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Source Characteristics of Interplate Earthquakes in Northeast Japan Inferred from the Analysis of Broadband Strong-Motion Records

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Abstract

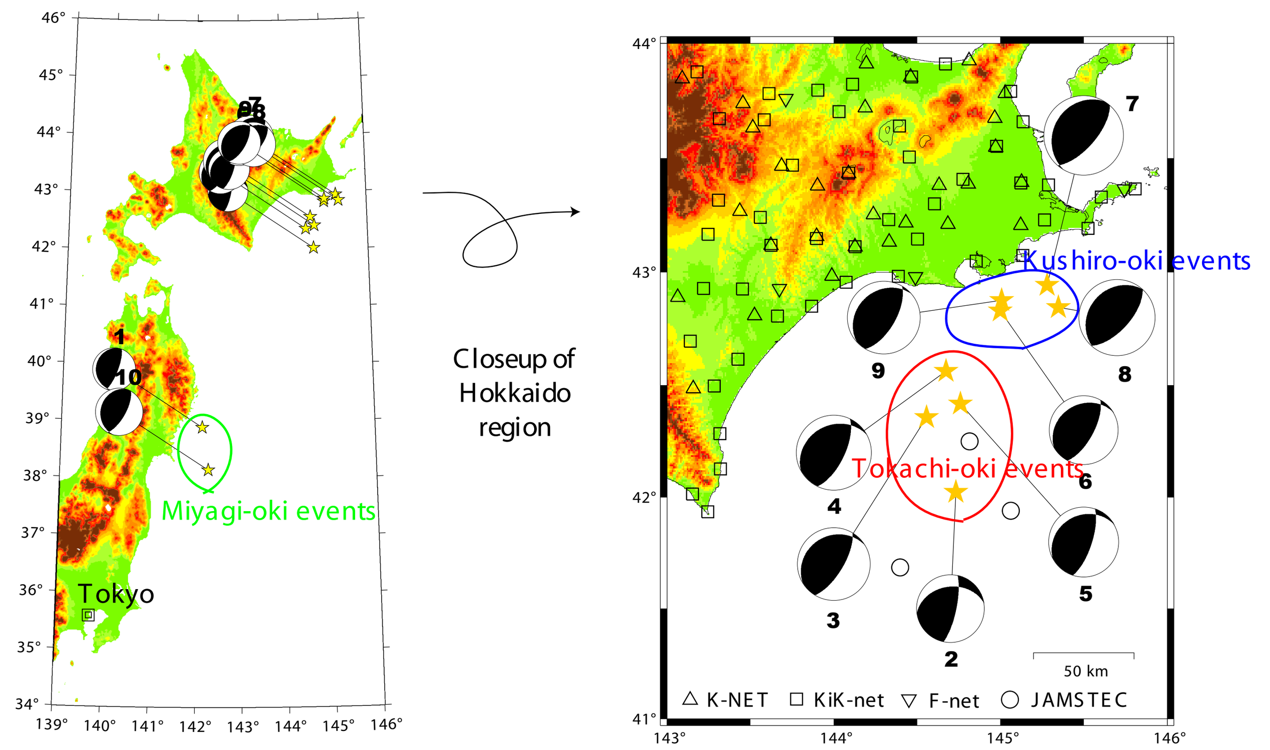
Observed broadband strong-motion records can be simulated assuming a relatively simple distinctive source model, which consists of large slip-velocity area within the total fault area with no explicit heterogeneity inside it, called "strong motion generation area (SMGA)", using the empirical Green's function (EGF) method. Scaling relationship of SMGAs is examined for crustal earthquakes (Miyake et al., 2003) and intraslab earthquakes (Asano et al., 2003). In order to investigate the broadband source characteristics of subduction zone, interplate earthquakes, we estimated the size and the location of SMGAs of Mw6.0-7.1 earthquakes which occurred along the Japan (the 2002 Miyagi-oki earthquake and the 2005 Miyagi-oki earthquake) and the Kuril (eight earthquakes which occurred in the off-shore of Hokkaido from 2003 to 2005) trenches.

