One Year after 2011 Great East Japan Earthquake

-International Symposium on Engineering Lessons Learned from the Giant Earthquake-

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Strong Ground Motions during the 2011 Pacific Coast Off Tohoku, Japan Earthquake

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Today’s Topics

1. Outline of National Hazard Map in Japan before the 11 March 2011 Mw 9.0 earthquake off the Pacific coast of Tohoku
2. Features of strong ground motions from the 2011 Pacific Coast Off Tohoku, Japan Earthquake
   - PGV and PGA attenuation-distance relation
   - Why were so large acceleration motions produced ?
3. Source model for generating strong ground motions
4. Summary
   Improvement of the recipe of predicting strong ground motions for mega-thrust earthquakes

Outline of National Hazard Map in Japan before the 2011 Pacific coast off Tohoku, Japan earthquake

- Long-term evaluation of earthquake occurrence (2003) and seismic hazard map (2010)
- Revision of long-term evaluation of earthquake occurrence in region from off-Sanriku to off-Boso by the Earthquake Research Committee (November, 2011)

Programs defining the Seismic Hazard in Japan

1. Headquarters for Earthquake Research Promotion

Long-term Evaluation:

Evaluate probabilities of the next occurrence of large earthquakes for major active faults and subduction-zones along troughs.

Strong Ground Motion Evaluation

Construct seismic hazard maps, probabilistic and deterministic.

Probabilistic hazard map: predicted likelihood of ground motion level occurring in a given area within a set period of time.

Shaking map for scenario earthquakes: strong ground motion from hypothetical source models for specified active faults

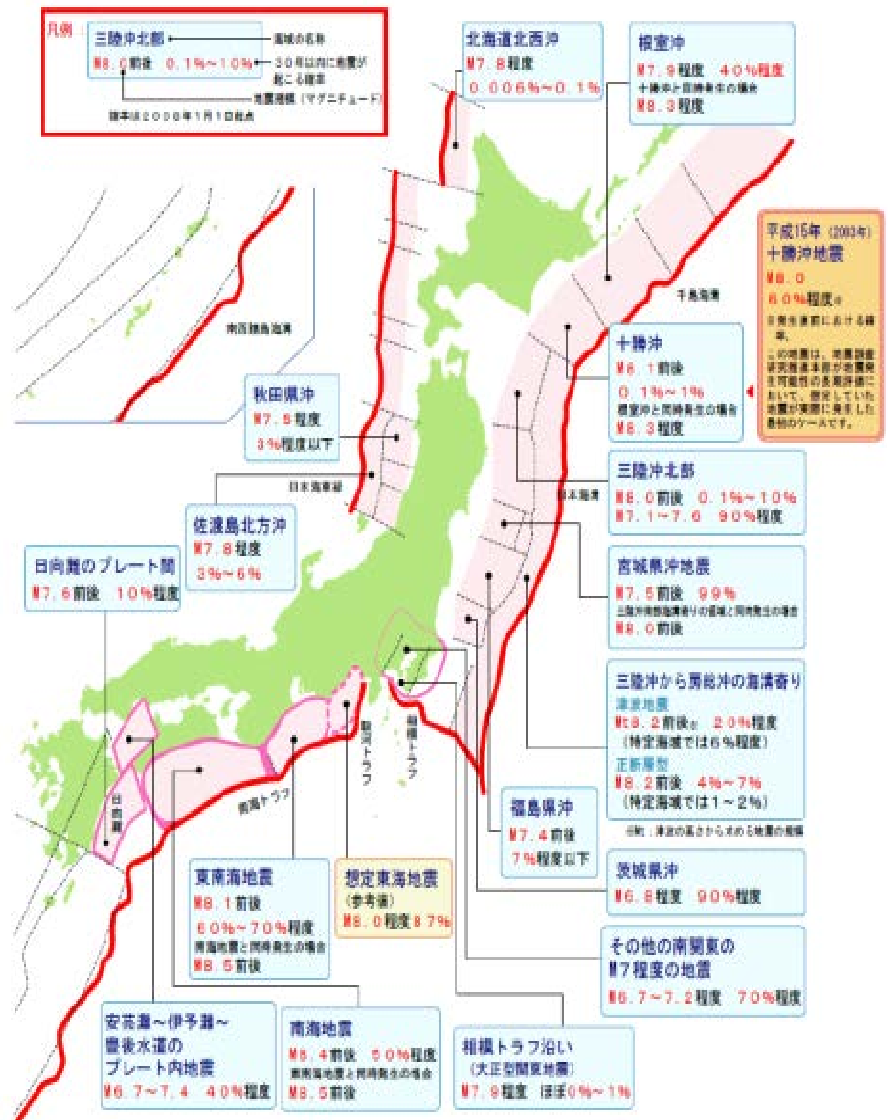
2. Central Disaster Management Council

Conduct damage assessments from specific disastrous earthquakes estimating the extents and sizes of the disasters and their impact on individuals and public facilities

Probability of Earthquake Occurrence in 30 years

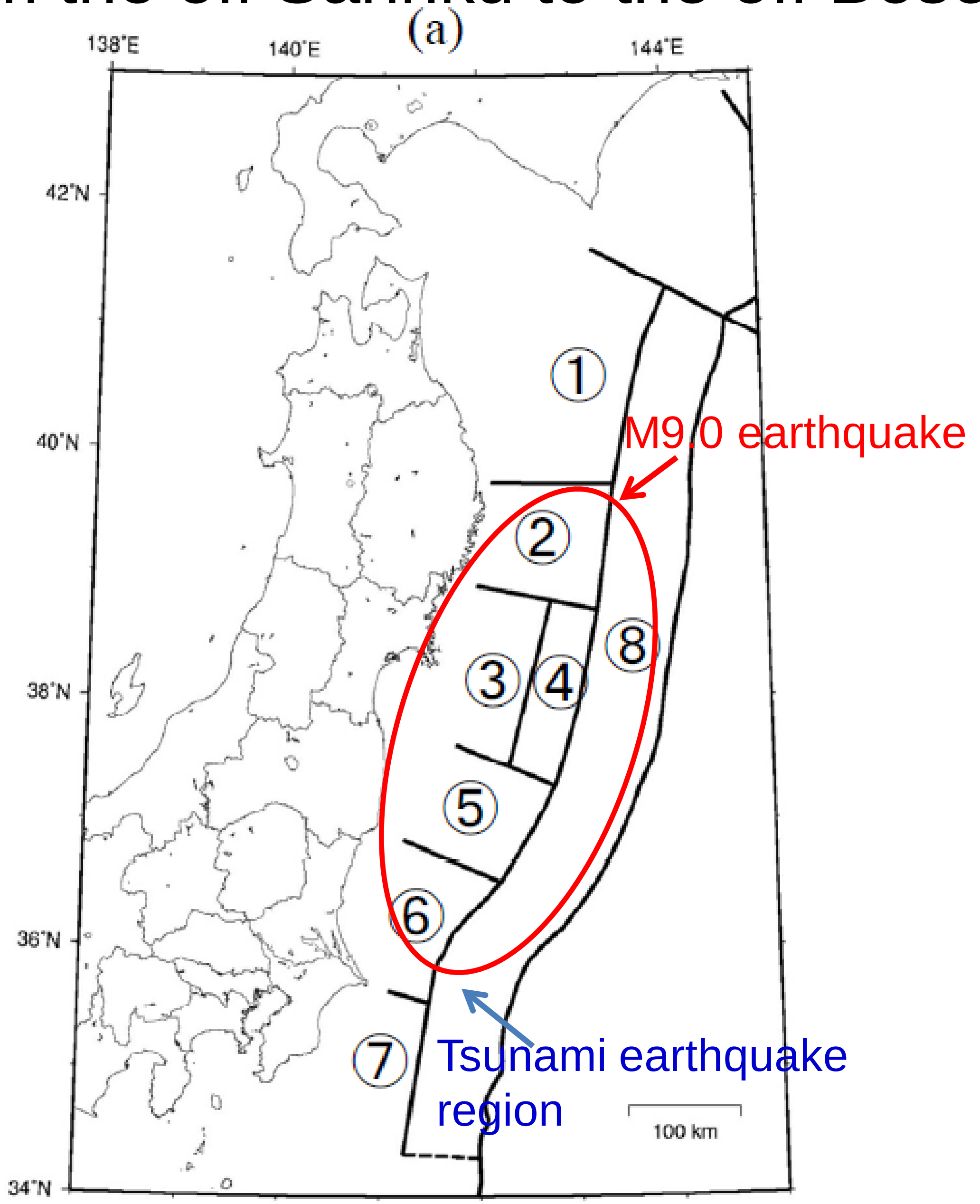
Inland Crustal-Earthquakes

Subduction Earthquakes



Headquarter of Earthquake Research Promotion (2010)

Long-term evaluation of seismic activity for the region from the off Sanriku to the off Boso



Long-term evaluation of seismic activity for the region from the off Sanriku to the off Boso

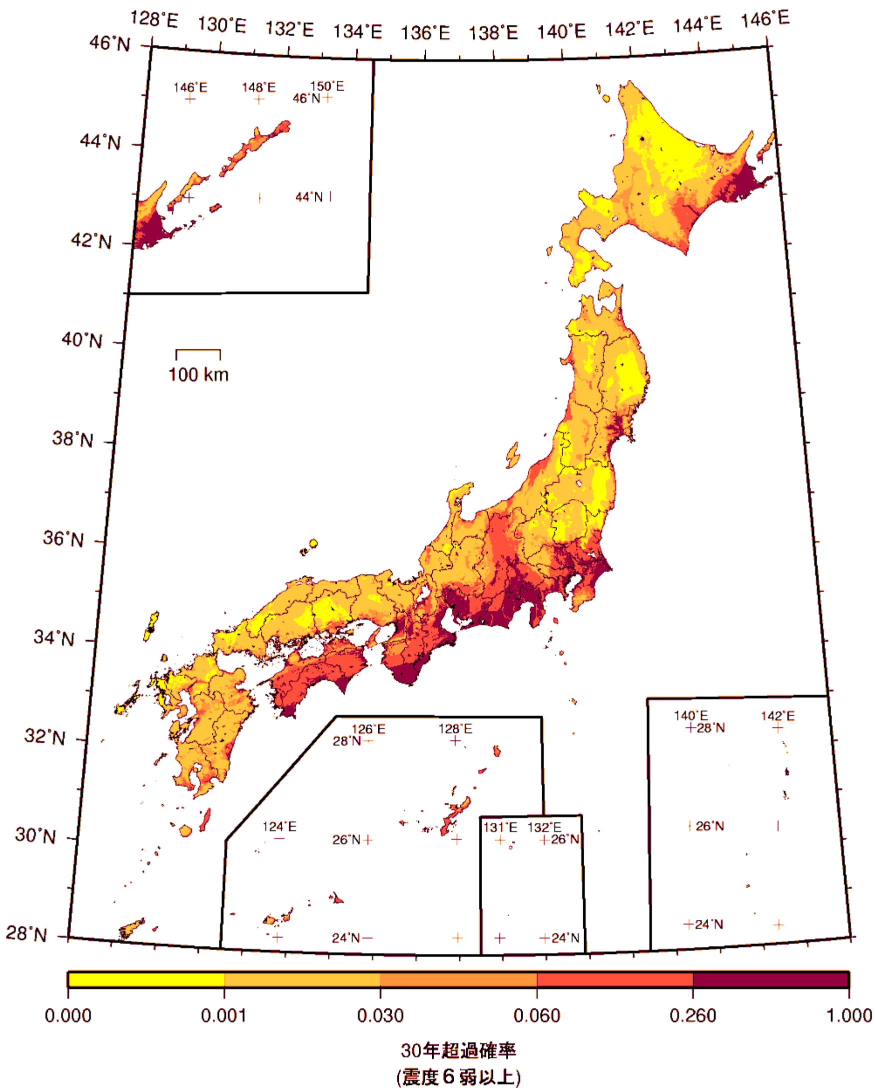
Earthquake	Magnitude	Occur. prob. within 30 years
Characteristic earthquake in ①	Approx. M8.0	0.2%～10%
Interplate earthquakes other than characteristic earthquake in ①	M7.1～M7.6	About 90%
Earthquakes in ②	Unknown	Unknown
Miyagi-oki earthquake in ③	Approx. M7.5	99%
Sanriku-nanbu earthquake in ④	Approx. M7.7 (M8.0 for correlated with Miyagi-ken-oki earthquake)	80%～90%
Interplate earthquakes in ⑤	Approx. M7.4 (Successive occurrence of multiple earthquakes)	About 7% or less
Interplate earthquakes in ⑥	M6.7～M7.2	About 90% or more
Earthquakes in ⑦	Unknown	Unknown
Tsunami bearthquake in ⑧	Approx. Mt8.2	About 20%
Intraplate earthquakes (normal fault type) in ⑧	Approx. M8.2	4%～7%

Rupture of Mw 9.0 started from this region.

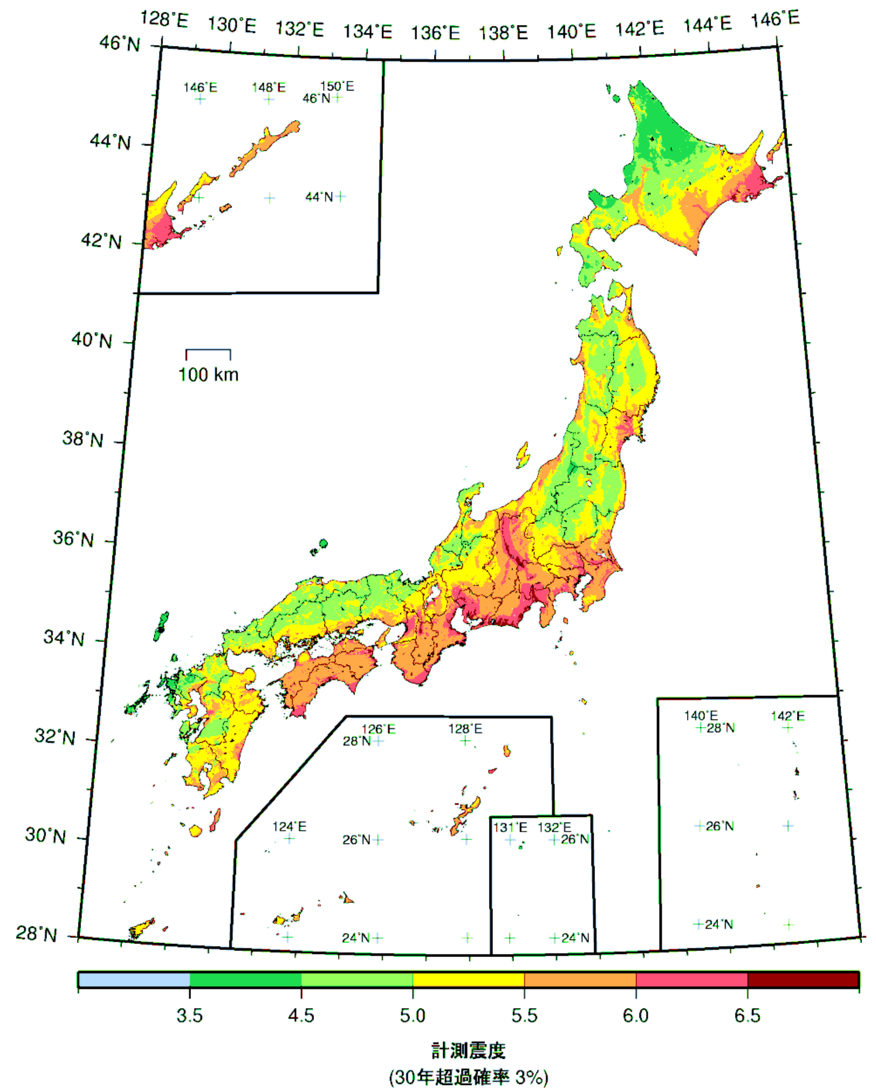
Large Tsunami was genarated

Earthquake Research Committee (2002)

Examples of Probabilistic Seismic Hazard Map



Probability of exceedance for more than seismic intensity 6- in 30 years



Seismic intensity map for 3 % probability of exceedence in 30 years

Revision of Probability of Earthquake Occurrence in the Region from the off Sanriku to the off Boso

Probability of earthquake occurrence of earthquakes such as the 11 March 2011 Tohoku earthquake just before the occurrence of the earthquake							
Name of past earthquakes and seismic magnitude		Probability of earthquake occurrence			Cumulative Probability*	Passage rate	Upper: Average return period
		10 years	30 years	50 years			Lower: Latest occurrence
Off Pacific Coast of Tohoku earthquake	9.0	4 – 6 %	10 – 20 %	20 – 30 %	30- 60 %	0.83 – 1.0	600 years
							about 500 – 600 years ago

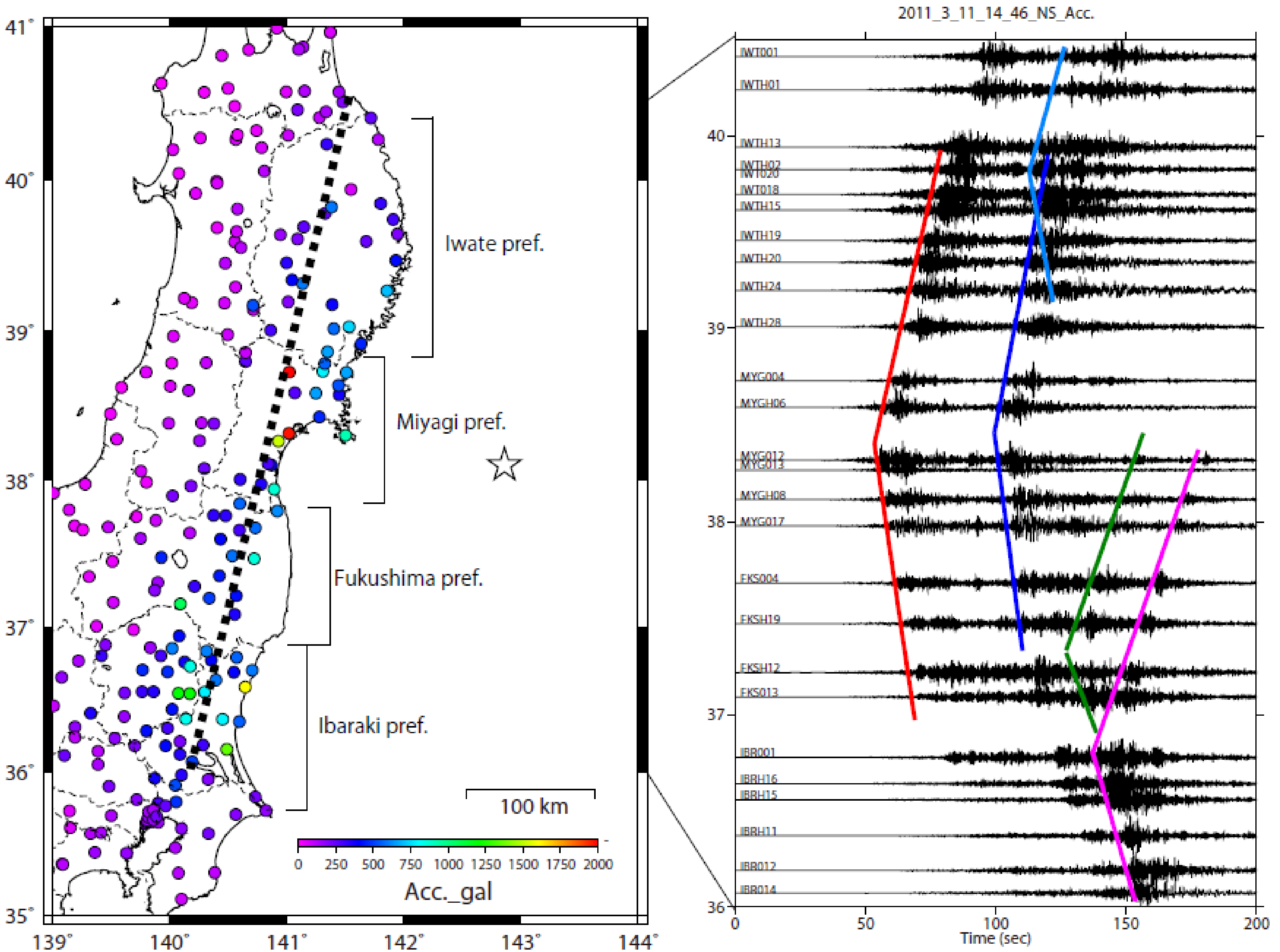
※Cumulative probability is defined as probability by that time.

