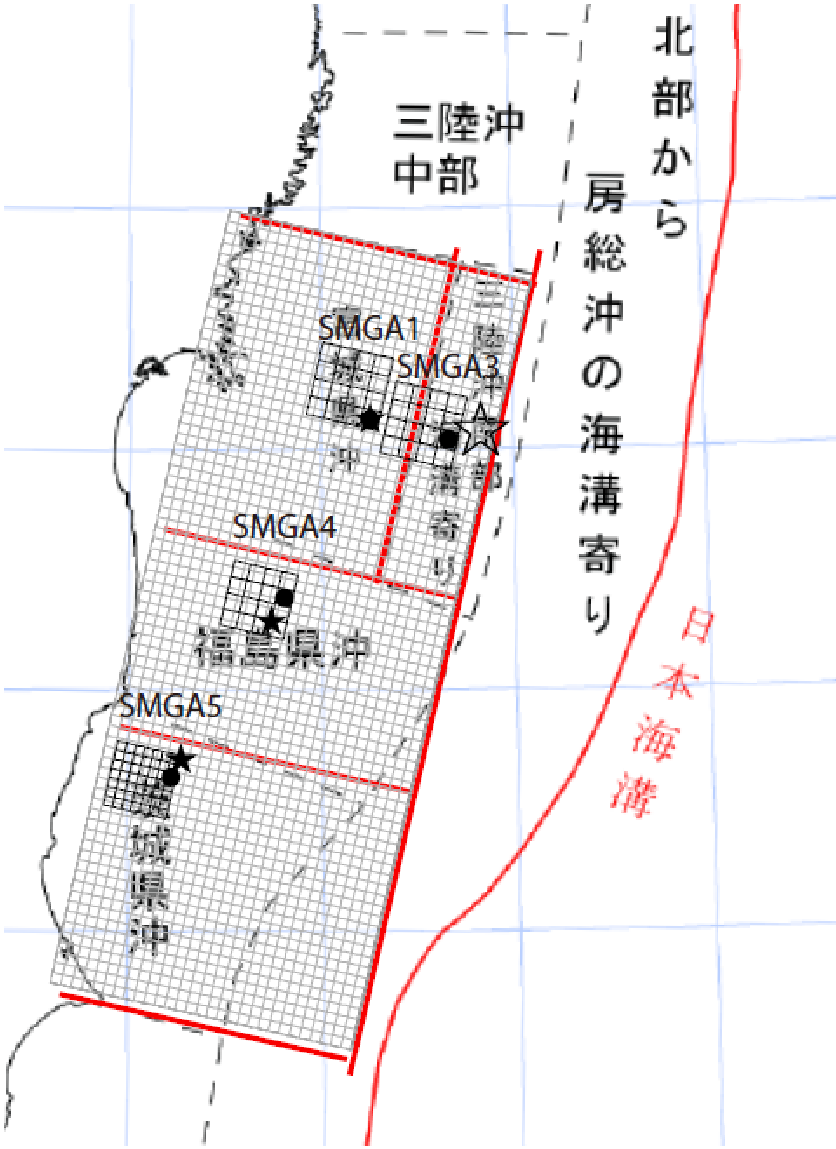
Comparison between SMGAs in this study and source locations of past earthquakes off the Pacific coast of Tohoku