Model parameters, such as the length, the width, the rise time, and the rupture starting subfault of the SMGA are estimated by fitting S-waves simulated using the EGF method by Irikura (1986) into the observed ones. We used the residual value of velocity waveforms and acceleration envelopes between observation and simulation so as to evaluate broadband strong motions. For the 2002 and 2005 Miyagi-oki earthquakes, we estimated the best model by forward modeling with considering the residual value. For eight Hokkaido events, we employed the genetic algorithm to derive the source model which gave the minimum residual values.

The estimated SMGA sizes are smaller than those predicted from the empirical relation for crustal earthquakes with the same seismic moment, which indicates the stress drop of the SMGA of these interplate earthquakes is larger than that of crustal earthquakes. For several earthquakes, slip distribution has been deduced by strong-motion or teleseismic waveform inversion analyses and the SMGA is found to be located in the large slip area.

It was not obvious that the stress drop depends on the focal depth, which Asano et al. (2003) found for the shallow intraslab earthquakes whose depth ranges from 30 to 100 km. Four events in the Kushiro-oki region tend to have larger stress drop than the other four events in the Tokachi-oki region. This shows that broadband strong-motion radiation by interplate earthquakes analyzed in this study seems to have regional characteristics in spite of their spatial proximity.

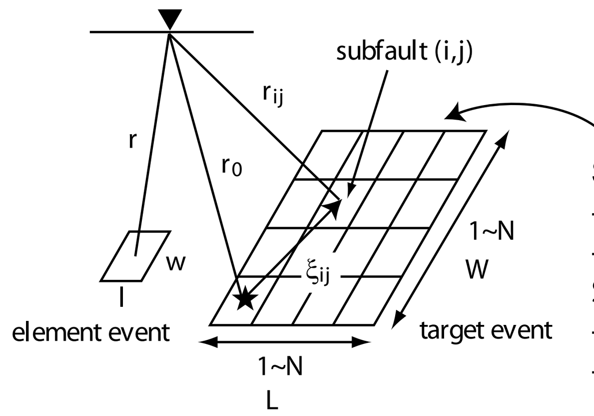
Target earthquakes



We classified ten earthquakes analyzed in this study into three groups: Miyagi-oki (green), Tokachi-oki (red), and Kushiro-oki (blue) events. Hypocenters are determined by JMA. These ten earthquakes are considered to be interplate earthquakes because focal mechanism (F-net moment tensor solution) shows that they have a nodal plane which corresponds to a subducting pacific plate.

#	Date	Latitude (deg)	Longitude (deg)	Depth (km)	Mw
1	2002/11/03 12:37	38.894	142.142	45.8	6.4
2	2003/09/27 05:38	42.023	144.732	34.4	6.0
3	2003/09/29 11:37	42.357	144.557	42.5	6.5
4	2003/10/08 18:07	42.563	144.674	51.4	6.6
5	2003/12/29 10:31	42.417	144.760	38.9	6.2
6	2004/04/12 03:06	42.830	144.998	47.3	6.1
7	2004/11/29 03:32	42.944	145.280	48.2	7.0
8	2004/12/06 23:15	42.845	145.347	45.9	6.7
9	2005/01/18 23:09	42.876	145.007	49.8	6.2
10	2005/08/16 11:46	38.151	142.280	41.6	7.1

Empirical Green's function (EGF) method and strong motion generation area (SMGA)



Advantage of EGF method

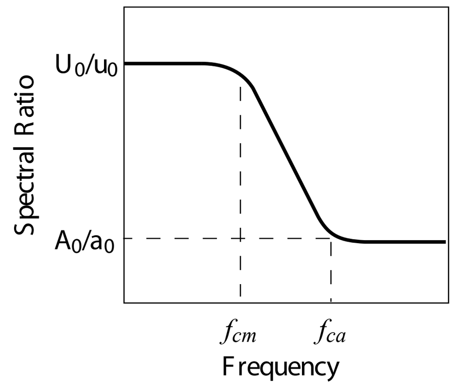
able to simulate waveforms over broadband frequency range including high frequency component

SMGA (named by Miyake et al., 2003)
- Account for broadband (0.1-10 Hz) strong motions
- Large slip velocity region within total rupture area

Some simplification
- Rectangular shape
- No explicit heterogeneities of stress drop and rupture velocity

EGF method proposed by Irikura (1986)

Based on
- Self-similarity of source parameters
  L/l=W/w=D/d=T/t=N
- ω^{-2} source spectral scaling law
  $CN^3=M_0/m_0=U_0/u_0$
  $CN=A_0/a_0$