Earthquake Research Committee (November, 2011)

Strong ground motions from the 2011 Pacific Coast Off Tohoku, Japan Earthquake

- Strong ground motions observed along the coast line near the source fault have several distinctive pulses.
- Attenuation-distance relations of PGA and PGV.
- Very little damage caused by ground motions, although accelerations at some sites near the source area were very high.

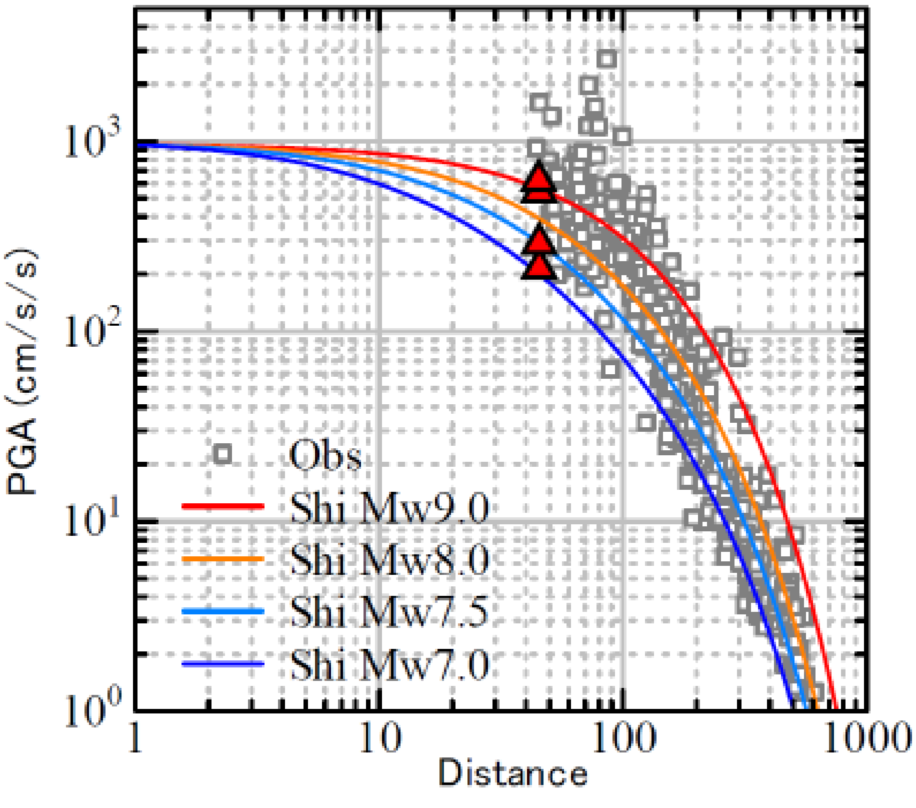
Record Section of Short-Period Motions



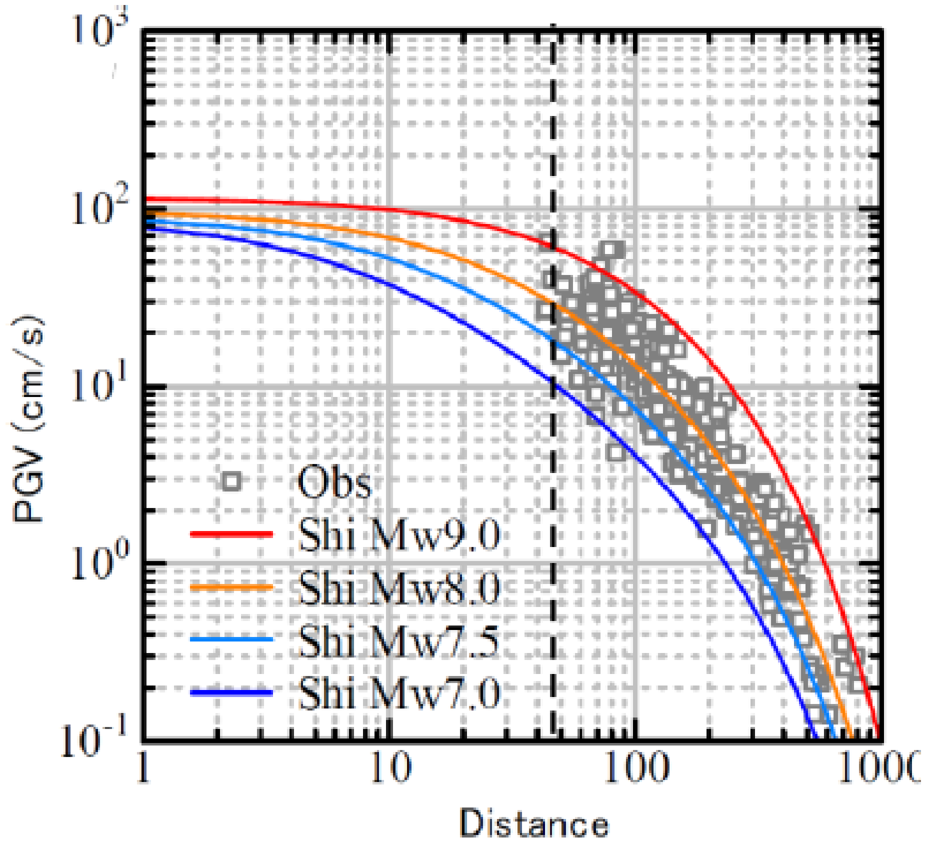
After Irikura and Kurahashi (2011)

Comparison of Observed Data and Attenuation Relationships of PGA and PGV

PGA



PGV



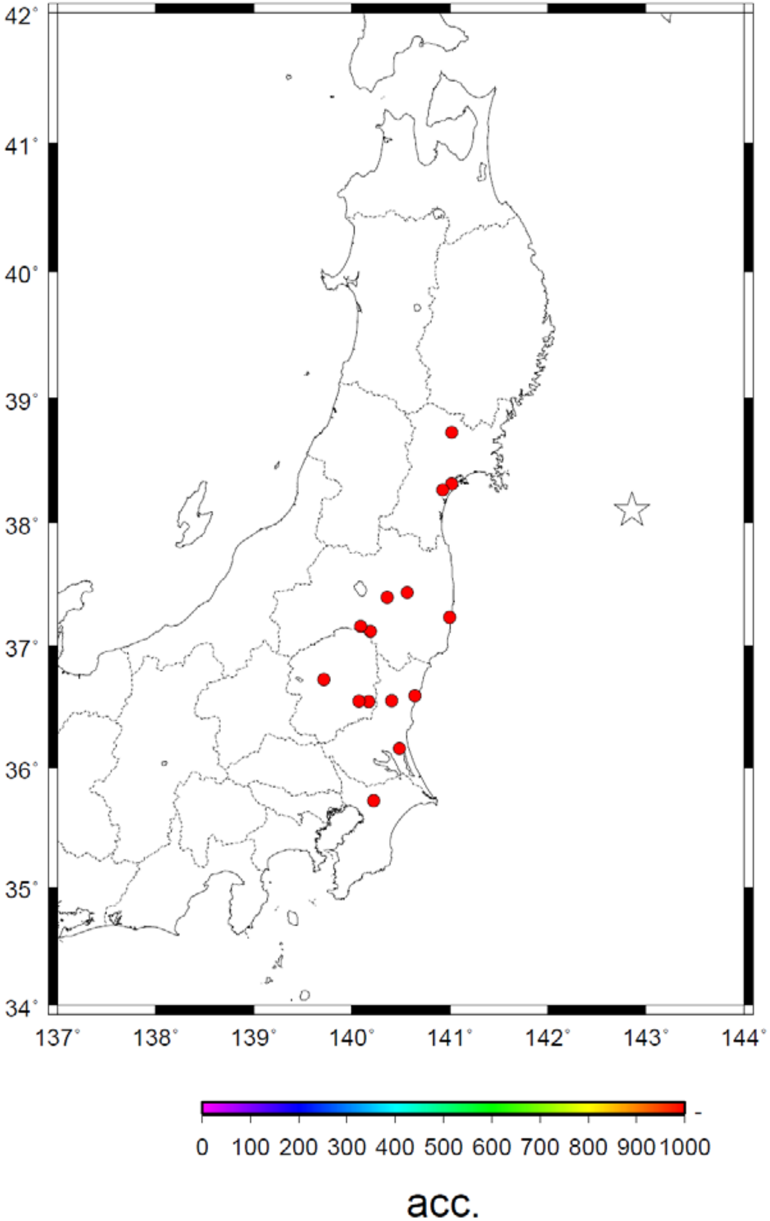
Features of Ground Motions Records with Extremely High Acceleration

- Two Causes of Extremely High Acceleration

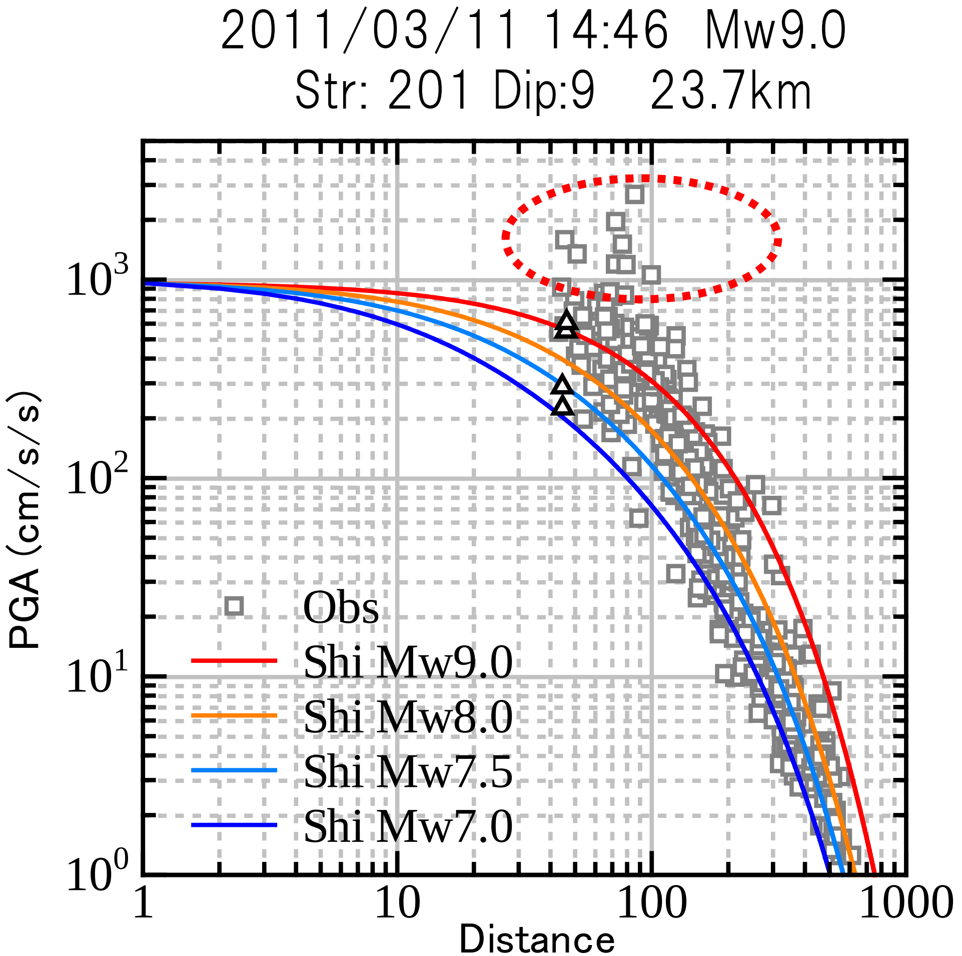
1) Ground Motions Records with more than 1000 gals remarkably deviated from attenuation-distance curves.
   Extremely high acceleration motions amplified by local surface geology, non-linear site effects.

2) Ground Motion Records with relatively high acceleration almost following attenuation-distance curves.
   Distinctive high acceleration pulses seem to propagate from station to station, attenuating with distance from fault distance.

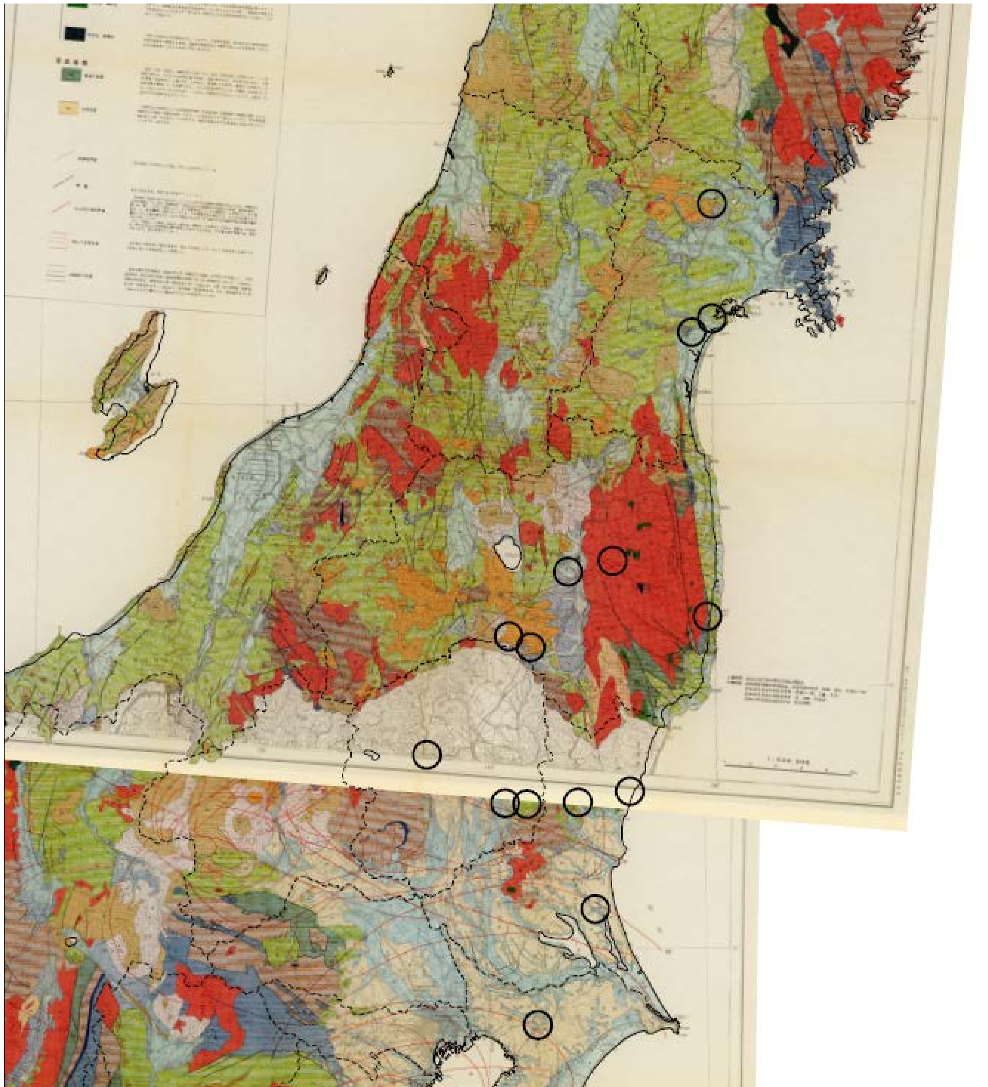
Stations where more than1000 gals were recorded.

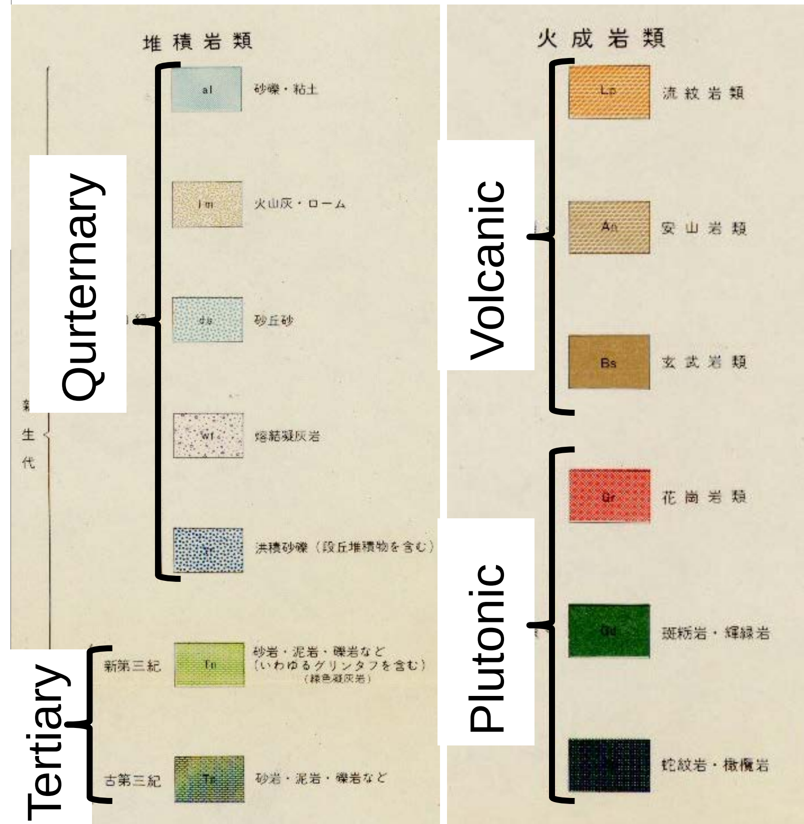


Some PGAs observed at sites near the source fault seem to be remarkably deviated from attenuation-distance curves.



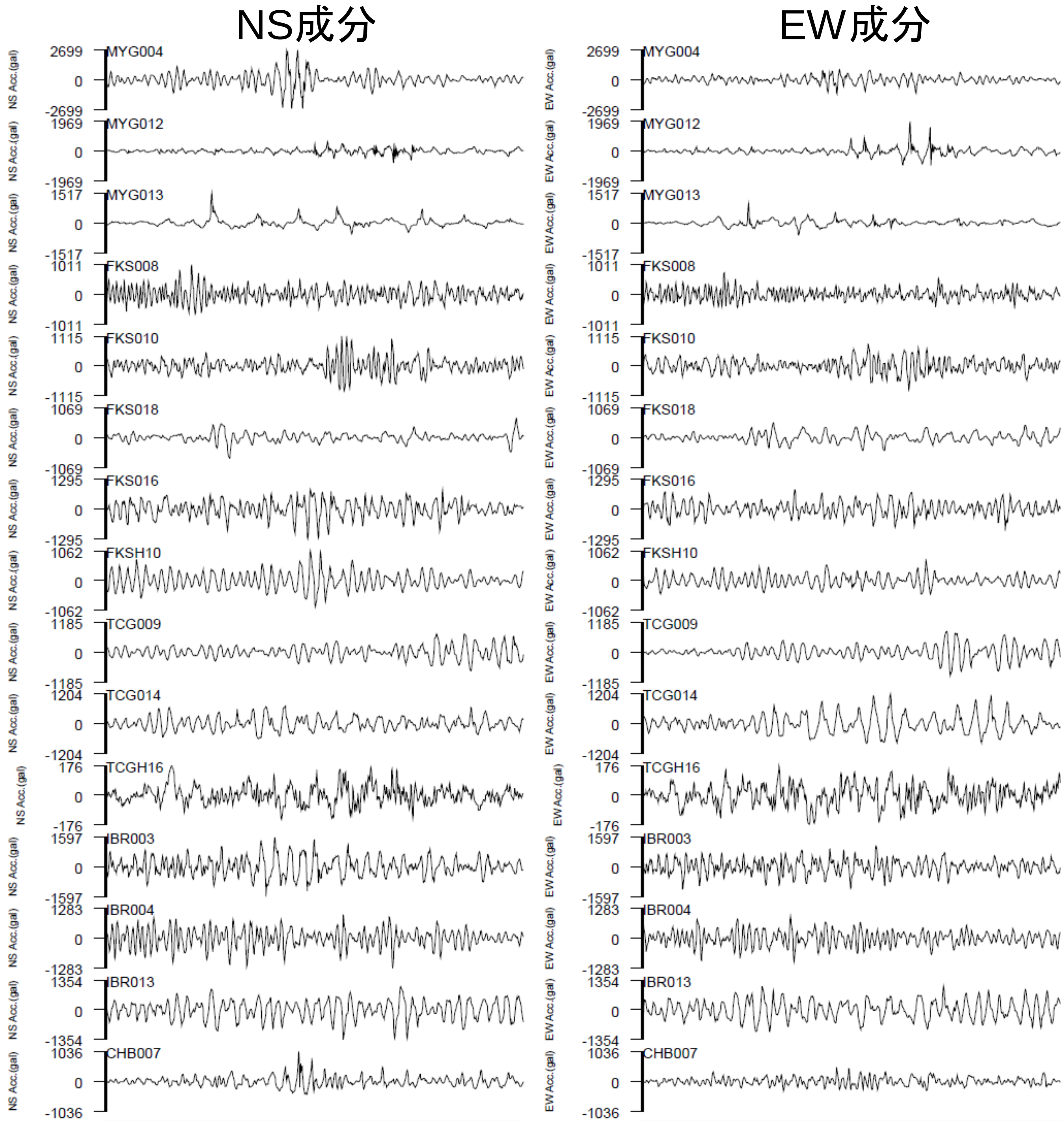
Surface Geology near Sites where more than1000gal were recorded.