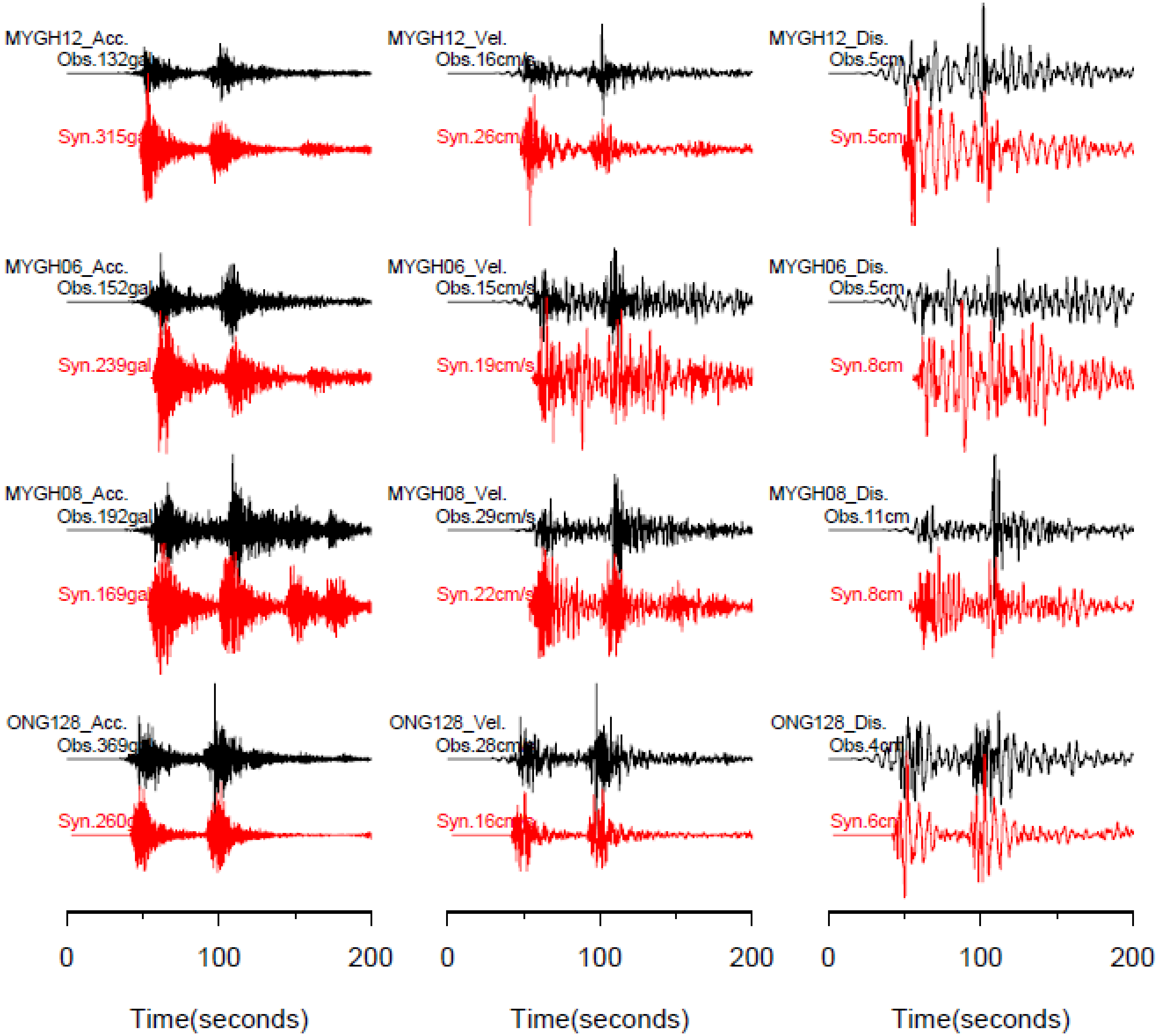


Basic Characterized Source Model

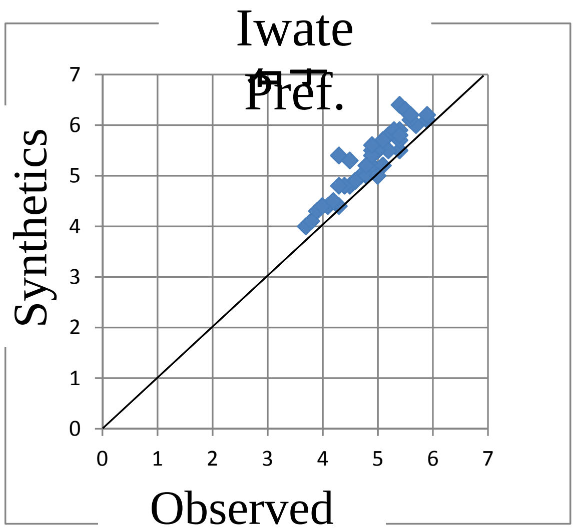
Step 1: Heterogeneous Model for Broad-band Motions from 0.1 to 10 sec