Formulation

$$U(t)=\sum_{i=1}^{N}\sum_{j=1}^{N}(r/r_{ij})\cdot F(t)*(C\cdot u(t))$$

$$F(t)=(t-t_{ij})+\frac{1}{n'(1-e^{-1})}\sum_{k=1}^{(N-1)n'}\left[\exp\left\{-\frac{k-1}{(N-1)n'}\right\}\cdot\left\{t-t_{ij}-\frac{(k-1)T}{(N-1)n'}\right\}\right]$$

$$t_{ij}=(r_{ij}-r_0)/V_s+\xi_{ij}/V_r$$

- Filtering function to adjust slip amount or rise time
- Kostrov-type like function (Irikura et al., 1997)

Estimation of SMGA parameters

We estimated the length, width, rise time, and rupture starting point of the SMGA by fitting synthesized waveforms of S-wave portion into observed ones over wide frequency range. For this purpose, we defined misfit function as to velocity waveforms (u) and acceleration envelopes (e) as follows. Here, frequency range of velocities is limited to lower than 1 Hz while that of acceleration is up to 10 Hz. Lower limit of frequency range depends on signal-to-noise ratio of EGF event.

$$res=\sum_{station}\sum_{component}\left[\frac{\sum_t (u_{obs}-u_{syn})^2}{\sqrt{\sum_t u_{obs}^2\sum_t u_{syn}^2}}+\frac{\sum_t (e_{obs}-e_{syn})^2}{\sqrt{\sum_t e_{obs}^2\sum_t e_{syn}^2}}\right]$$

For earthquakes numbered #2-#9 in left table, we used the genetic algorithm to search model parameters by minimizing the misfit function. For #1 and #10, we estimated model parameters by trial-and-error search consulting the misfit function.

Strong-motion records
- K-NET and KiK-net by NIED (mainly used)
- Ocean bottom seismometers by JAMSTEC for several Hokkaido events in order to improve station coverage
- F-net strong motion data by NIED recorded by velocity-type seismometer

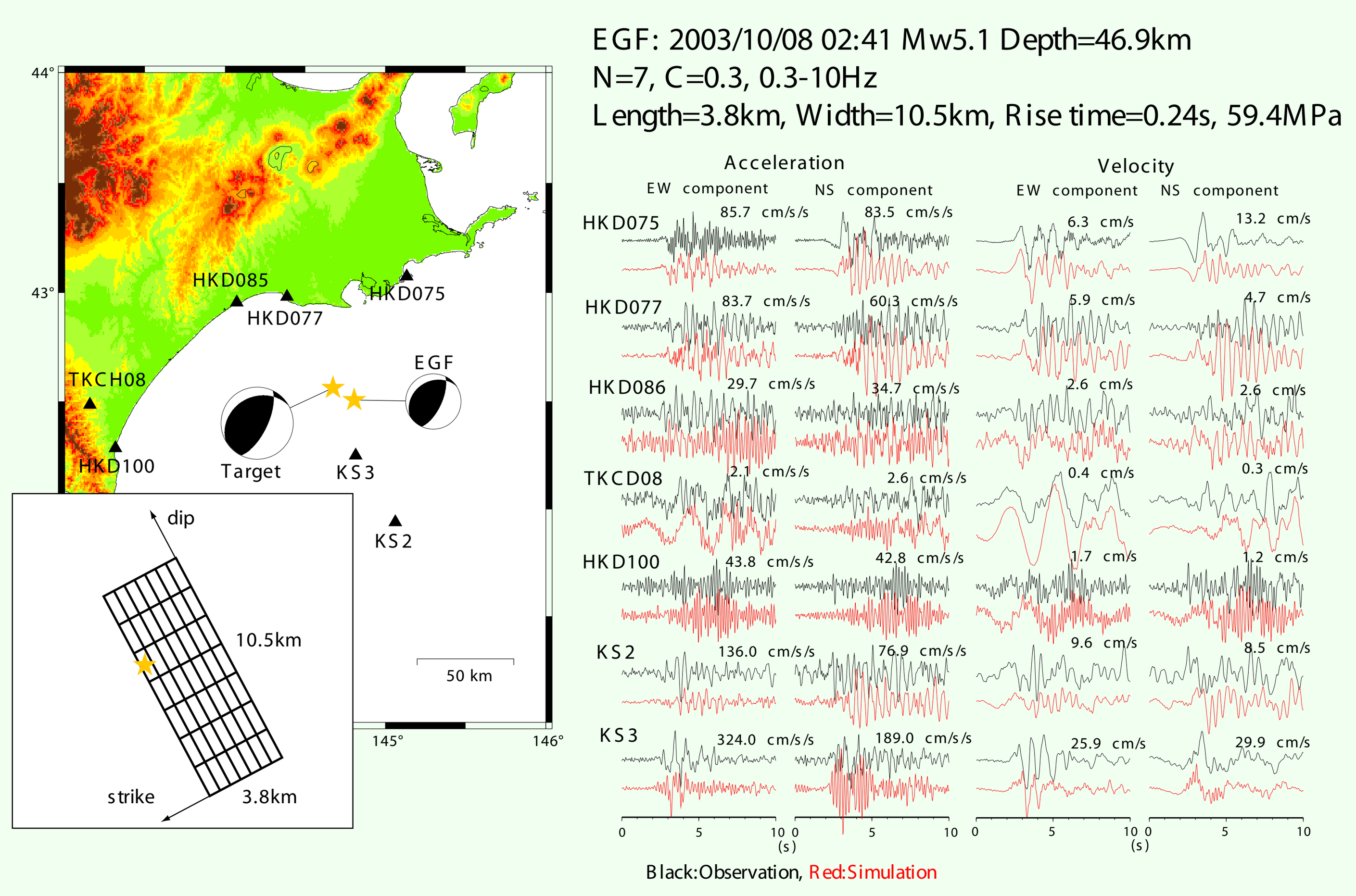
Assumptions for simulation and parameter search
- Hypocenter determined by JMA is assumed to be the rupture starting point of SMGA except for #10
- SMGA is on the fault plane determined from F-net moment tensor solution
- Rupture velocity is fixed to be Vr=3.0km/s, that is approximately 70% of S-wave velocity around rupture area
- For #3 and #10, two SMGAs are assumed
- For #10, SMGA is assumed to be square