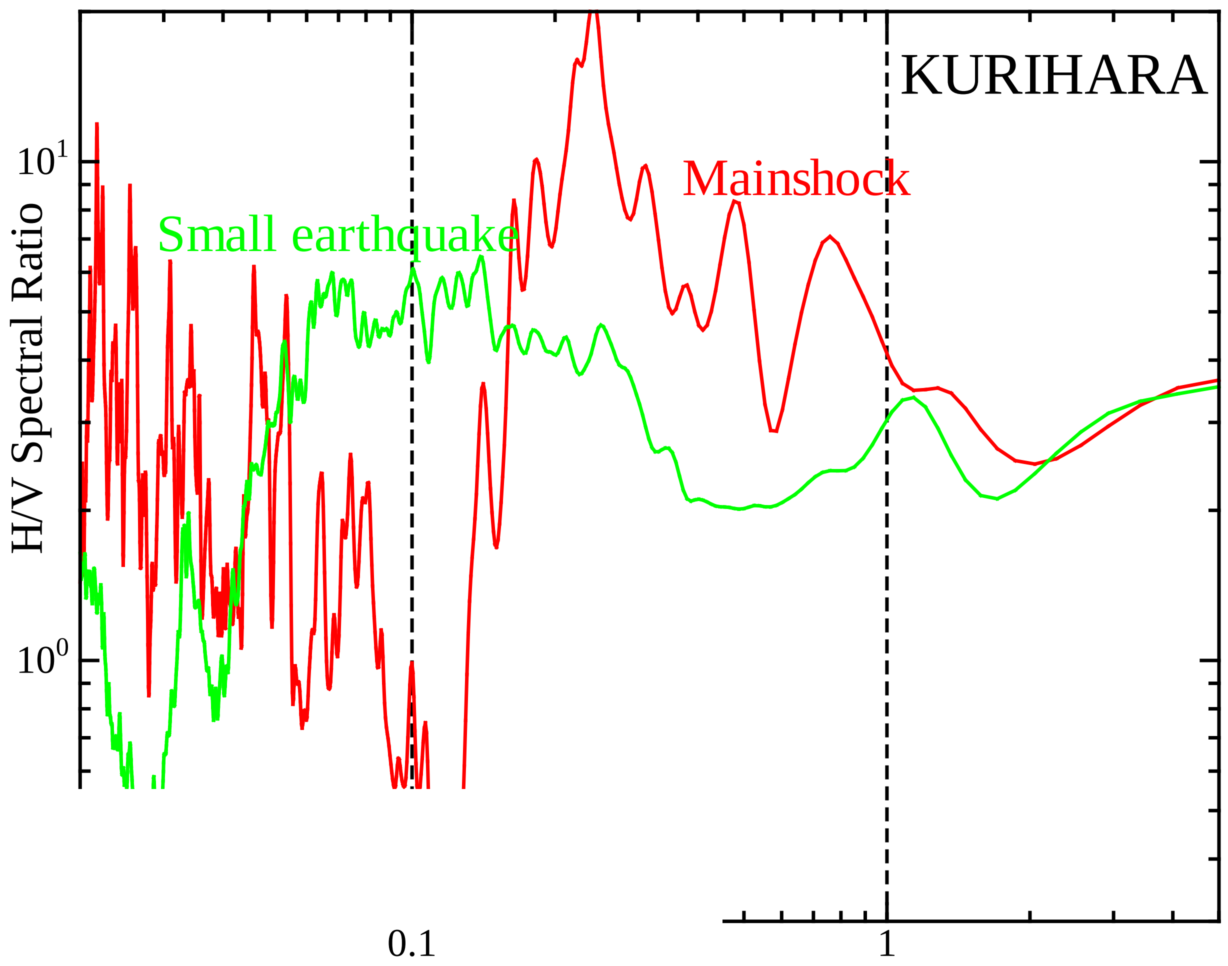


Accelerations more than 1000 gals were recorded at relatively soft soil sites.

Closeup of acceleration waveforms for ground motion records with more than 1000 gals

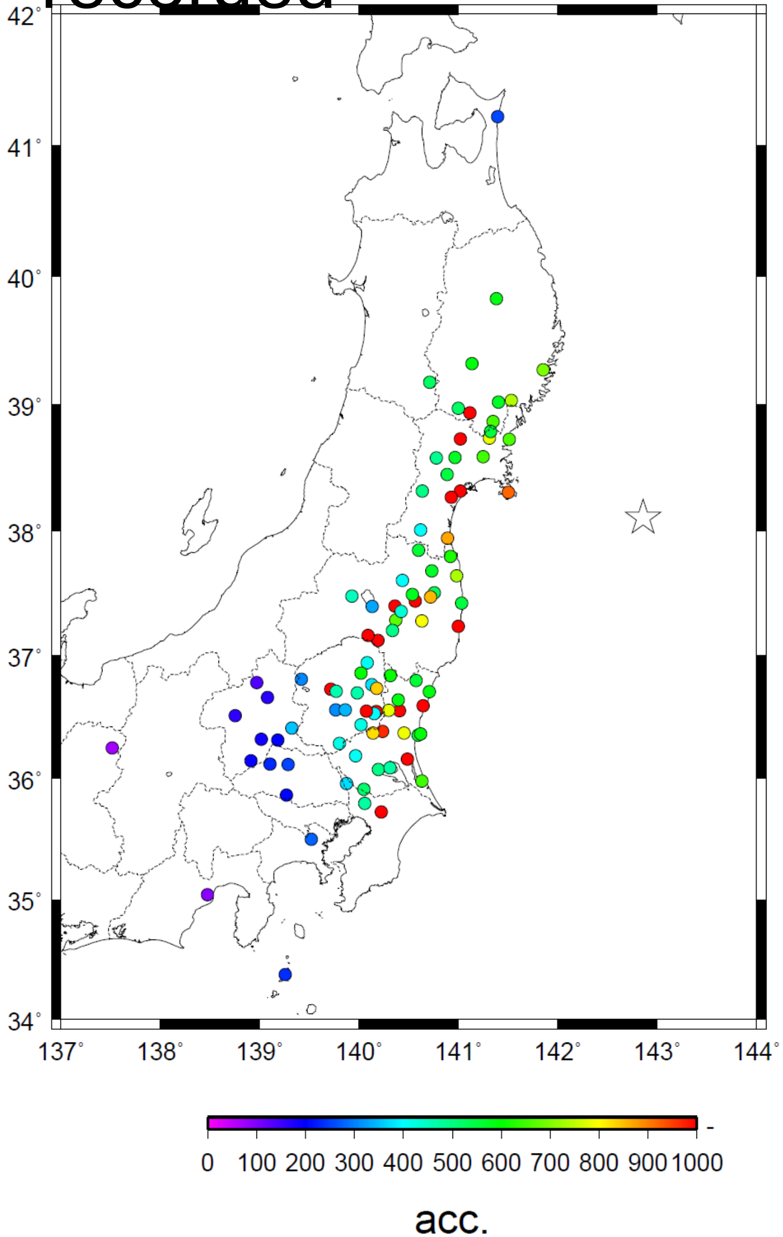


H/V spectral ratio of ground motions at Tsukidate (K-NET) between mainshock and small earthquakes

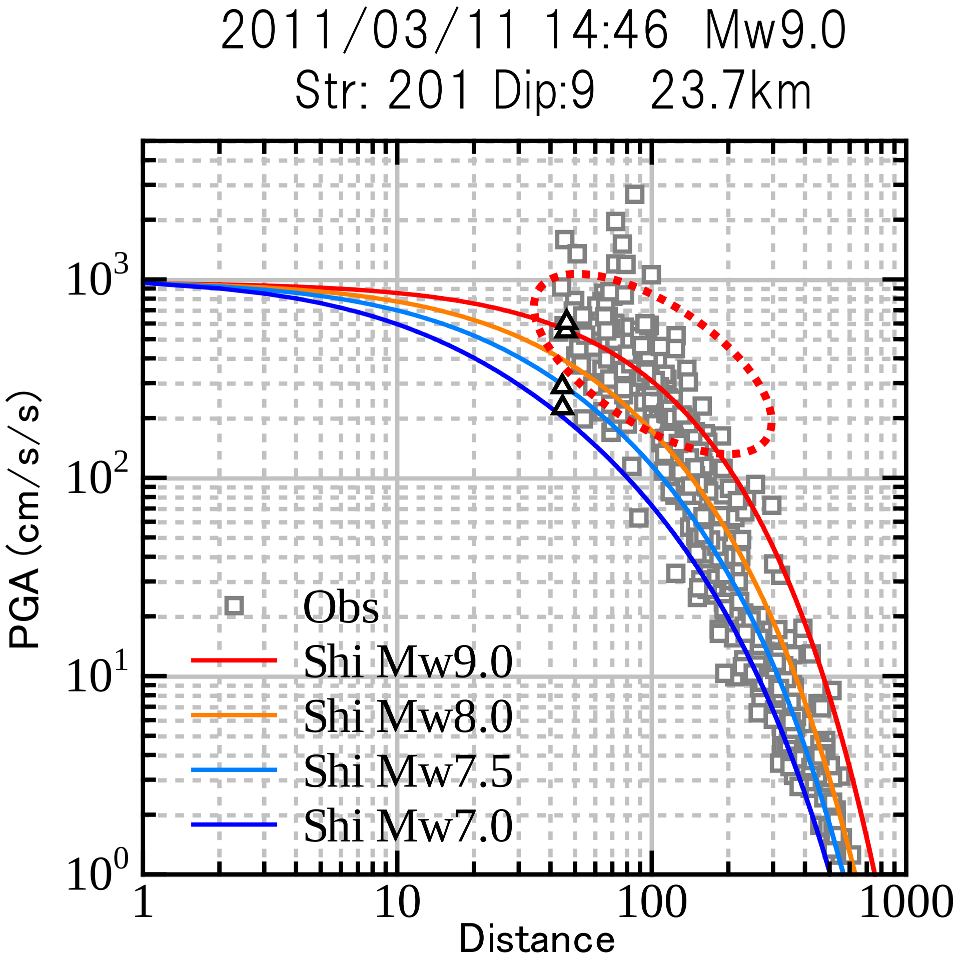


Tsukidate (**PGA**=2933gal, **DR**=21.4%)

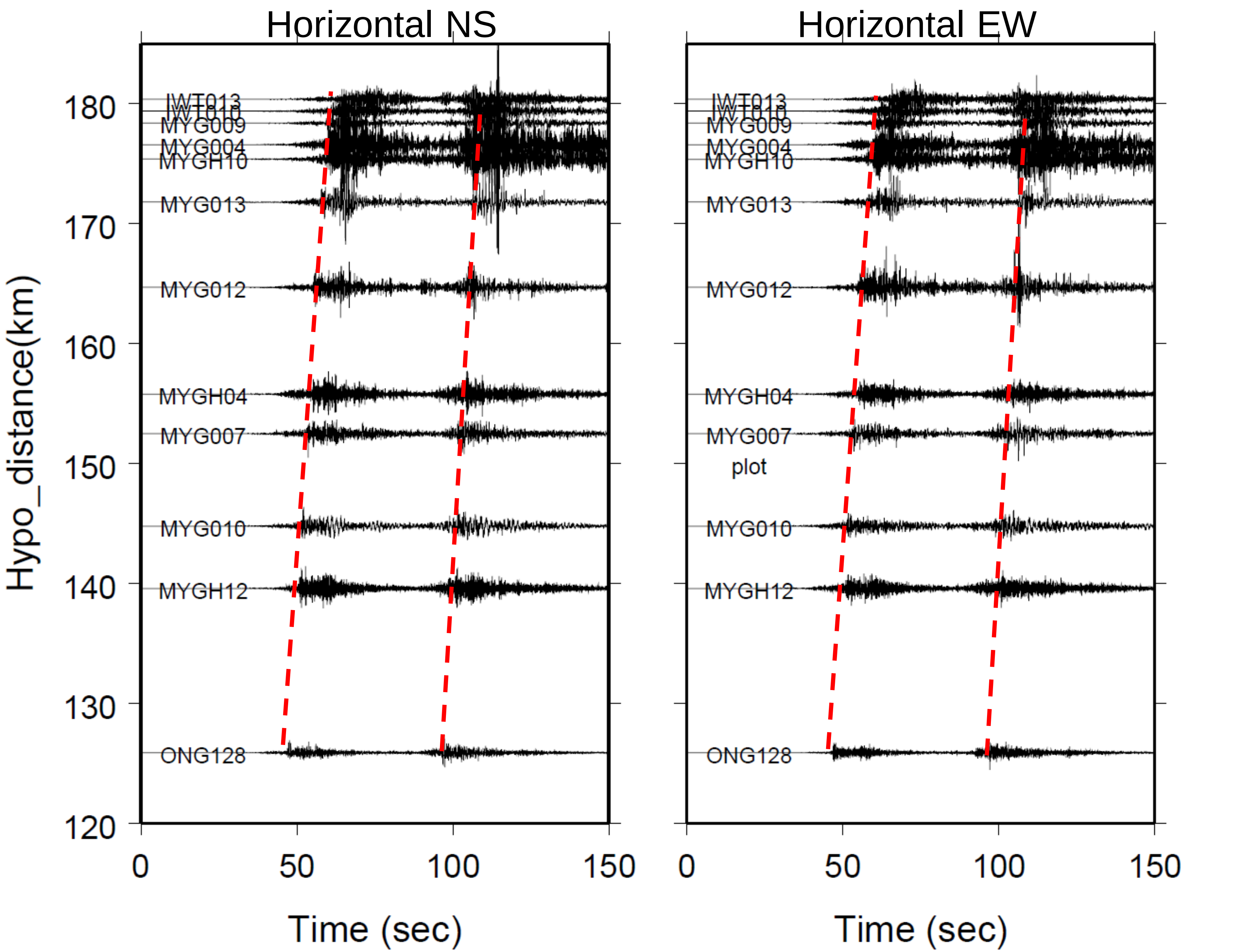
Stations where relatively high accelerations were recorded



Relatively high accelerations at stations near the source fault almost following attenuation-distance curves.



Acceleration Records with remarkable distictive pulses

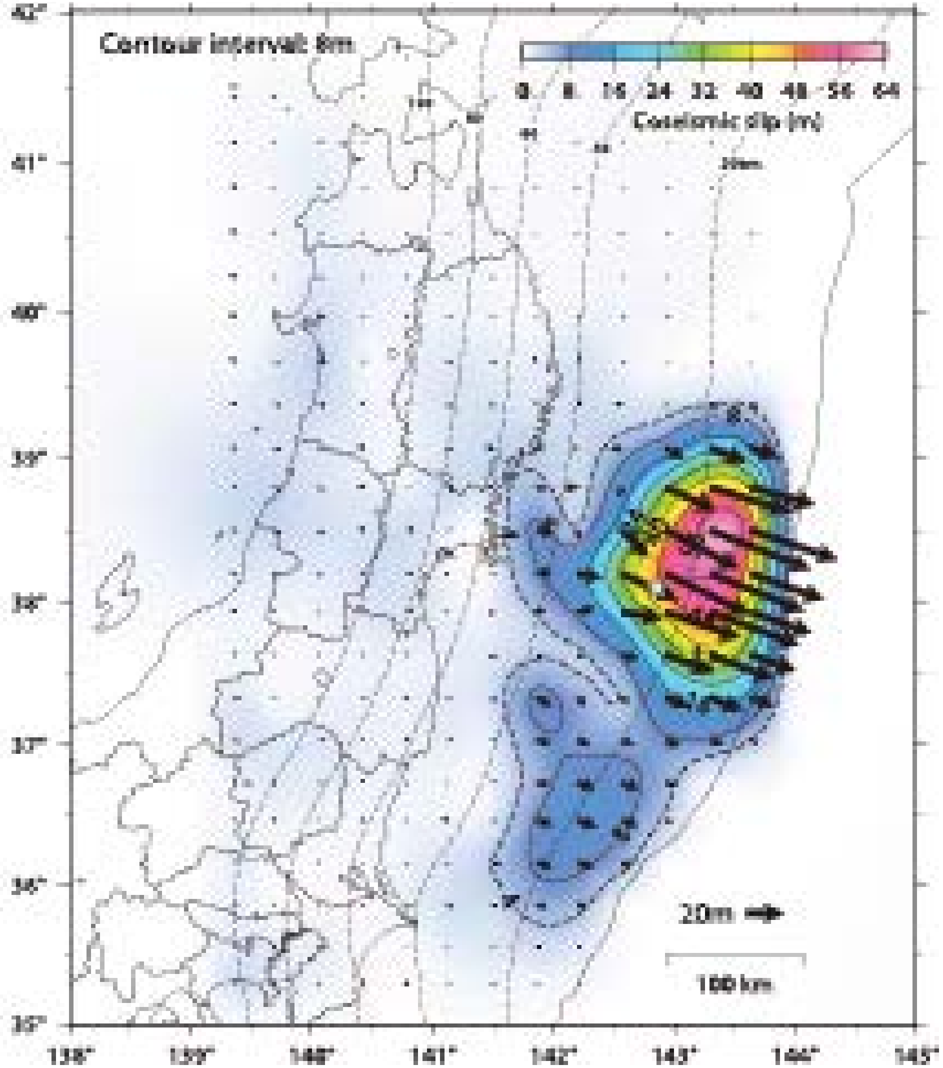


Source Model for Generating Strong Ground Motions during the 2011 Pacific Coast off Tohoku, Japan Earthquake

■ The short-period source model proposed by Kurahashi and Irikura (EPS, 2011) is revised based on re-estimation of locations of strong motion generation areas (SMGAs) using semblance analysis for estimating azimuths of seismic waves from the SMGAs.