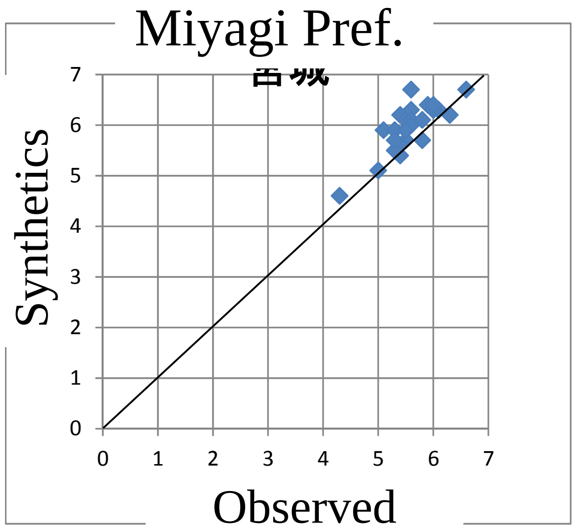


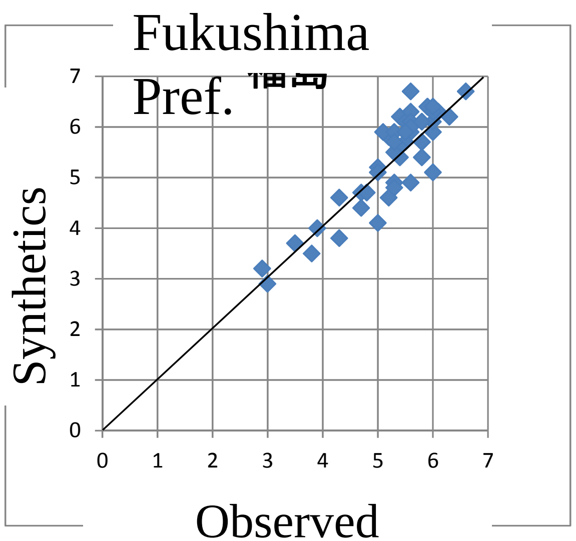
Comparison between observed and synthetic waveforms in the region near the source fault (Miyagi and Onagawa)

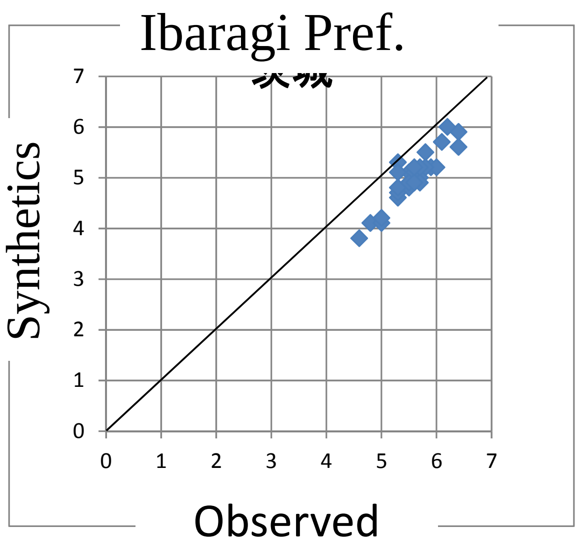


Comparison of Seismic Intensity between Observed and Synthetics









Summary 1

1. This earthquake on the plate boundary along the Japan trench produced a devastating tsunami and caused about 16,500 fatalities (including missing) and serious damage to nearby Fukushima nuclear power plants.

2. The size of the maximum earthquake based on the characteristic earthquake model was underestimated as M ~ 7.5, while the epicenter was near Miyagi-oki, where the probability of earthquake occurrence was evaluated as the highest (99 % in the next 30 years) in Japan.

3. From the forward modeling of the source model for simulating short-period ground motions such as acceleration and velocity seismograms, there are five SMGAs over the source fault located west of the hypocenter and along the down-dip edge of the source fault.

Summary 2

4. Synthetic motions from the SMGAs match well with observed motions in the period-range from 0.1 to 10 sec.

5. Period-dependence of rupture process was found, that is large slips in shallow zones of the source fault near the trench west of the hypocenter and short-period generation in deeper zones west of the hypocenter.

6. Strong ground motions of engineering interest in the period-range from 0.1 to 10 sec are estimated using the characteristic source model with outer-fault parameters and inner fault parameters as the recipe of predicting strong ground motions for subduction earthquakes.