#	N	C	Frequency band(Hz)	No. of Stations	Length(km)	Width(km)	Rise time(s)
1	5	2.5	0.2-10	4	5.0	5.0	2.00
2	4	0.7	0.25-10	8	3.0	5.0	0.28
3	3	1.5	0.30-10	5	3.8	3.6	0.23
	5	2.0			6.3	6.0	0.31
4	7	0.3	0.30-10	7	3.8	10.5	0.24
5	4	1.5	0.30-10	7	3.4	7.3	0.24
6	4	0.9	0.25-10	6	3.1	2.2	0.13
7	11	5.0	0.3-10	4	3.5	5.4	0.33
8	10	3.0	0.2-10	4	7.7	4.1	0.47
9	6	1.7	0.4-10	7	2.4	4.7	0.53
10	5	10.0	0.2-10	6	6.0	6.0	0.40
	5	10.0			6.0	6.0	0.40

Examples of estimated SMGA and waveform fittings

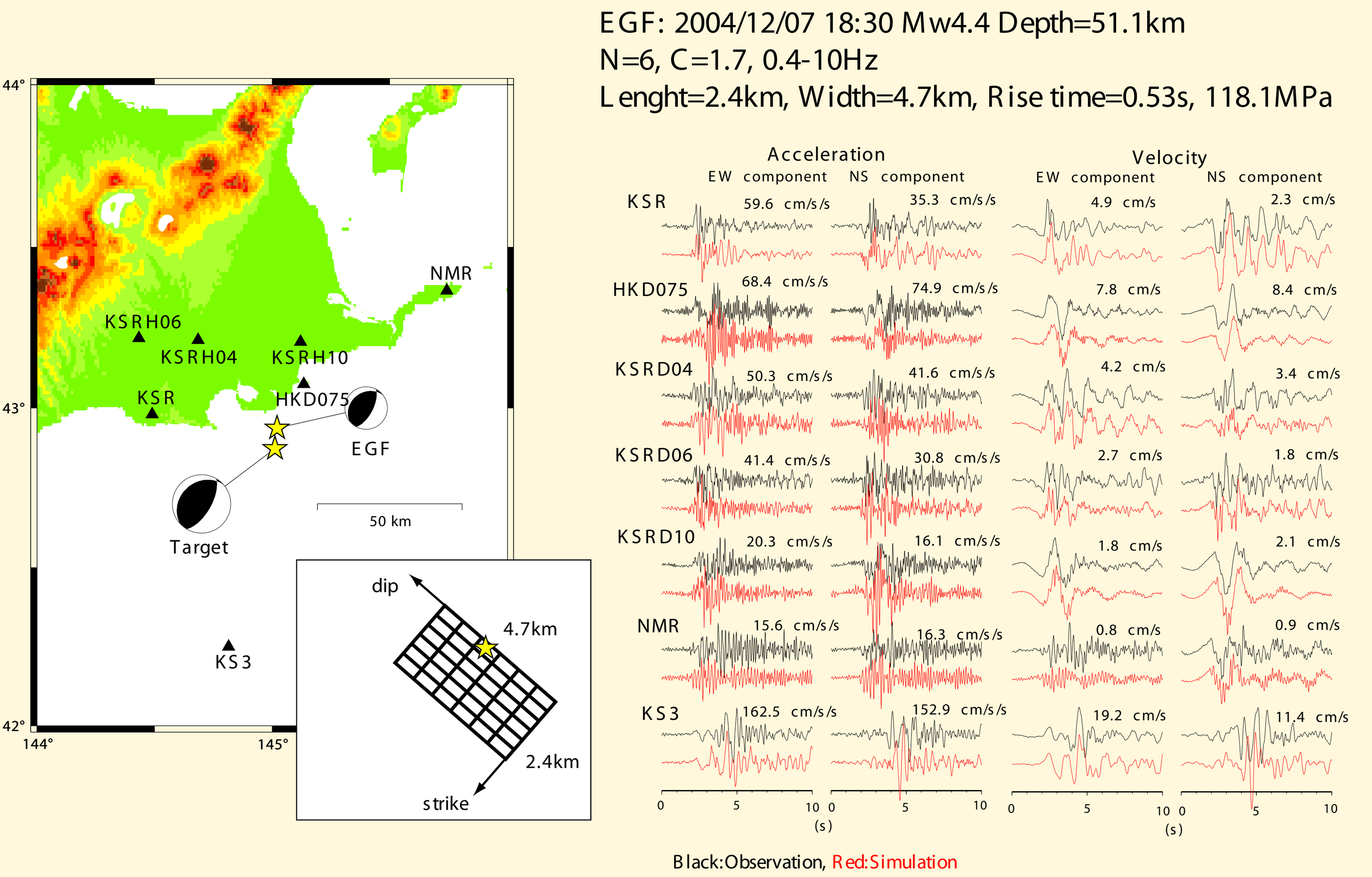
Tokachi-oki event (#4: 2003/10/08 18:07 Mw6.6 Depth=51.4km)

EGF: 2003/10/08 02:41 Mw5.1 Depth=46.9km
N=7, C=0.3, 0.3-10Hz
Length=3.8km, Width=10.5km, Rise time=0.24s, 59.4MPa



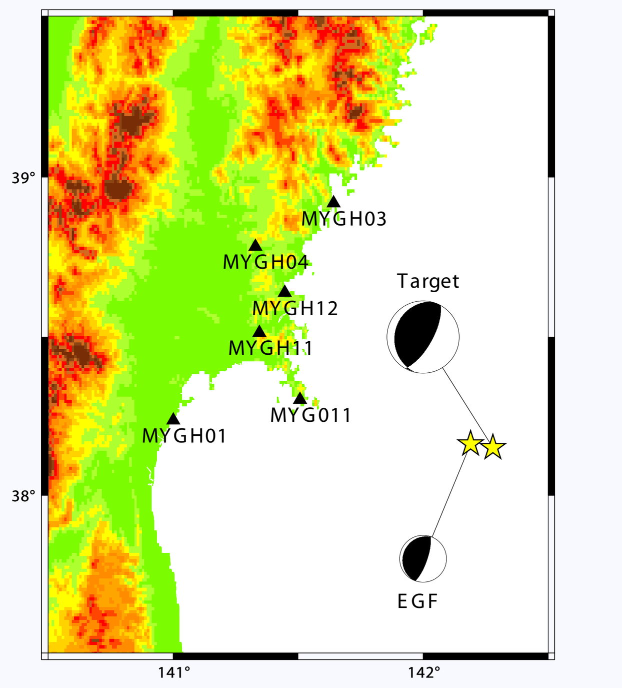
Kushiro-oki event (#9: 2005/01/18 23:09 Mw6.2 Depth=49.8km)