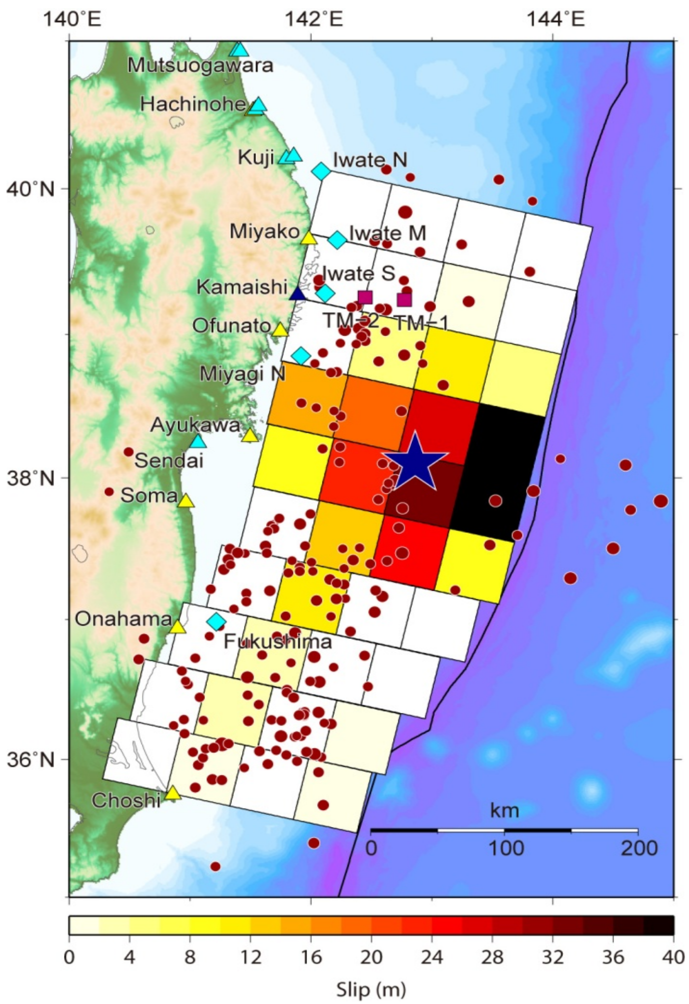
Slip Distribution of the 2011 Tohoku Earthquake

DPS data including inland and off-shore observation



Geographical Institute (2011)

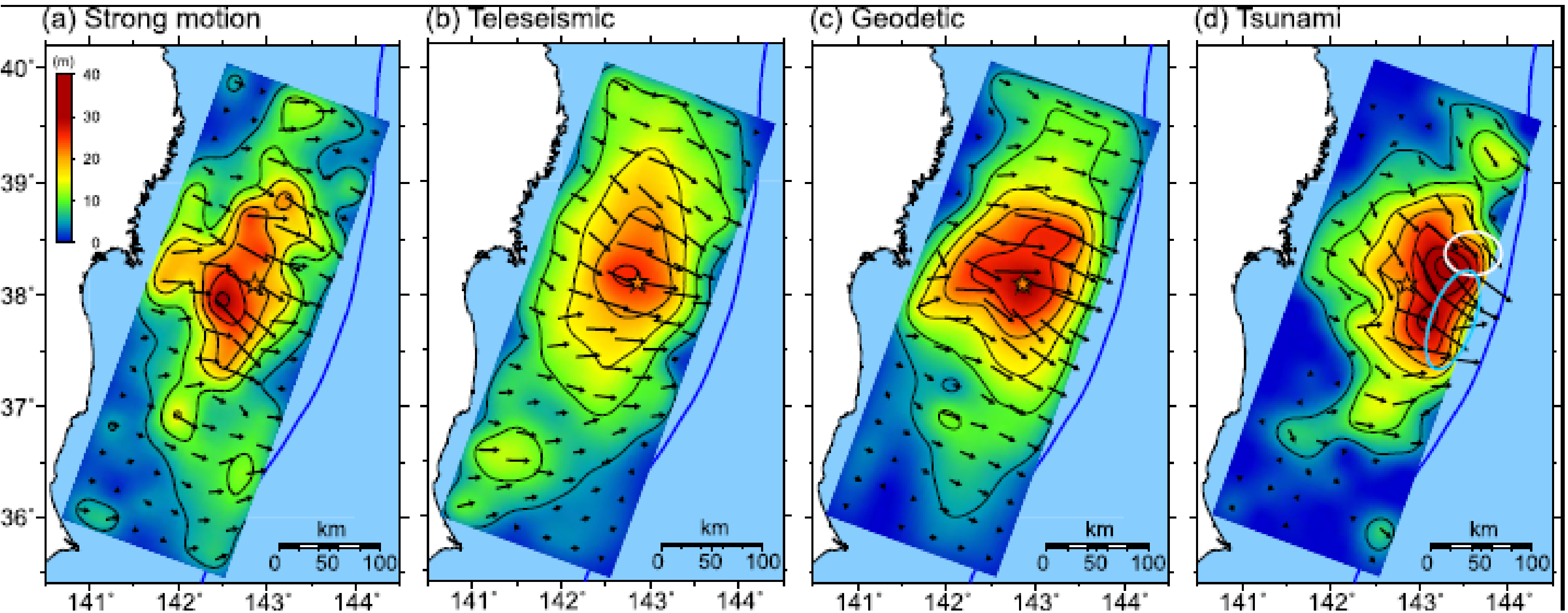
Tsunami Waveform Data



Fujii and Satake (2011)

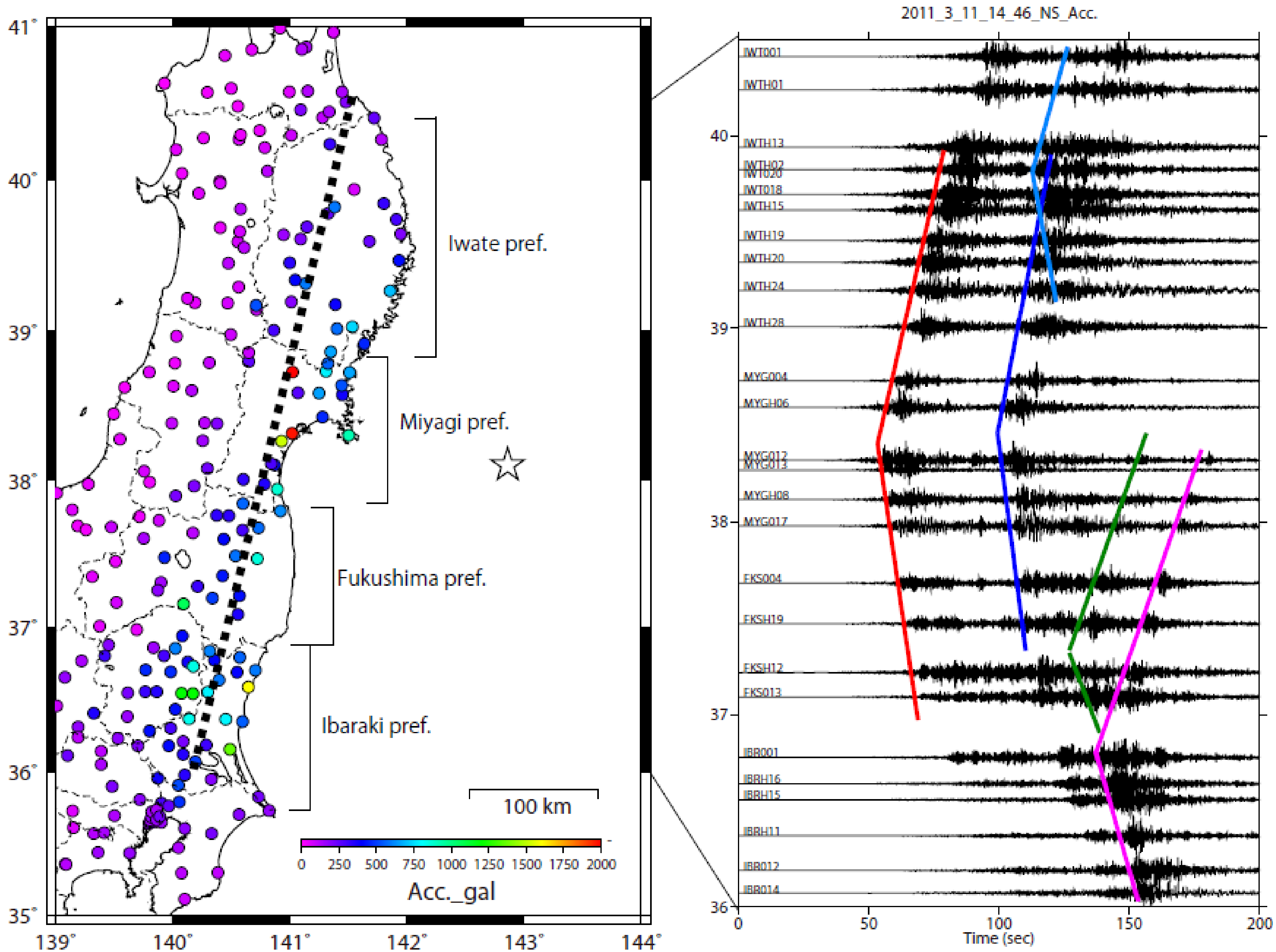
Source Model of the 11 March 2011 off Tohoku, Japan Earthquake

Slip Distributions by the separate inversions of (a) strong motion, (b) teleseismic, (c) geodetic, (d) tsunami datasets.



Yokota et al. (GRL 2011)

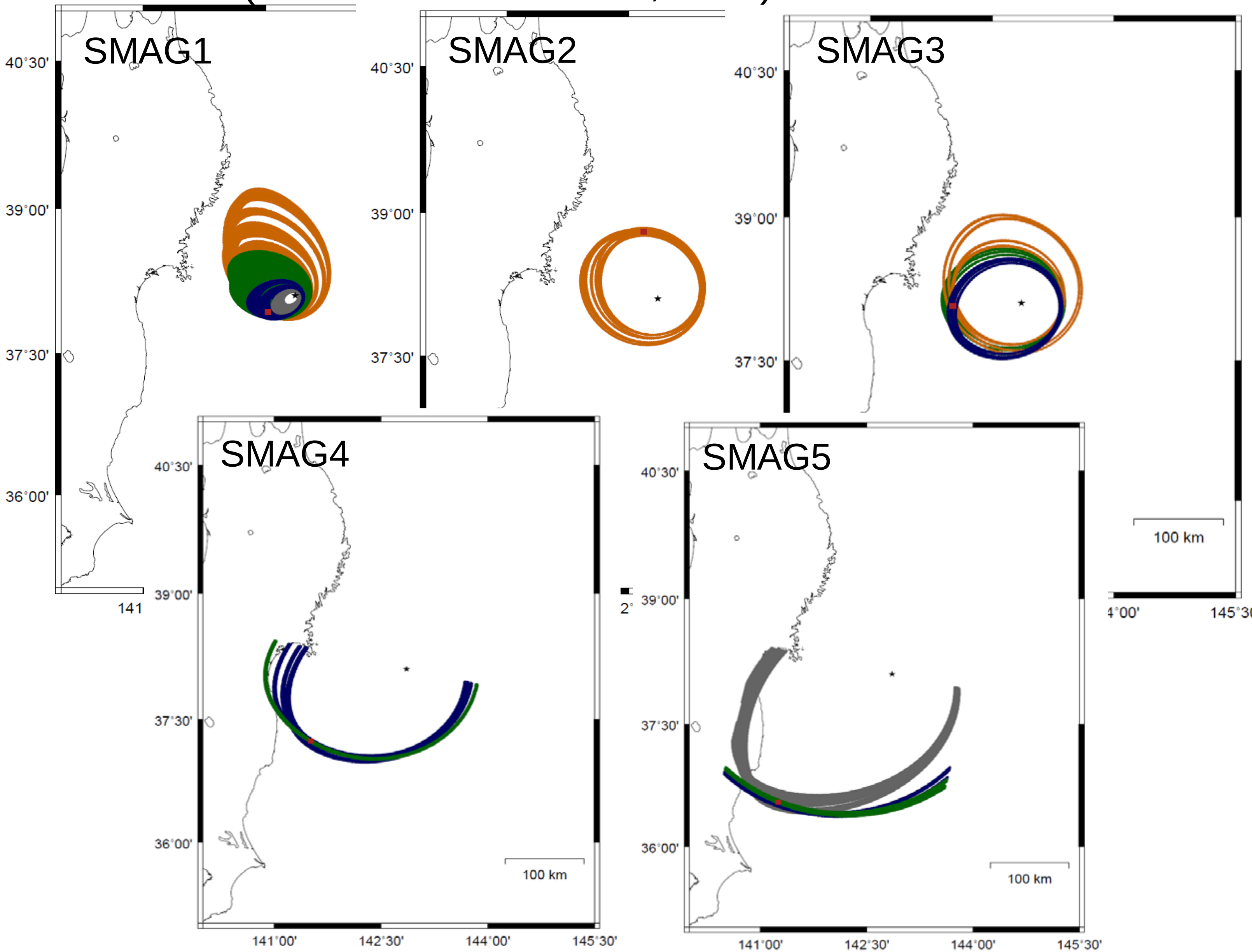
Record Section of Short-Period Motions



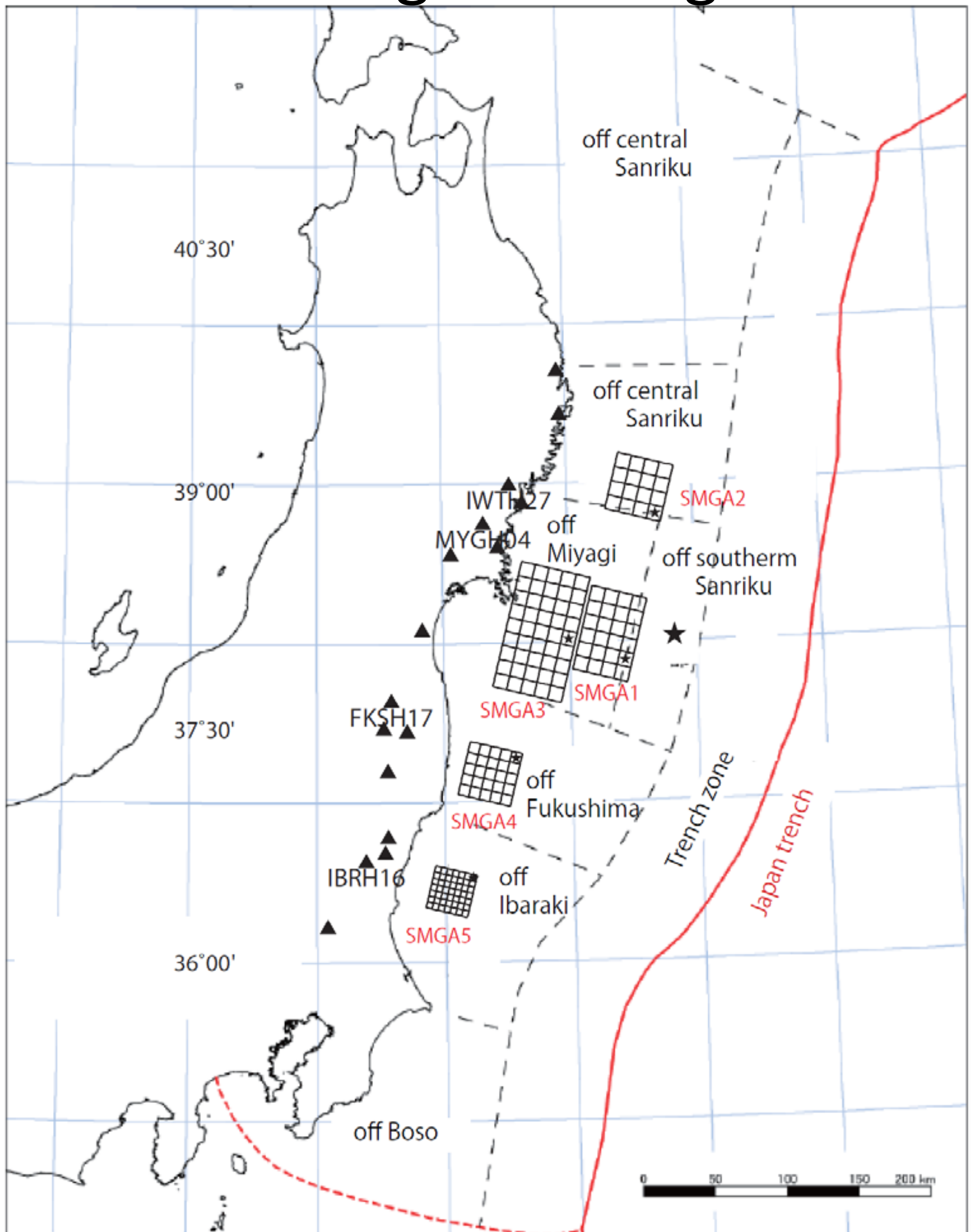
After Irikura and Kurahashi (2011)

Starting Points of SMGAs Estimated by Back-propagation Method

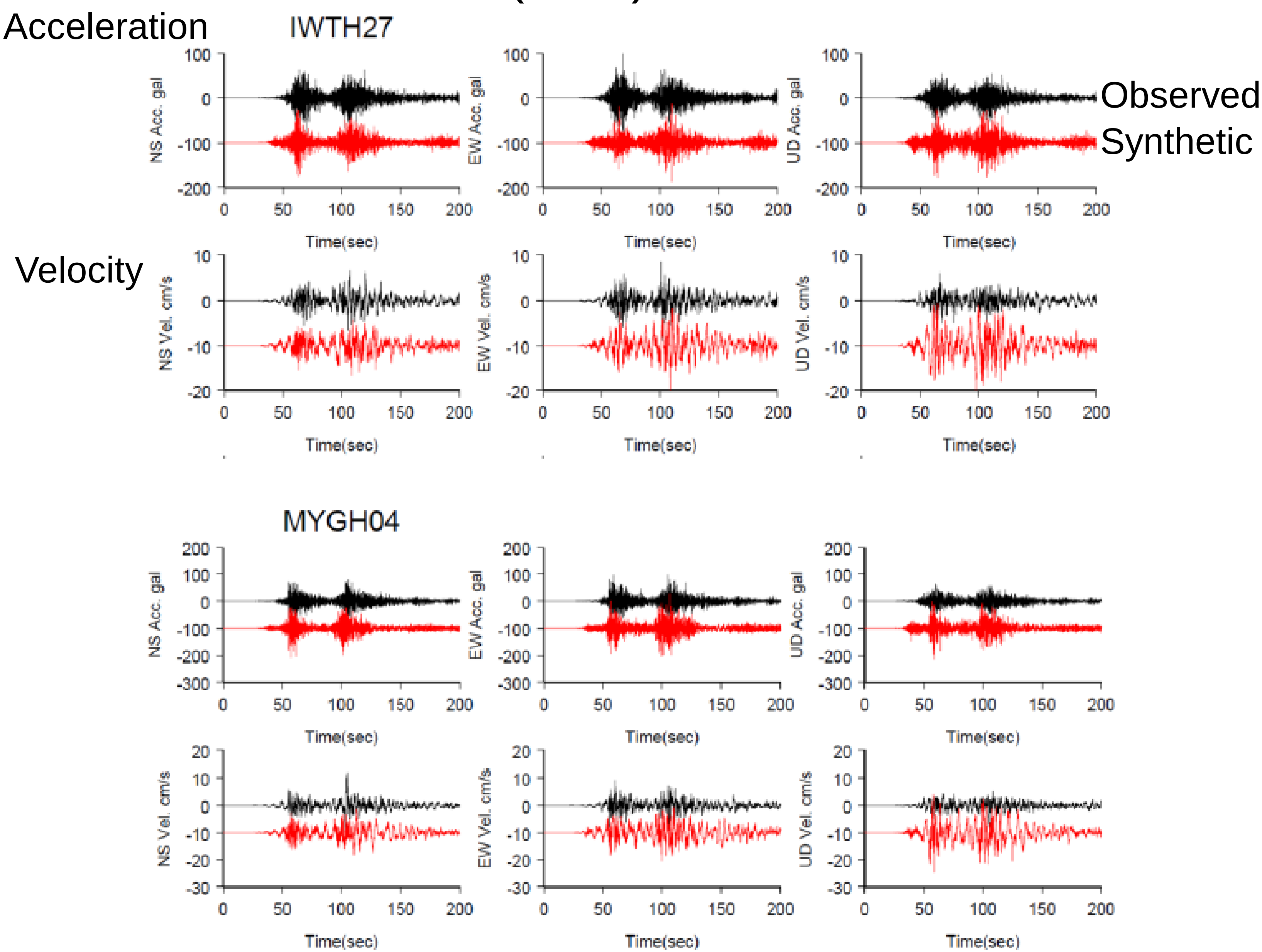
Location of each SMGA is estimated using a back-propagation method for previous model (Kurahashi and Irikura, 2011).



Strong Motion Generation Areas by Kurahashi and Irikura (2011) by Forward Modeling of Strong Motion Waveforms

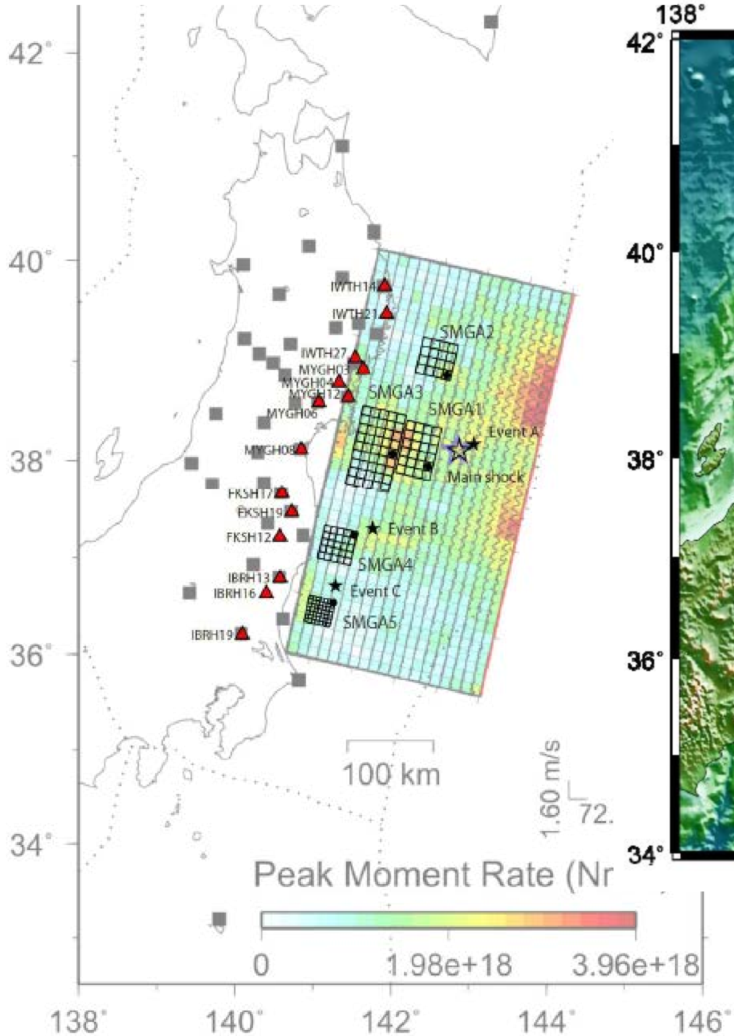


Comparison of Observed and Synthetic Seismograms Kurahashi and Irikura(2011)

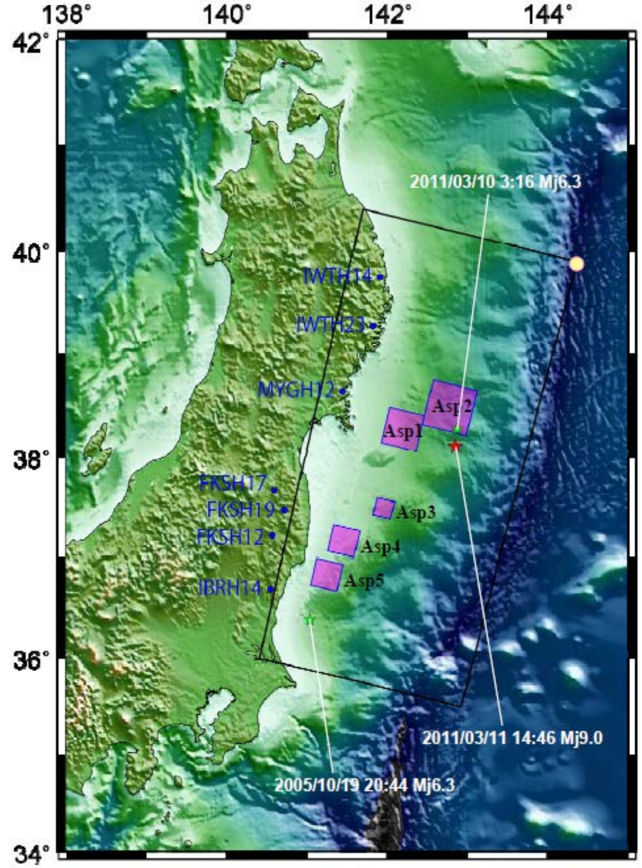


Comparison of Source Models for Generating Short-Period Motions

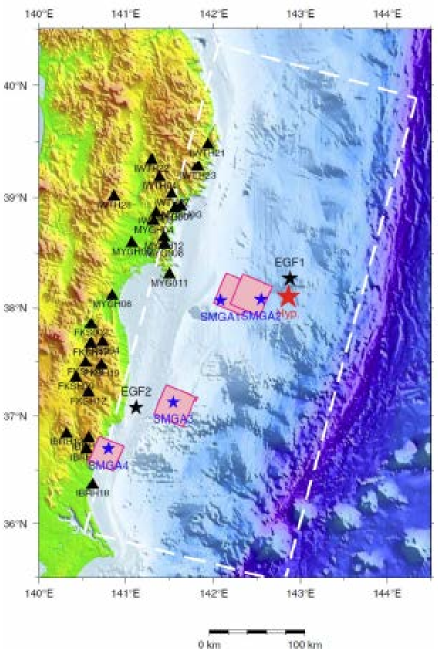
Kurahashi and Irikura (2011)



Kawabe and Kamae (2011)



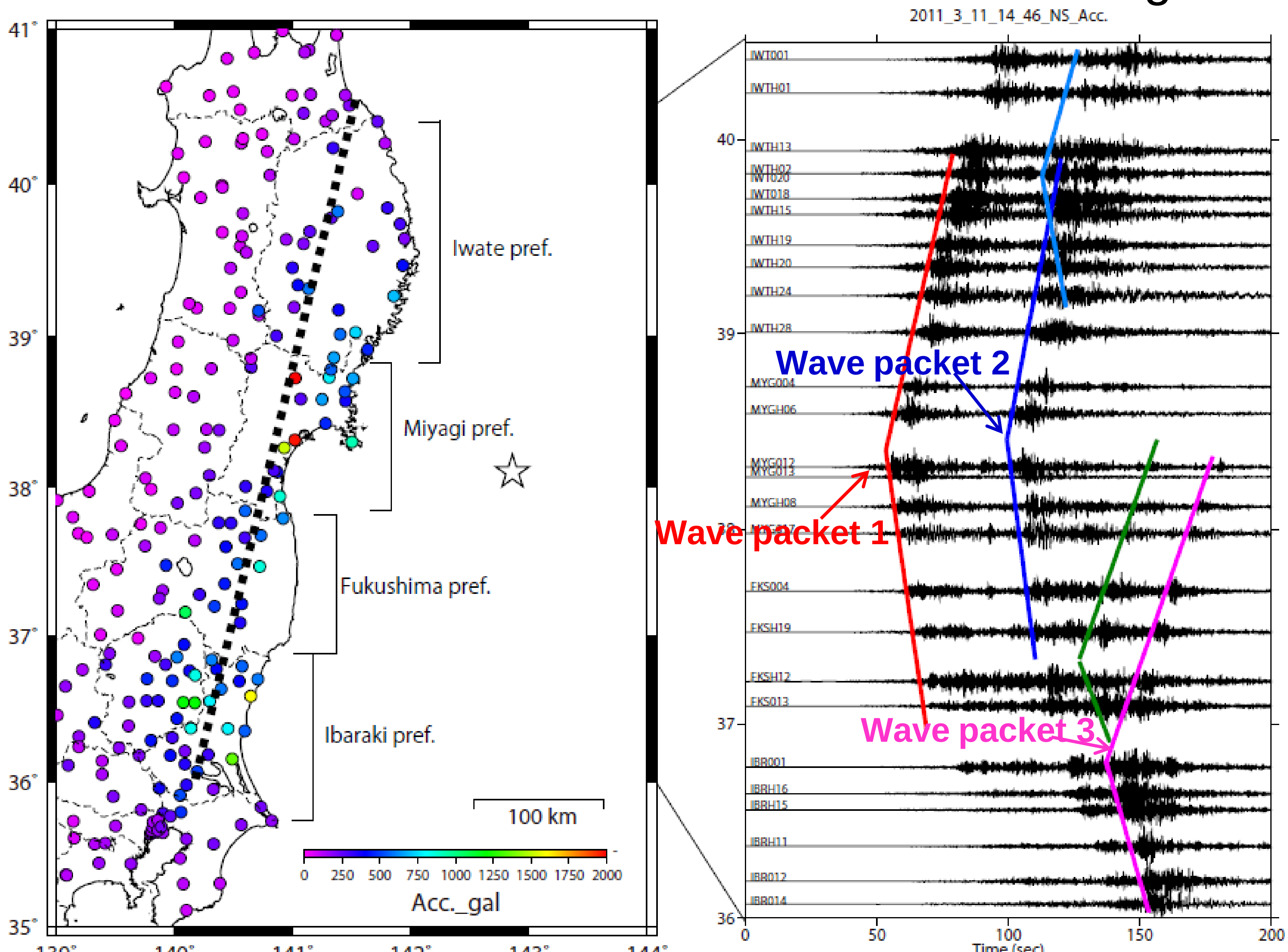
Asano and Iwata (2011)



Reconsideration of locations of strong motion generation areas of the 2011 Pacific Coast off Tohoku, Japan Earthquake

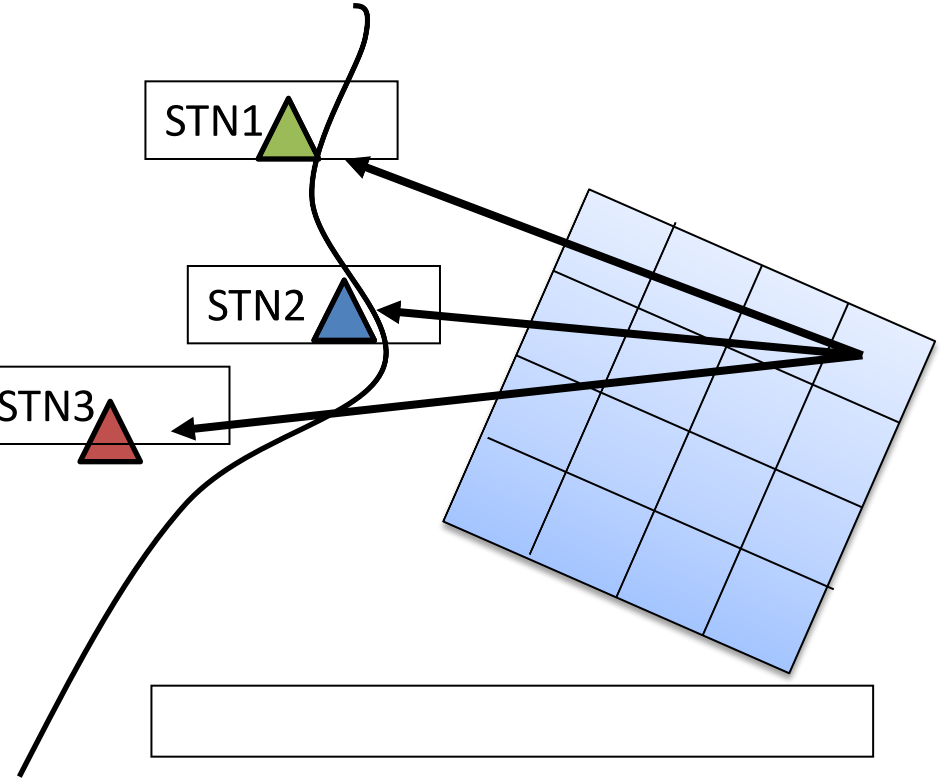
Estimation of locations of SMGA from azimuths of seismic waves from each SMGA using small arrays.

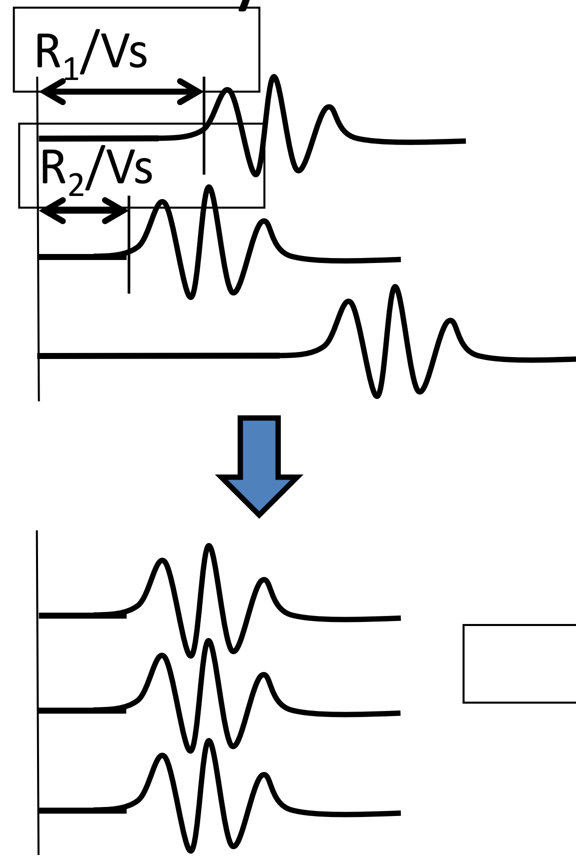
Re-estimation of Locations of SMGAs from Semblance Analysis of Wave-Packets seen in Short-Period Seismograms



After Irikura and Kurahashi (2011)

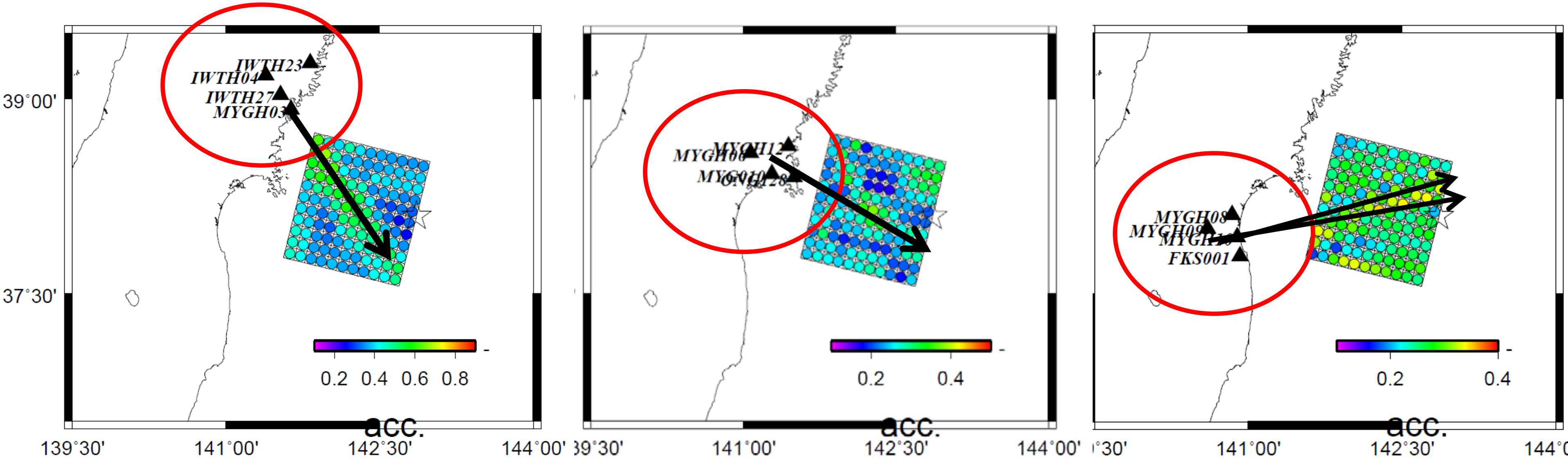
Semblance Analysis for Wave Packets using Local Arrays



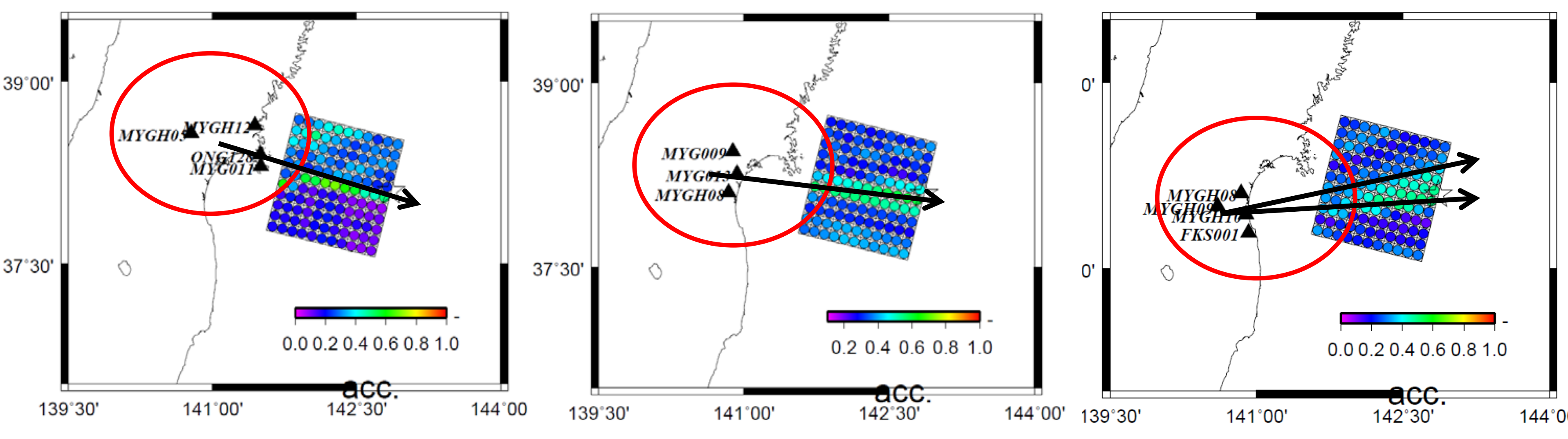


$$S_e(s) = \frac{1}{N} \frac{\sum_{k=1}^{M} \left[\sum_{i=1}^{N} u(x_i, t_k + s \cdot x_i) \right]^2}{\sum_{k=1}^{M} \sum_{i=1}^{N} u(x_i, t_k)^2}$$