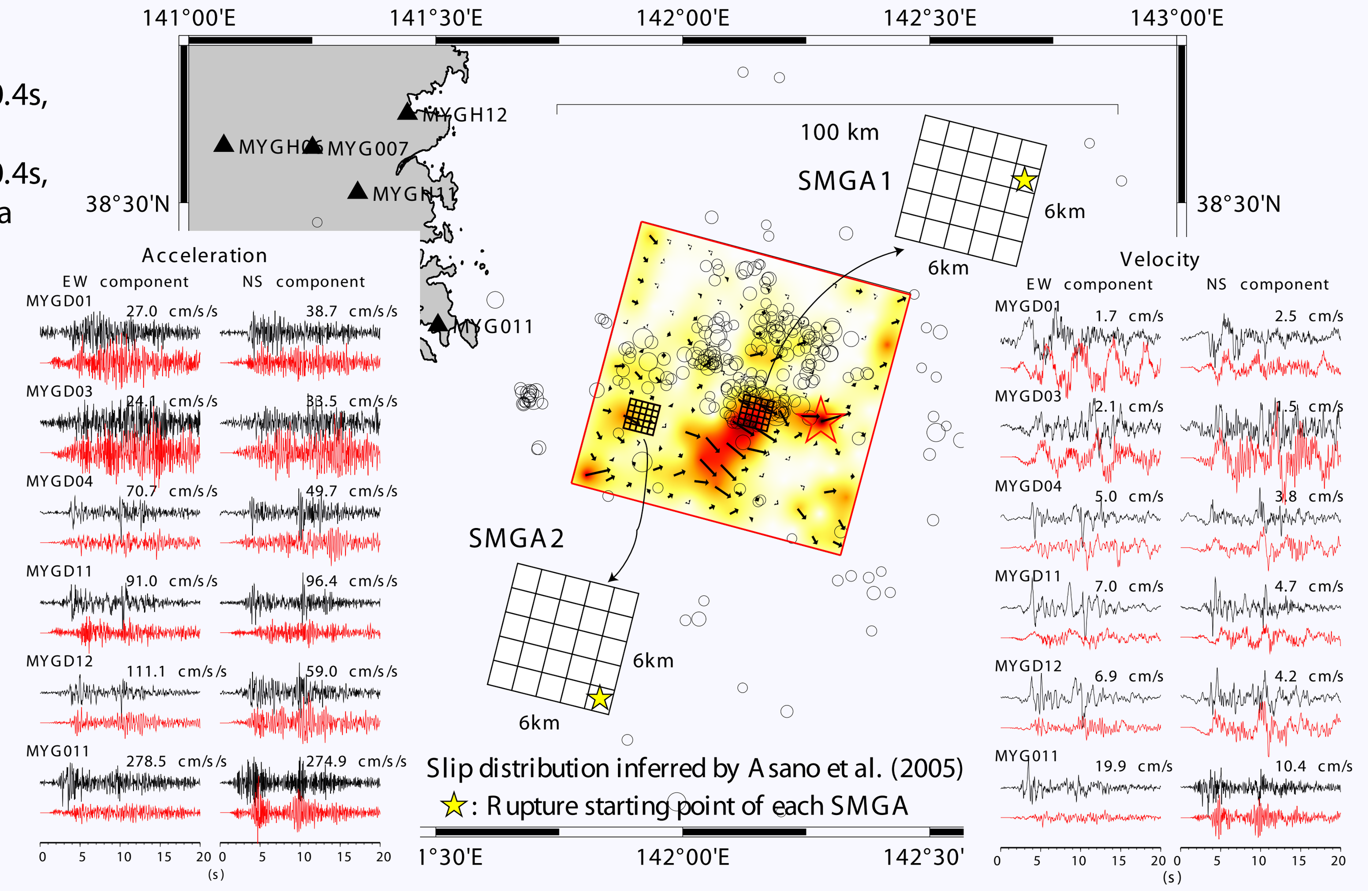
EGF: 2004/12/07 18:30 Mw4.4 Depth=51.1km
N=6, C=1.7, 0.4-10Hz
Lenght=2.4km, Width=4.7km, Rise time=0.53s, 118.1MPa