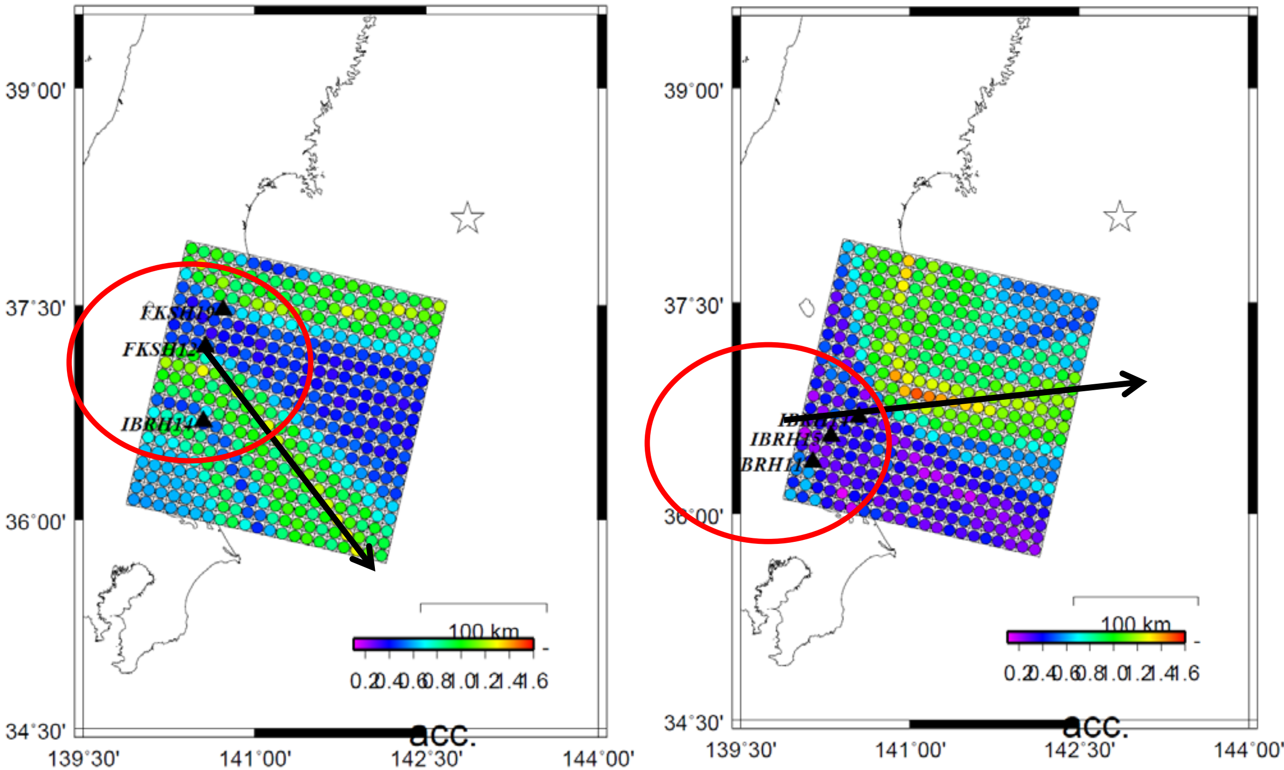
Result of semblance analysis for WP1



Result of semblance analysis for WP 2

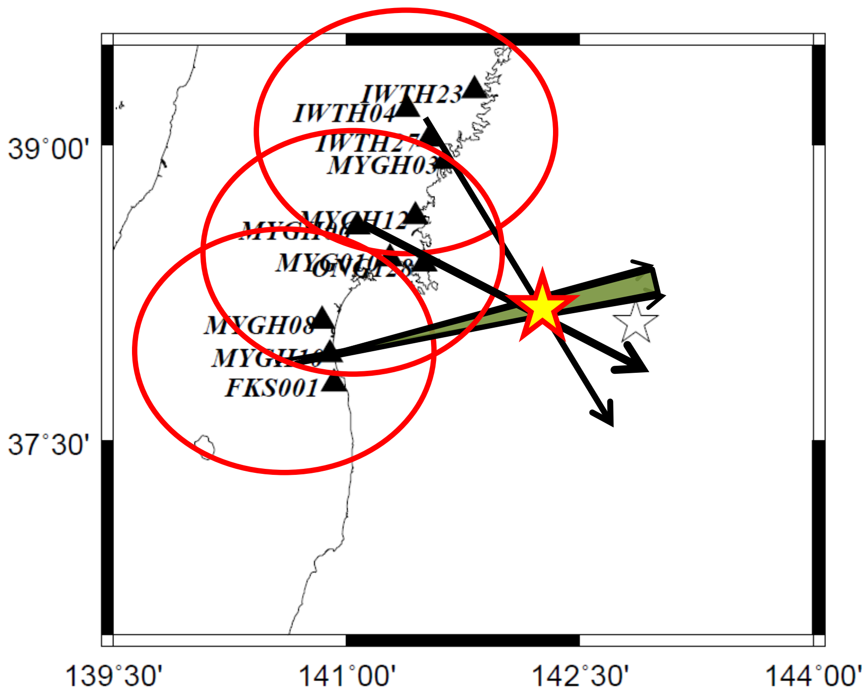


Result of semblance analysis for WP 3

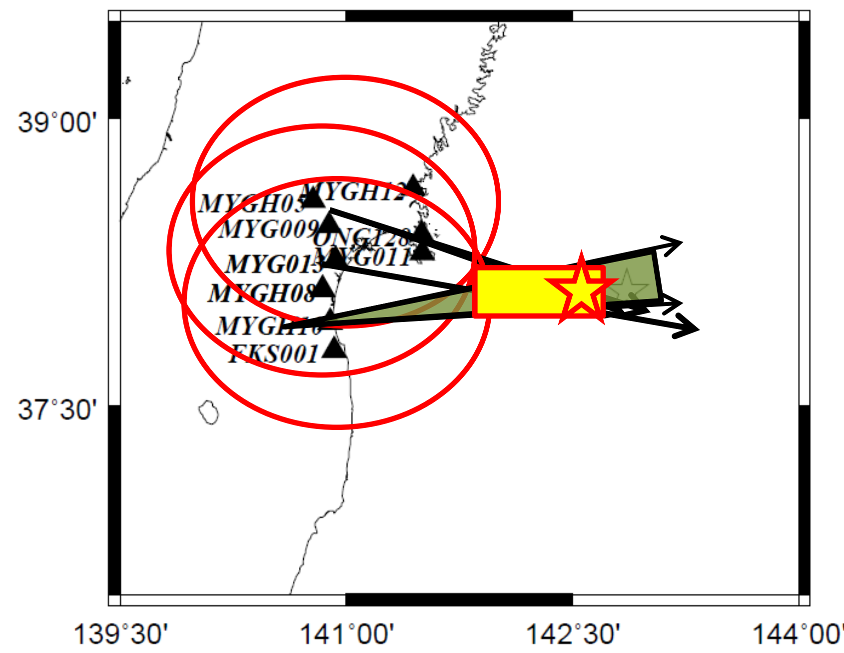


Estimation of locations of SMGA1 and SMGA3 from semblance analysis

Location of SMGA1 from WP1

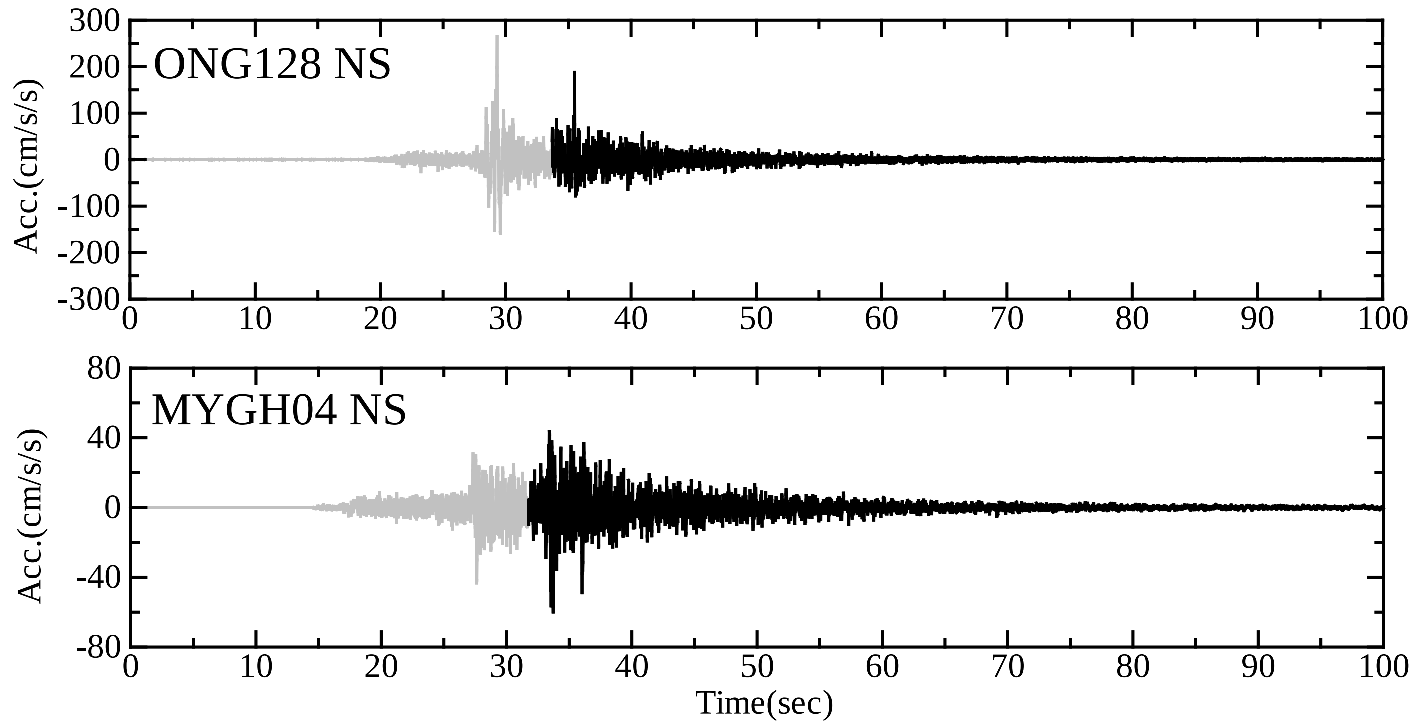


Location of SMGA3 from WP2



Selection of Empirical Green's Functions (EGFs) for Simulating Short-Period Motions from SMGAs

Strong motion records of the 2005 Miyagi-oki earthquake



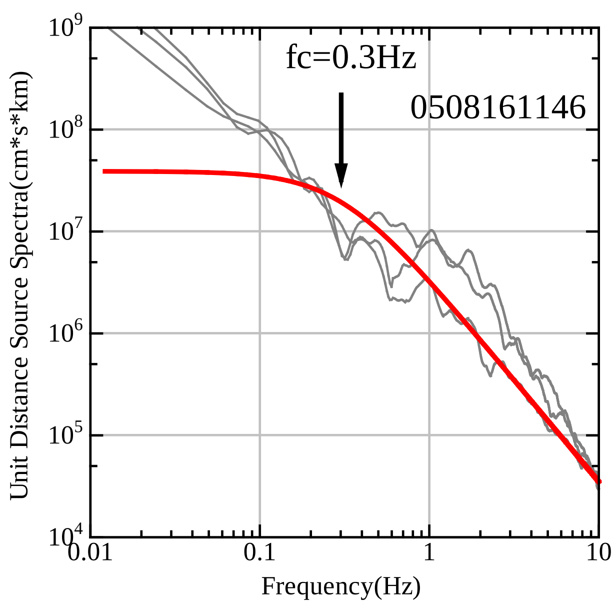
The records have clearly two wave-groups from SMGAs. Waveforms of the second wave-group are used as the EGFs for simulating ground motions from SMGA3 (WP 2).

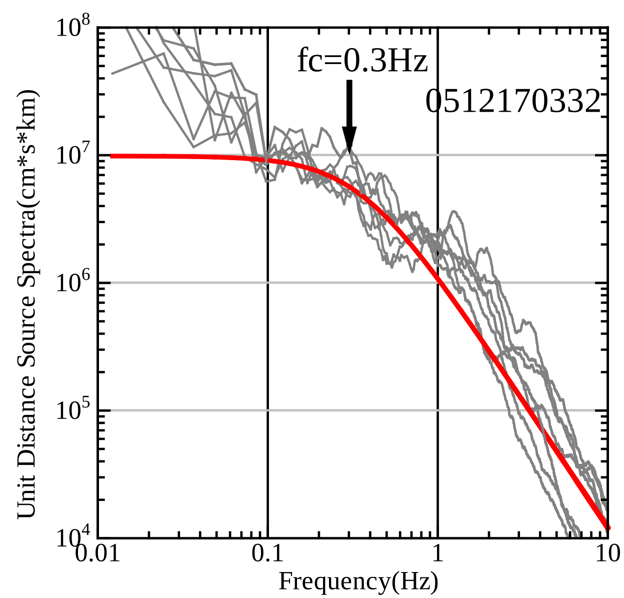
Fourier Spectra of the EGFs

EGF

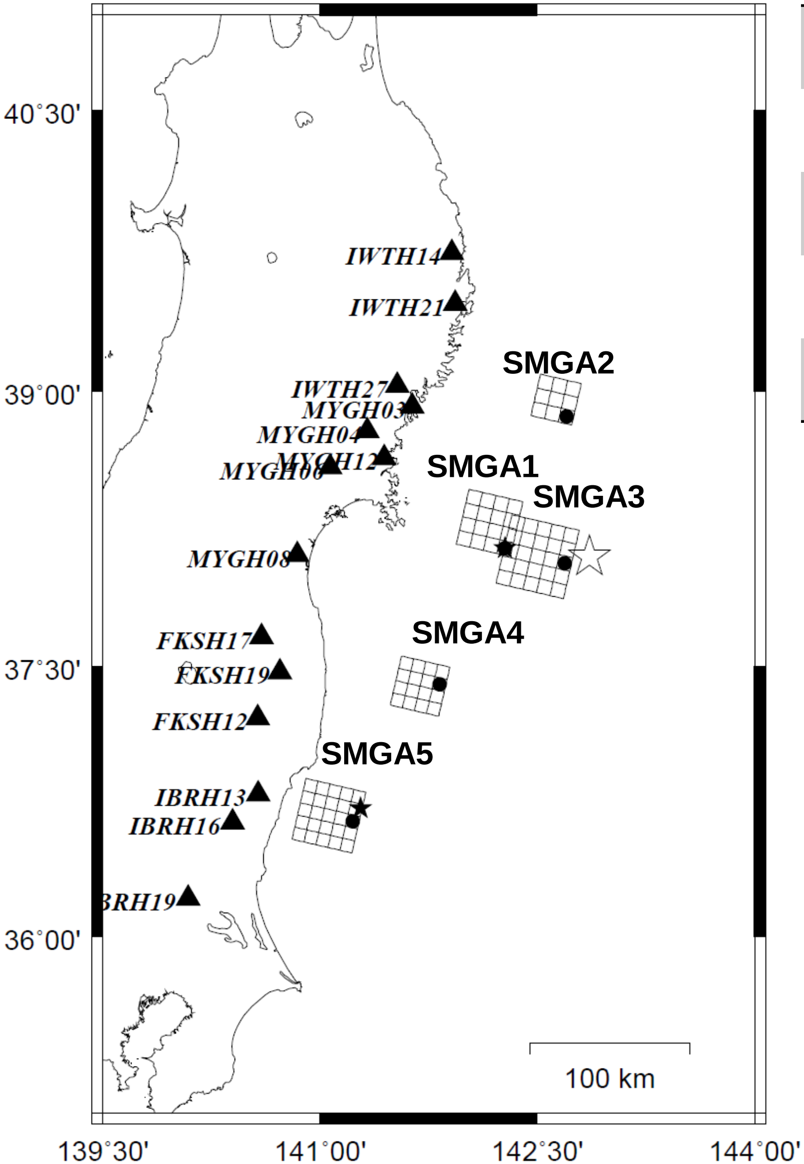
	2005/08/16 11:46	2007/11/26 22:51
Name	EGF1	EGF2
M	7.2	6.0
Dx,dw	8.5 km	7.7km
Stress Drop	20MPa	4.2MPa
Mo	5.23E+18 **	7.66E+17

** Suzuki and Iwata (2007) only Asp2



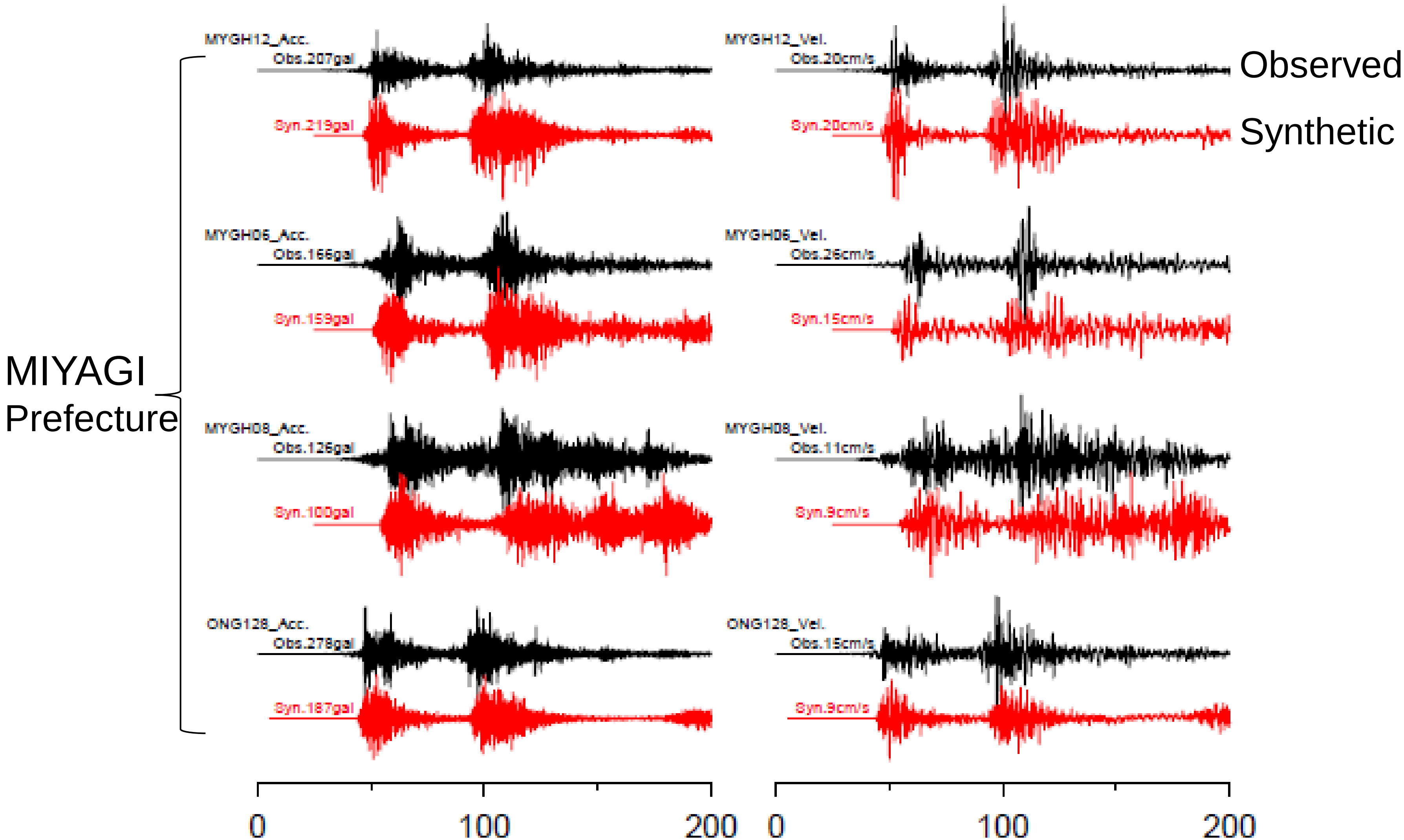


Revised Model

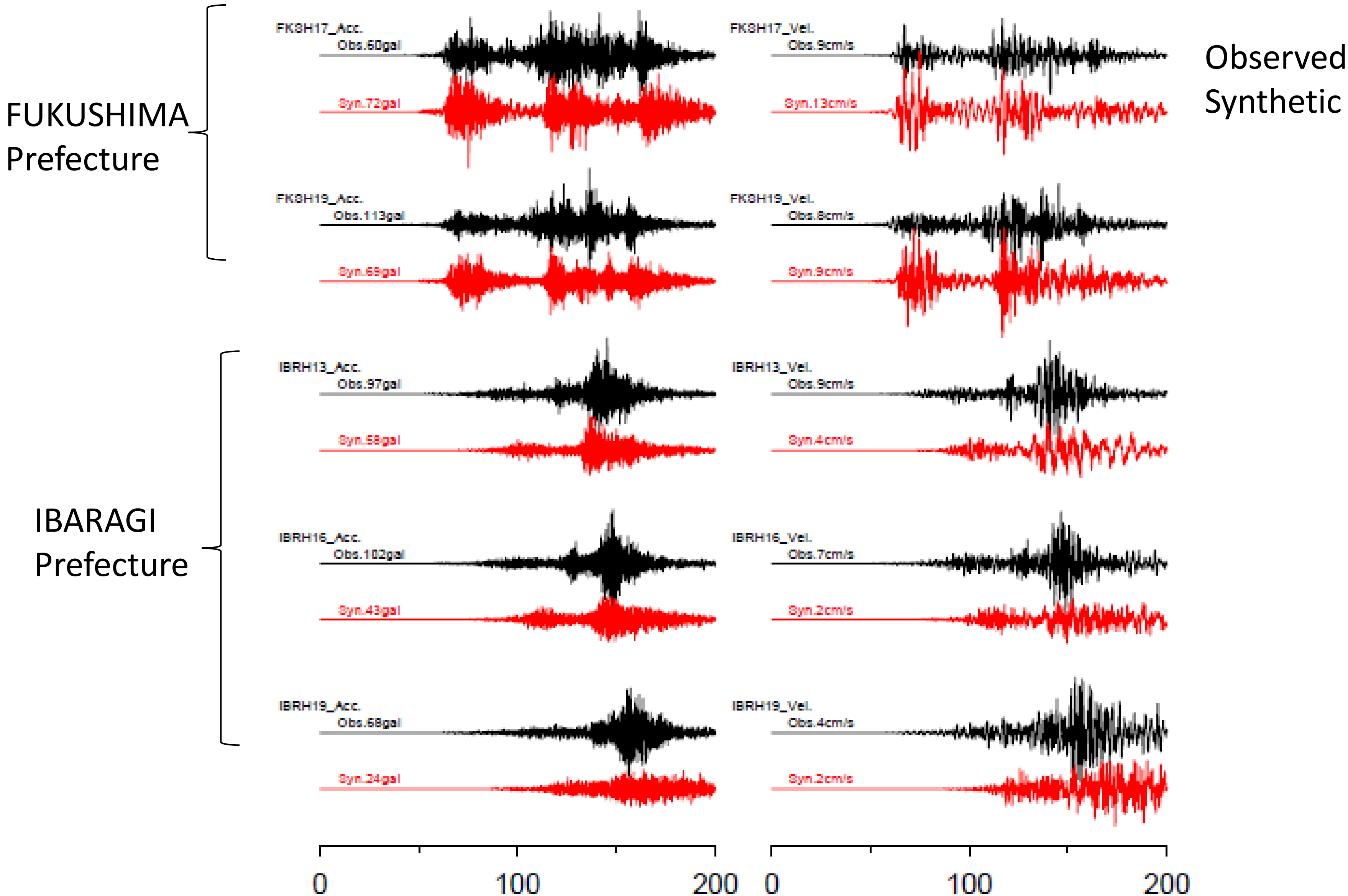


	L,W	Mo	Stress drop
SMGA1	34 × 34	2.68E+20	16
SMGA2	23.1 × 23.1	1.41E+20	20
SMGA3	42.5 × 42.5	6.54E+20	20
SMGA4	25.5 × 25.5	1.24E+20	25.2
SMGA5	38.5 × 38.5	5.75E+20	25.2

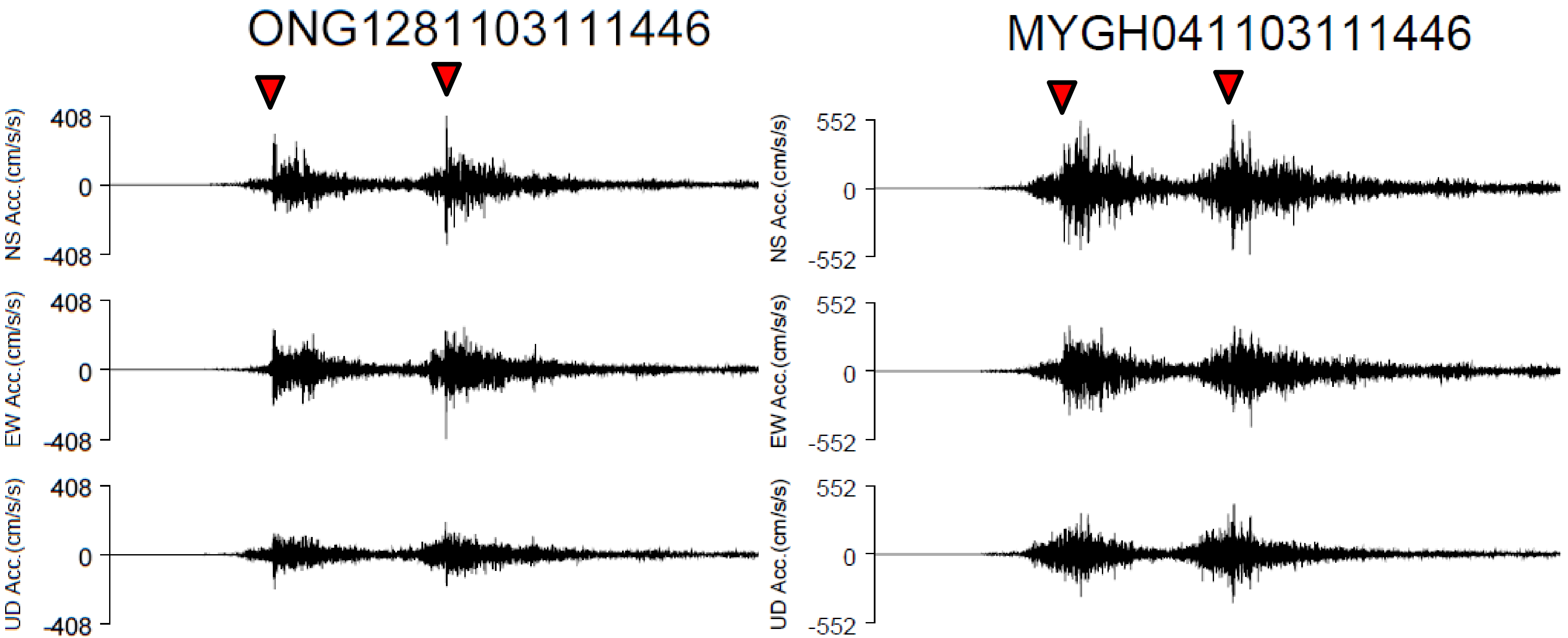
Comparison between Observed and Synthetic Motions



Comparison between Observed and Synthetic Motions

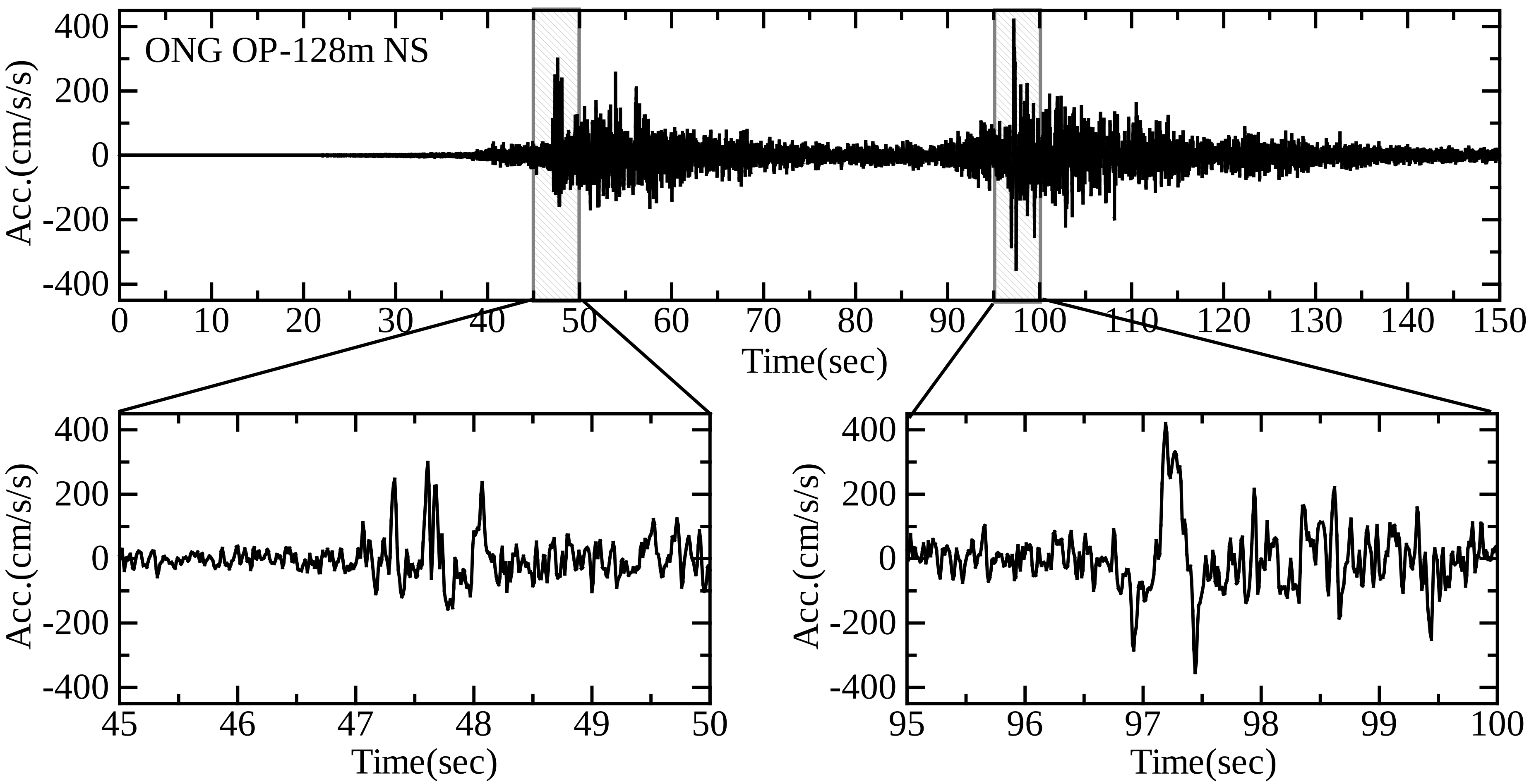


Distinctive High Acceleration Pulses

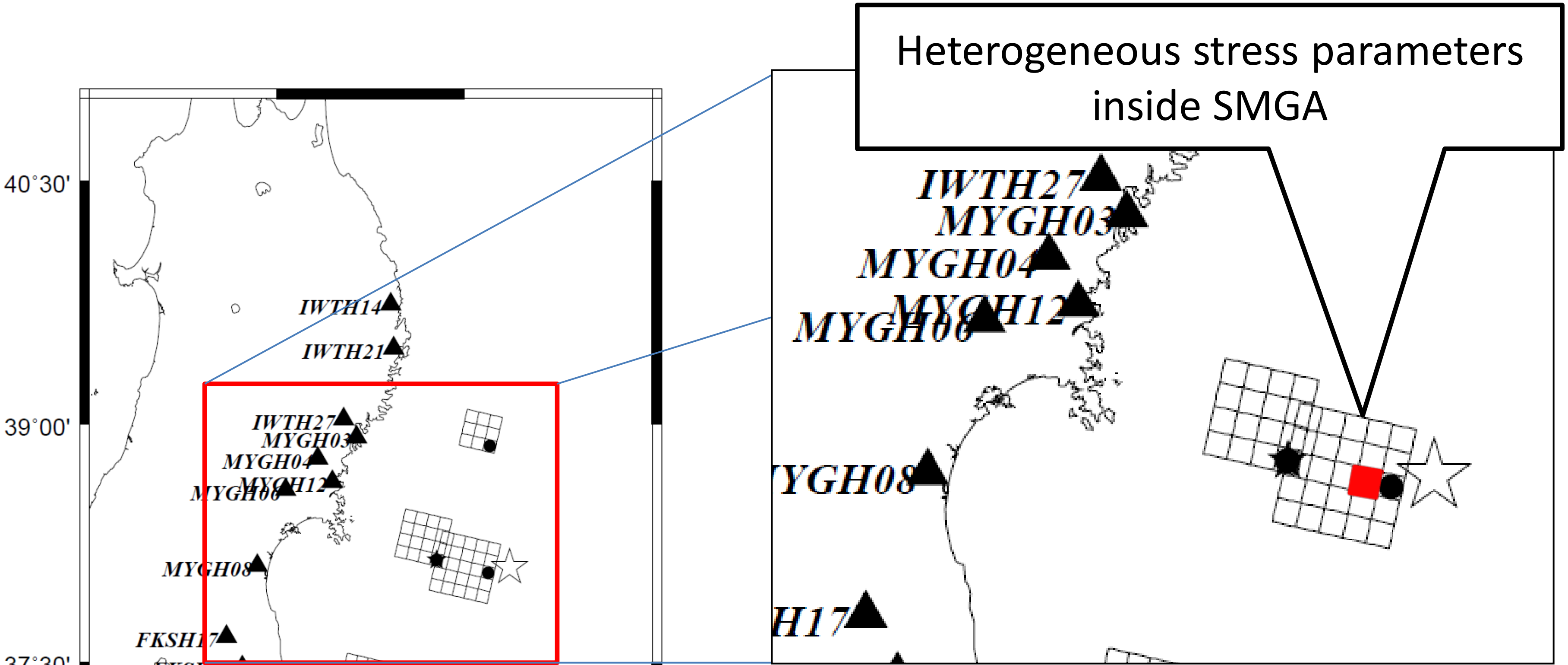


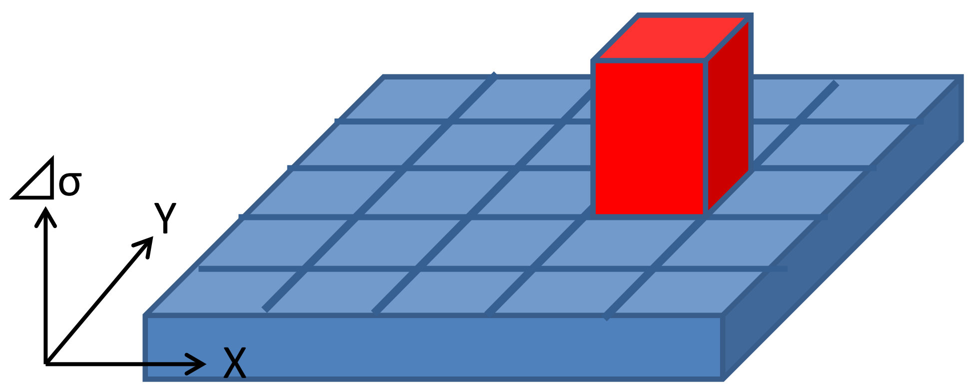
Distinctive High Acceleration Pulses

Borehole station OP -128m at Onagawa NPP

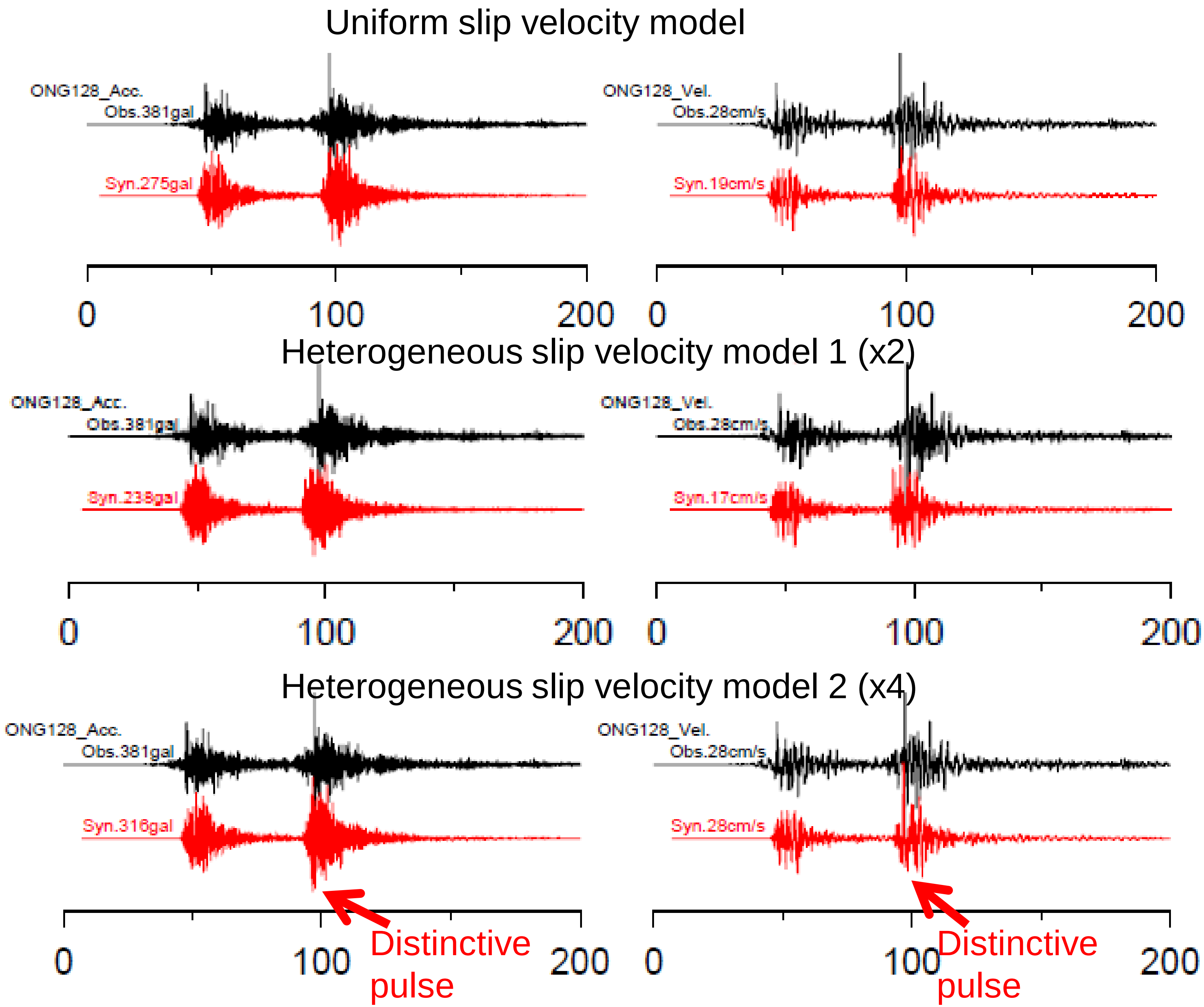


Source Model of Simulating Distinctive Pulses



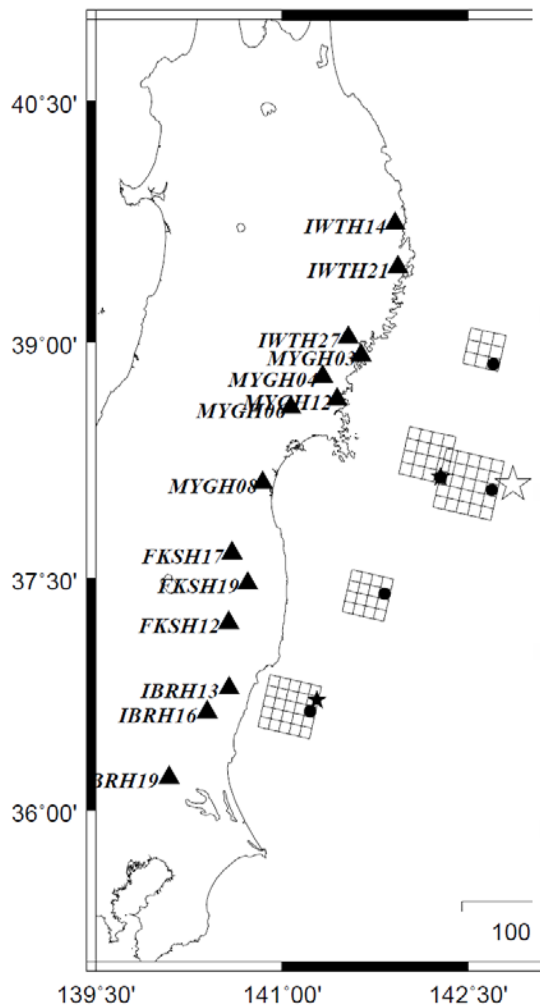


Matsushima and Kawase (2006)