Miyagi-oki event (#10: 2005/08/16 11:46 Mw7.1 Depth=41.6km) This the result has been revised in 2006

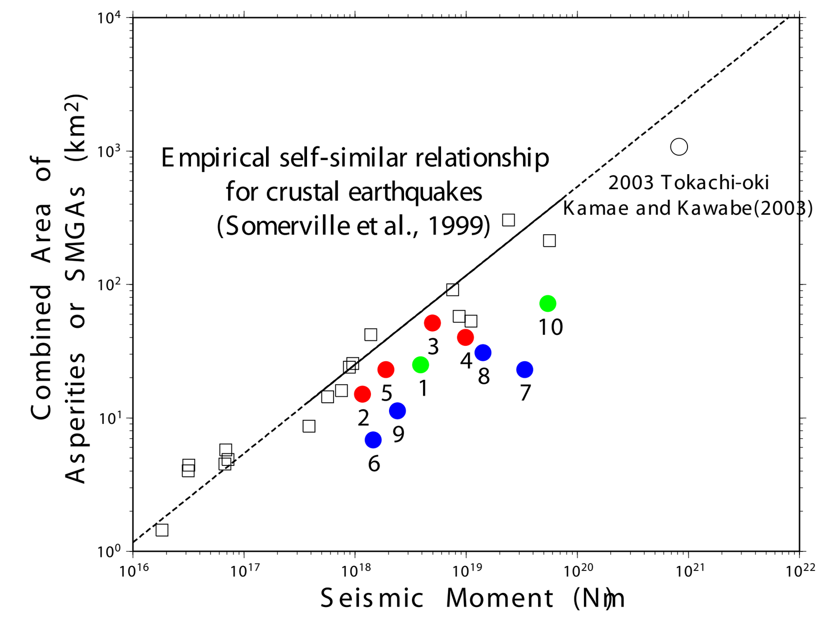
EGF: 2005/09/12 04:28 Mw4.6 Depth=41.9km
Two square SMGAs, 0.2-10Hz
SMGA1: Length=6km, Width=6km, Rise time=0.4s, Rupture delay time=3.0s, Stress drop=134.5MPa
SMGA2: Length=6km, Width=6km, Rise time=0.4s, Rupture delay time=10.0s, Stress drop=134.5MPa





A comparison of velocity waveforms produced by estimated model, double-size model and half-size model to see how waveform change by size variation. Estimated model fits best among three.

Relationship between SMGA size and seismic moment



●: Tokachi-oki events, ●: Kushiro-oki events, ●: Miyagi-oki events

It can be seen that SMGAs of crustal earthquakes indicated by □ follow this relationship whereas SMGA of interplate earthquakes analyzed here tend to have smaller size than predicted from the empirical relationship. This may indicate that interplate earthquakes have larger stress drop on the SMGA than crustal earthquakes. We can also observe that SMGA of Kushiro-oki events is smaller than that of Tokachi-oki events for the same seismic moment.

Conclusion

We estimated source model which is comprised of SMGAs for ten interplate earthquakes along Northeast Japan. Such models could explain main characteristics of broadband strong motions. SMGAs are roughly corresponding to the large slip regions inferred from kinematic source inversion using lower-frequency waveforms. The size of SMGA tends to be smaller than that for crustal earthquake with the same seismic moment predicted from the empirical self-similar relationship. This may imply that interplate earthquakes have larger stress drop than crustal earthquakes on the SMGA. As for the size of SMGA, we also observed the regional characteristics between Tokachi-oki events and Kushiro-oki events. Kushiro-oki events tend to have larger stress drop than Tokachi-oki ones on the SMGA. Although the amount of the analyzed earthquakes is small, Miyagi-oki events may also have larger SMGA stress drop.

Acknowledgements
We used strong-motion data of K-NET, KiK-net, F-net maintained by NIED, and JAMSTEC ocean bottom seismometers. We used JMA hypocenter catalog and F-net moment tensor catalog for source information. We thank them for providing the valuable data.

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