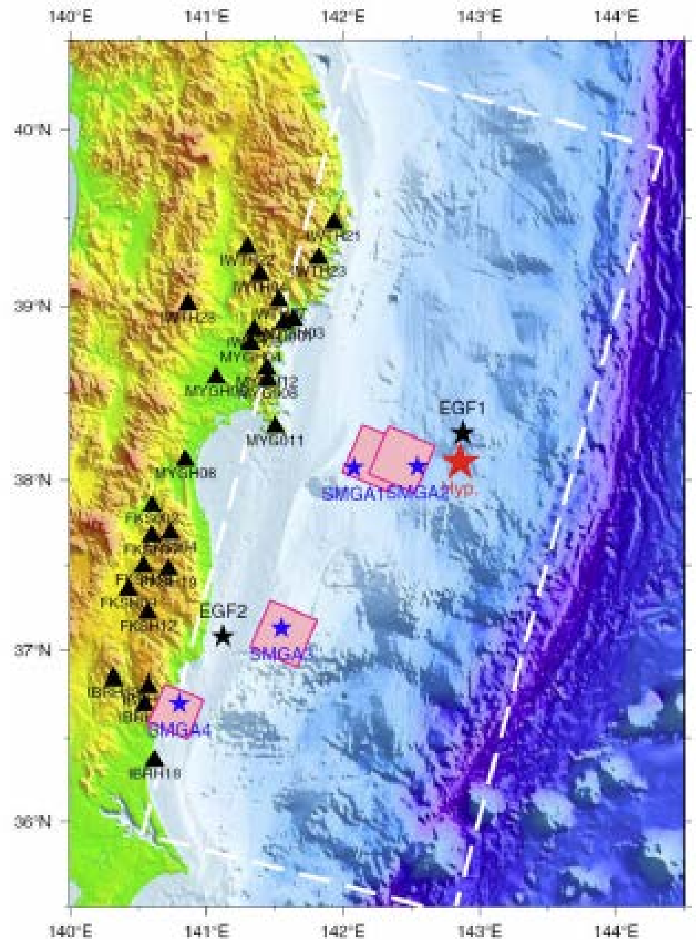


Uniform slip velocity model
ONG128_Acc.
Obs.381gal
Syn.275gal
ONG128_Vel.
Obs.28cm/s
Syn.19cm/s
0
100
200
0
100
200
Heterogeneous slip velocity model 1 (x2)
ONG128_Acc.
Obs.381gal
Syn.238gal
ONG128_Vel.
Obs.28cm/s
Syn.17cm/s
0
100
200
0
100
200
Heterogeneous slip velocity model 2 (x4)
ONG128_Acc.
Obs.381gal
Syn.316gal
ONG128_Vel.
Obs.28cm/s
Syn.28cm/s
0
100
Distinctive pulse
200
0
100
Distinctive pulse
200

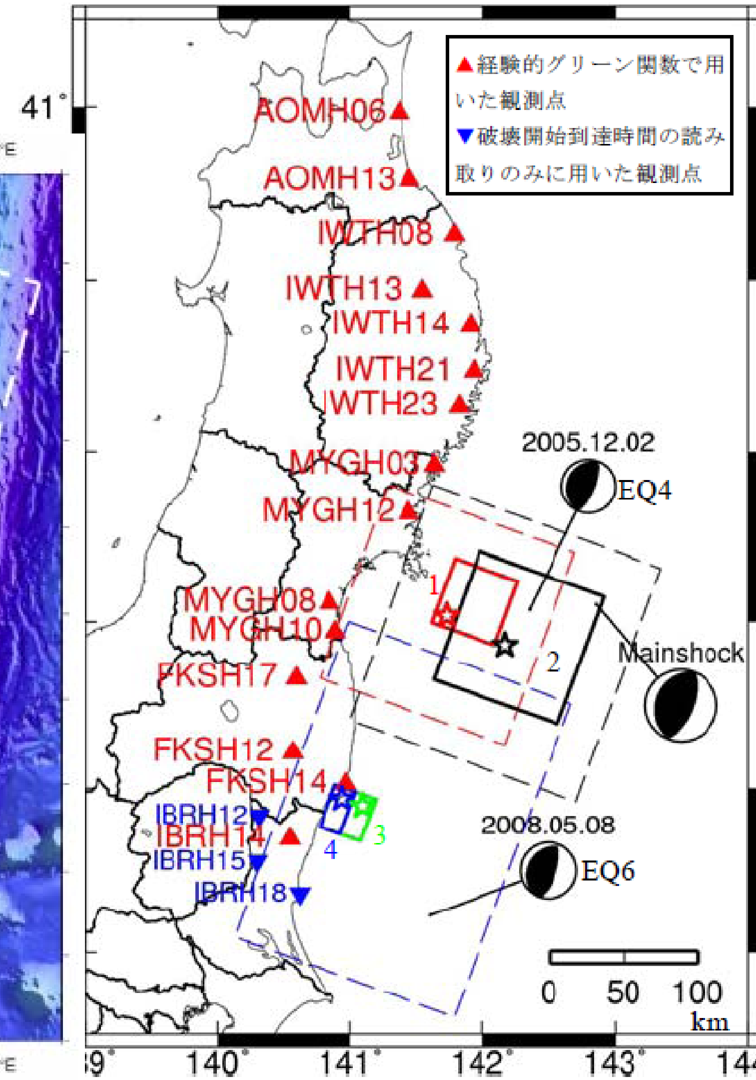
This study



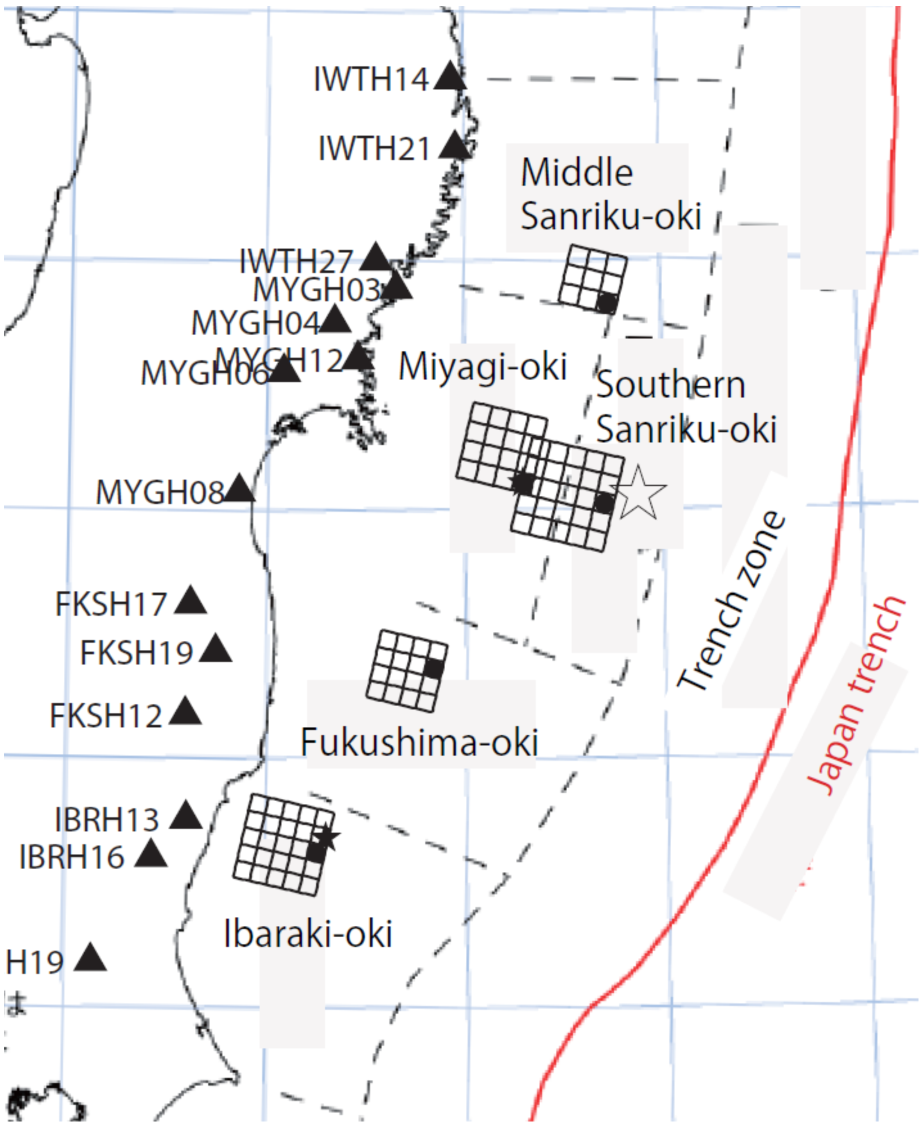
Asano and Iwata (2011)

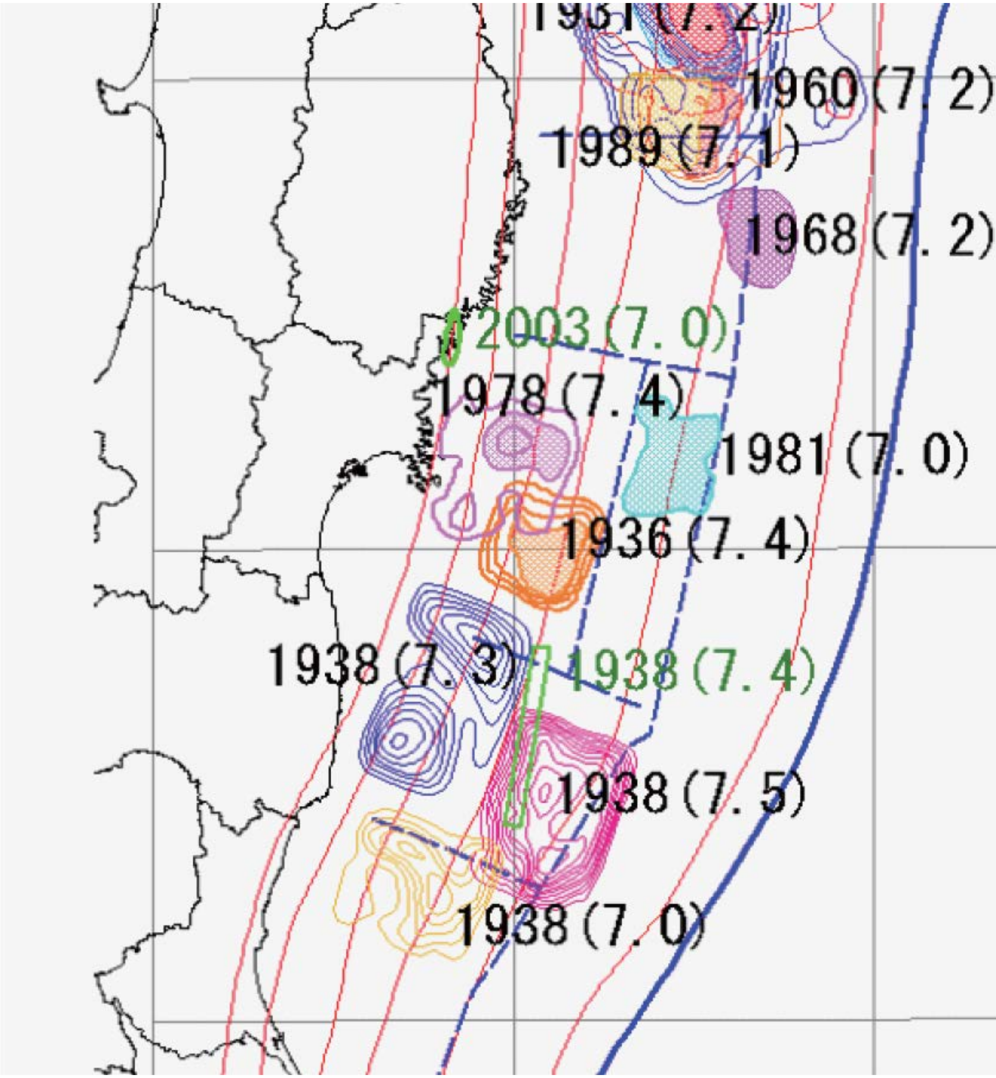


Satoh (2012)

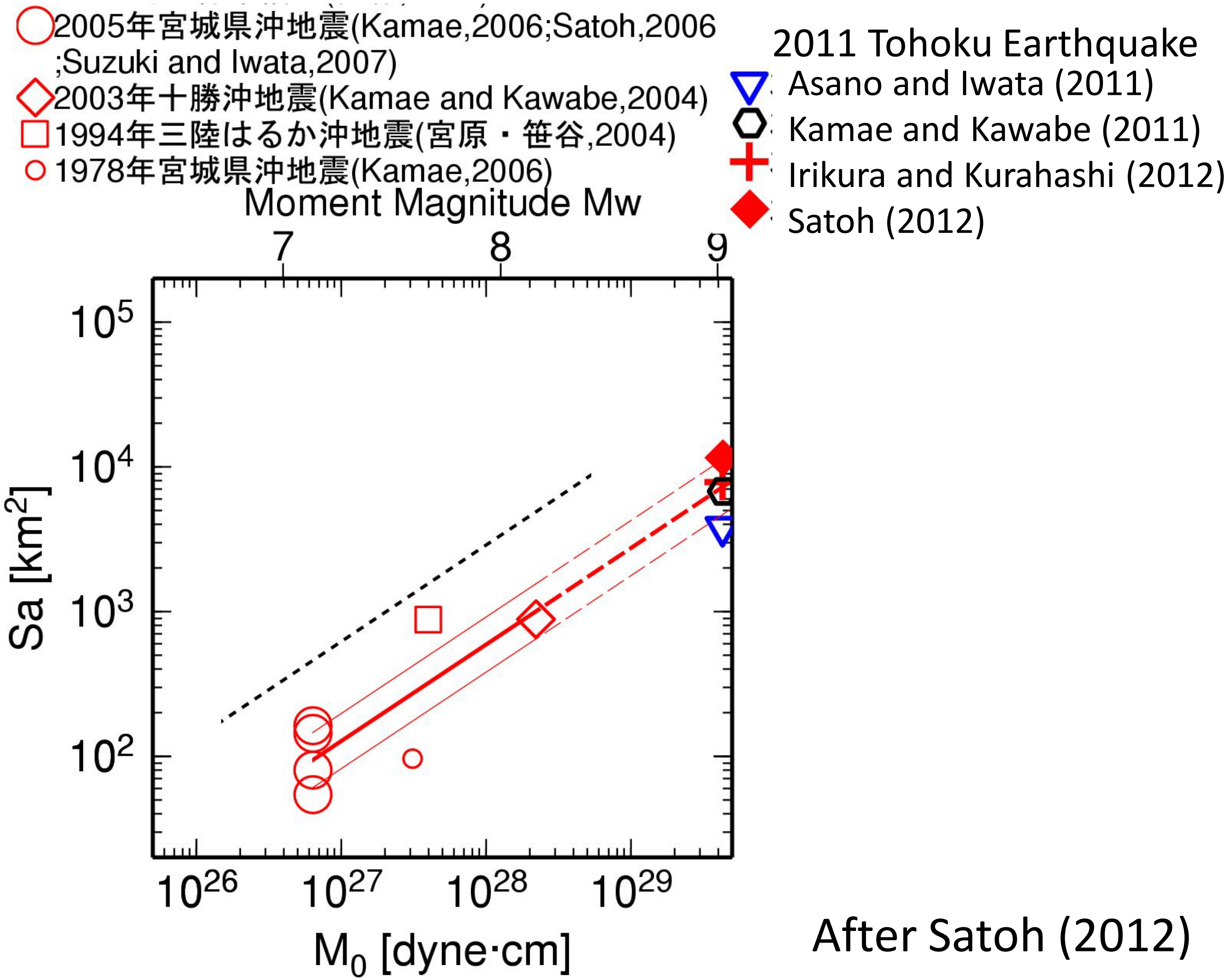


Comparison between SMGAs in this study and source locations of past earthquakes off the Pacific coast of Tohoku



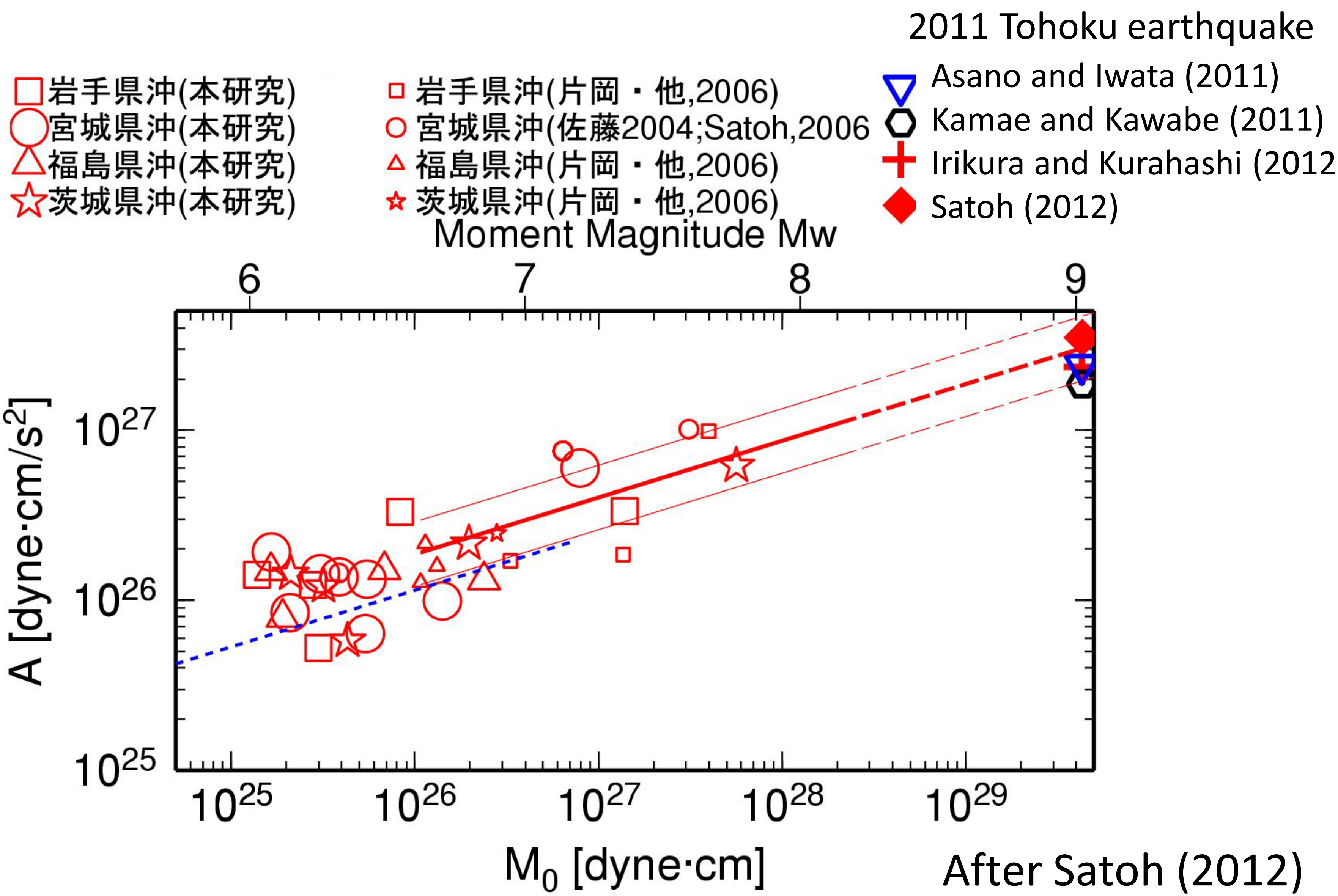


Strong Motion Generation Area versus Seismic Moment for Subduction Earthquakes



After Satoh (2012)

Acceleration Spectral-Level versus Seismic Moment for Subduction Earthquakes



After Satoh (2012)

Summary 1

Based on the results of our analysis in this study, we improve the recipe of predicting strong ground motions to be able to apply it to mega-thrust earthquake.

Outer source parameters

1. Source area and seismic moment of a target earthquake:
   Source area is set from the tectonic background in the objective regions.
2. Average stress drop over the entire source area:
   Average stress drop is estimated from the empirical scaling relation of source area versus seismic moment.

Summary 2

Inner fault parameters

3. Segmentation:
   The segments of the source area are divided from seismic activities and geo-morphological setting in the target region.

4. Strong motion generation areas (SMGAs):
   SMGA is arranged to assign one per a segment.

5. Average stress parameter for SMGA:
   About 25 MPa from empirical relation

6. Heterogeneity of stress parameters inside SMGA
   (Matsushima and Kawase, 2006)